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Article

Benefits of an Electric Road System for Battery Electric Vehicles

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Abstract: Electric road systems (ERS)—infrastructure that allows for charging while driving—are currently considered in Sweden for electrifying long-haul trucking. The technology can also charge battery electric passenger vehicles (BEVs). This study utilizes real-world car movement data in Sweden and detailed spatial analysis to explore to what extent ERS could displace stationary charging if it is available for BEVs and the expected benefits. We find that ERS utilization and the minimum battery ranges depend more on visited locations and home locations and less on the annual travel distances of car users. The median battery ranges required by rural residents are 15–18% greater than for urban residents. Our scenarios suggest that a mix of ERS and home-charging would achieve the most significant benefits. ERS with home charging reduces the required battery range by 62–71% in the main scenarios, and the net savings from smaller BEV batteries exceed the cost of ERS. Eliminating all stationary charging is feasible for many but not all vehicles. Utilizing ERS could also significantly reduce peak BEV charging by distributing charging throughout the day. We also find that there is a considerable difference between the maximum possible and minimum needed charging on ERS, which can significantly influence ERS revenues. Future studies can expand to include other modes (e.g., trucks) to provide more holistic assessments of economic benefits and charging needs.

Keywords: electric road system; dynamic charging; electric battery; battery electric vehicle; electric charging infrastructure



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1. Introduction

In Sweden, transport accounts for roughly 30% of CO₂ emissions [1], and passenger cars represent about 60% of these emissions [2]. Electrification of transportation, such as switching to battery electric vehicles (BEVs), is poised to mitigate these emissions especially well in Sweden, which features high energy efficiency and low electricity emissions [3,4]. The Swedish government has already proposed a ban on new gasoline and diesel passenger cars from 2030 onwards [5], which will require the pace of electrification to speed up. BEV charging technologies and infrastructures are considered central in this process [6]. They include conventional stationary charging and electric road systems (ERS) that allow for charging vehicles while driving [6]. Relying solely on home chargers would limit BEV adoption because of limited battery capacity, obstructing the electrification of the transport sector [7]. Currently, the focus is on constructing more stationary (fast) chargers outside home locations, which will require a large number of charging points and impact the vehicle's range, charging time [8–10], and the power grid [7].

Different ERS technologies have been developed and tested at small scales, ranging from a few hundred meters at test sites to a few kilometers on public roads in Sweden, Germany, and the US. [11,12]. Agreements between Germany and Sweden have already been initiated to intensify cooperation in ERS research [13]. However, ERS technology is not yet ready for passenger vehicles. Germany is considering overhead ERS technology that only serves heavy vehicles [14], while Sweden is still testing different technologies for different vehicle types. Other countries, e.g., Norway and Denmark, have recently started considering ERS for fleet electrification as well [12,13,15,16]. Heavy vehicles constitute 4% of all vehicles in Sweden and 18% of CO₂ emissions; passenger cars are 94% of all vehicles

and 67% of total CO₂ emissions from vehicles [17,18]. Charging passenger BEVs on the road could increase the utilization of ERS infrastructure and improve its value. The battery is an expensive component of a BEV. For a Chevrolet Bolt with a 400 km battery range, for example, the battery is 30% of the cost [19]. Reducing the battery capacity required to meet all driving needs would significantly decrease BEV prices [8], possibly encouraging more people to buy them [20]. Reducing required battery capacity would also solve many large-scale adaptation challenges that prevent a car user from switching to a BEV, e.g., long charging times [8–10]. Furthermore, drivers who use stationary charging prefer to mainly charge at home in the evening, when power demand is often already at its peak [7,21]. By contrast, ERS could impact peak power less by spreading charging throughout the day.

Given that there are significant technology lock-in effects and path dependencies in developing a large-scale ERS system [22], a thorough assessment of the tradeoffs and benefits of different configurations of ERS using realistic assumptions based on real-world data is critically needed to make a deliberate and informed choice.

1.1. Literature Review

Recent research has inspected the economic and environmental impact and infrastructure rollout of implementing large-scale ERS in a variety of locations [8,15,22–26]. In general, proposals place these systems on the roads with the most traffic [8,12,15]. Connolly [15] investigates BEV economics in Denmark with and without electric roads. The study compares the results to those for conventional vehicles, concluding that BEVs on ERS are the most viable option. Fuller [27] inspects the potential for dynamic charging to address range and recharge issues of BEVs in California, USA. Li and Mi [28] predict an 80% reduction in BEV battery capacity with an inductive ERS compared to stationary charging. Fyhr et al., Marquez-Fernandez et al., Domingues-Olavarria et al., Refs. [17,29,30] show that installing ERS that serves both heavy and passenger vehicles in Sweden results in a significant added value to society and reduces costs compared to stationary charging. Chen et al. [11] suggest that using ERS to charge vehicles attracts more drivers and generates more revenue than stationary charging. Taljegard et al. [16] investigate an ERS electrification of E39 in Norway and the resulting charging pattern and its impact on the electricity grid. Domingues-Olavarria et al. [30] analyze the societal cost benefits of implementing ERS in Denmark that can be used by commercial and passenger vehicles. Finally, Limb et al. [8] show the huge economic and environmental impacts of implementing ERS that serves all vehicle types in the USA.

In the studies mentioned above, the effects of ERS on BEV charging and battery capacities/ranges were based on general assumptions of vehicle use and driving patterns. For example, Fuller [27] assumes travel pathways that approximate the route a BEV might take between pairs of origins and destinations. Marquez-Fernandez et al. and Fyhr et al. [17] attempt to minimize the system costs by assuming arbitrary shares of electric driving over the total travel distance. Taljegard et al. [16] also assume a share of travel distance for vehicles in Norway using E39. Chen et al. [31] use a macroscopic model with mathematically tractable averages to characterize the deployment and operation of ERS and stationary charging. However, none of the ERS studies use the real movement patterns of cars, nor do they consider the possible role of ERS as complementary to stationary charging. Some studies are exceptions to that. Limb et al. [8] use detailed driving patterns in six US cities surveyed between 2001–2015 to explore ERS benefits assuming two arbitrary battery ranges and assuming that BEVs can be charged whenever and wherever stopped for more than one hour. Marquez-Fernandez et al. [29] use microscopic agent-based simulations to capture the behavior of each simulated vehicle to assess the impact that different charging infrastructure system parameters have on all vehicle types in Sweden with different scenarios and assumptions for stationary charging durations and locations, battery sizes, and ERS extension.

1.2. Our Contributions

Previous studies are based on simplified assumptions of driving patterns without individual details. Such assumptions prevent an accurate estimate of the heterogeneity of the required BEV-fleet battery ranges, potential economic effects associated with large-scale ERS deployment, and the temporal distribution of BEV power demand. The lack of a realistic understanding of the power demand and revenue for the various charging options prevents policymakers from making informed decisions. To the best of our knowledge, no research has been published based on the individual driving patterns of real vehicles on the effects of the demand on the power grid and required BEV battery ranges of ERS replacing or complementing stationary charging. Such data capture empirical information at the level of individual cars, including travel distance, parking areas/time, and home location, allowing us to calculate realistic estimates of the heterogeneity and unique characterization associated with range limitations, utilized roads, and charging events.

This research investigates the potential implications and benefits of including ERS as a charging option in terms of (1) the shares of driving on ERS roads, (2) required BEV battery ranges, (3) savings in individual vehicle costs, (4) use of ERS and stationary infrastructure for charging, and (5) temporal distribution of electric charging. This is one of the first studies, to the best of our knowledge, based on real-life individual movement patterns of passenger cars in Sweden and a detailed geographic information system (GIS)-based infrastructure system. The dual-infrastructure system (i.e., stationary and ERS charging) is compared to a system with 100% battery electric vehicles only charged with stationary charging and, when possible, to ERS-only charging infrastructure. The economic impacts specifically vehicle battery costs savings and corresponding infrastructure costs are estimated. The research constitutes a principal analysis assuming all technical issues and configurations of the ERS are solved when it is fully implemented. It is also a static analysis in that neither the ERS build-up phase nor the transition to a 100% BEV fleet are included.

2. Methodology

This study proposes several ERS placement scenarios in Sweden as described in Section 2.1. The study then simulates BEVs' battery state of charge (SoC) according to the detailed movement patterns of 412 privately driven cars in Sweden. The car movement patterns and ERS coverage are mapped to the Swedish road network using GIS (Section 2.2). Different stationary charging patterns are explored (Section 2.3). The required battery range, economic benefits, and temporal distribution of charged electricity are examined with different assumptions for ERS placement, charging rate, and availability of stationary charging given as sensitivity analysis (Sections 2.4–2.7).

2.1. Electric Road System

We use the road traffic data (i.e., the average daily traffic) provided by the Swedish Transport Administration [32] to determine the placement of ERS. The European (E) and National (N) roads constitute 4% of Sweden's total road length [32] while encompassing more than 50% of the national vehicle traffic counts (that is, all traffic, including cars, trucks, busses, etc.) [12]. This research applies ERS to different cases of the Swedish E and N roads that include different lengths and traffic volumes: E roads only, N roads only, and 25% of both E and N roads, E and N25 (including 50%, 75%, and 100% in the sensitivity analysis, or E and N50, E and N75 and E and N100, respectively), with "most traffic" determined by truck traffic volume (Figure 1). Truck traffic is used to prioritize road selection as it is assumed that ERS is mainly implemented to electrify heavy vehicles while passenger cars also benefit. While most (88%) of the traffic on the selected roads are passenger cars, the difference between selecting roads by truck traffic or by all vehicles is not large, with a 90% overlap between the two methods. E roads and N roads are almost equal in total length, whereas the E roads cover about 58% of the truck traffic on these roads. E and N25 and E and N50 cover about 53% and 81%, respectively, of the truck traffic on both E and N roads.

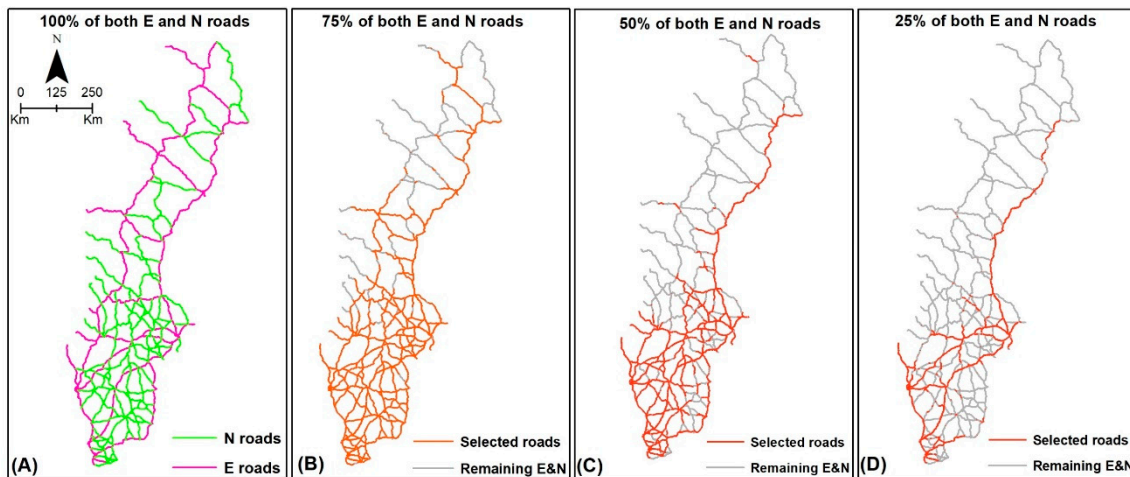


Figure 1. European (E) and National (N) roads in Sweden and the road segments with the top 100% (A), 75% (B), 50% (C), and 25% (D) truck traffic volume.

In the analysis, the only utilized technical specification of the ERS is the delivered charging rate, which is assumed to be proportional to the energy-use rate of each vehicle and dependent only on the distance driven, i.e., a constant specific energy use e (kWh/km) independent of, for instance, vehicle size, speed, road conditions, traffic, load, and weather. The charging rate e maintains the vehicle's battery SoC. In contrast, higher charging rates recharge the battery and increase the SoC (i.e., increases battery range) while driving on ERS. In the main scenario, we examine a charging rate for cars of $2e$, which thus corresponds to an added range of 2 km to the battery per km of ERS. ERS charging rates of e and $4e$ are also examined as a sensitivity analysis to provide insight into the impacts of charging rates.

The assumptions mean that the net charging power delivered to the vehicle increases linearly with vehicle speed. For example, when driving at 100 km/h and using 0.18 kWh/km, the ERS charging power is 18, 36, and 72 kW, for the rates e , $2e$, and $4e$, respectively. The net charging power assumption disregards any electricity losses, e.g., from the electricity grid to the battery. For comparison, a Tesla Model 3 is rated at 0.165 kWh/km by US EPA for highway driving and achieves 0.18 kWh/km at a constant speed of 120 km/h [33]. For comparison, other studies have considered that the ERS can deliver charging powers of 20–60 kW with different efficiencies [8,10,28,34,35].

2.2. Car Movements Patterns

The study uses GPS measurement data from the Swedish Car Movement Data project [36] to describe individual internal combustion engine (ICE) car movement patterns. For that project, the cars were selected from the car registry by a stratified sampling regarding ownership (company car/private car), car age (0–3/3–8 y), car weight (≤ 1500 / >1500 kg), fuel type (diesel/non-diesel), and residency (city/non-city) in Western Sweden. Data were gathered for each car for about two months. GPS loggings were performed during 2010–2012 and covered all seasons. The dataset is considered representative of all of Sweden in terms of urban and rural areas, city size, household size, income and population density, car size, and car fuel type [37] and has been used to study the adoption of electric vehicles and implications for electric systems in Sweden [12,16]. Only cars with at least 30 days of GPS measurements are selected for further analysis, resulting in 412 cars with loggings for 30–80 days. Trips or trip parts occurring outside Sweden are excluded from this study.

The residences of the drivers are classified as urban or rural by overlaying their home locations with the land-cover/land-use data obtained from the European Union's Earth Observation Programme [38], as implemented in [39,40]. A third of the drivers reside in rural areas, while the remaining reside in urban areas. On average, rural cars are driven 17% more annually than urban ones. The extrapolated average annual travel distance for the cars is 22,155 km/year.

2.3. Stationary Charging Patterns

This study considers three stationary charging scenarios: “home-only stationary charging” (HomeSC), “home and other stationary charging” (MixedSC), and “no stationary charging” (NoSC). HomeSC is presented as the main charging strategy, with most BEVs being charged overnight [7]. In MixedSC, drivers complement home charging with non-home stationary charging, mainly at workplaces. Subsequent calculations consider stationary charging both with and without ERS to explore how these technologies depend on/complement each other. In NoSC, drivers only use ERS to charge their BEVs. NoSC represents an extreme case and is set up to investigate the possibility of complete independence of stationary charging when having dynamic charging in the form of an ERS.

The study applies a temporal approach to identify charging occasions for the two charging strategies, HomeSC and MixedSC. For our main charging scenario (i.e., HomeSC), stationary charging events occur when parking time exceeds 10 h, or 8 h if the parking time includes 03:00 am. Selected parking times are meant to effectively pick out home or overnight parking [41], during which we assume cars have access to chargers. In the MixedSC case, stationary charging occurs when the parking time exceeds 4 h, which we here, in addition to home or overnight charging, identify as charging at workplaces or commuting parking lots (a major part of charging events) and other destinations (minor part). The resulting mean (95th percentile) trip distances between charging events for HomeSC and MixedSC scenarios are 57 (190) and 40 (132) km, respectively.

2.4. BEV Energy Use and Required Battery Range

The minimum required battery range to fulfill each trip starting from a full battery is calculated with and without ERS. In all three stationary charging scenarios, cars are assumed to start their respective trips fully charged (i.e., SoC is 100%). The aforementioned parking times are assumed to be enough to fully charge a vehicle’s battery. With ERS-driving, vehicles simultaneously add energy/range to their batteries at rates depending on the various assumed ERS-charging rates or, when the battery is full, at a rate that maintains 100% SoC. Finally, the required battery range for each vehicle is taken as the maximum of all its minimum required trip ranges. Impact on the power grid is analyzed with temporal information for charging events.

2.5. Vehicle Cost Savings

The battery cost c_B is assumed to be ~106 EUR/kWh. The cost of lithium-ion batteries has continuously dropped with technological advances and scale of production, from ~250 EUR/kWh in 2015 [20,42,43] to 160–207 EUR/kWh in 2017–2019 [44–46]. The battery price is expected to drop further to reach a range of ~85–135 EUR/kWh in 2025 [42,45]. In a similar analysis to estimate the economic benefits of small batteries, Ref. [8] considers a battery cost of ~190 EUR/kWh. To achieve cost competitiveness with combustion engine vehicles, Refs. [42,45] argue that the battery cost needs to fall below ~106–126 EUR/kWh. Therefore, our estimated cost savings from reduced battery capacity (range) with 106 EUR/kWh could be considered conservative. During the ERS lifetime, the reduced battery range required with the technology, less the cost for the pick-up system, yields monetary savings $s_{B,i}$ in the investment cost for car i :

$$s_{B,i} = (R_{st,i} - R_{ERS,i}) \times e \times c_B \times N_B - (c_{PU} \times N_{PU}) \quad (1)$$

where $R_{st,i}$ and $R_{ERS,i}$ are the battery ranges required with stationary and ERS charging, respectively, for car i . The average specific energy use e is assumed to be 0.18 kWh/km, equal to the average specific energy use of a VW e-Golf [47]. N_B is the number of generations of batteries saved during the ERS lifetime = ERS lifetime/BEV battery lifetime. For ERS, a technical lifetime of 35 years is expected, which is similar to what is typically applied for railway investments [48]. Assuming that an electric battery would serve up to 15 years [8,15], this yields at least two batteries within the ERS lifetime. Therefore, the study assumes the

economic benefits of two reduced battery capacities for each BEV examined, i.e., N_B is set to 2. c_{PU} is the investment cost of the pick-up system mounted on the vehicle to pick up the electricity from the ERS [12]. N_{PU} is the number of pick-up systems during the ERS lifetime. The research estimates a c_{PU} of EUR 1010 and N_{PU} of 3 for passenger BEV as described in [12].

The total savings $S_B(\Delta)$ for a certain share Δ of the total Swedish vehicle fleet V adapted to ERS is estimated by scaling the number of modeled vehicles (M) assuming either the economically optimal order (i.e., $S_{B,opt}(\Delta)$), where drivers with the highest battery capacity savings switch to ERS first as in Equation (2), or a random order (i.e., $S_{B,rdm}(\Delta)$), where drivers switch in random order to ERS as in Equation (3):

$$S_{B,opt}(\Delta) = \max_i \left[\frac{\sum_i^{\Delta M} s_{B,i}}{\Delta M} \right] \times \Delta \times V \quad (2)$$

$$S_{B,rdm}(\Delta) = \left(\sum_i^M s_{B,i} \right) / M \times \Delta \times V, \quad (3)$$

2.6. ERS Costs

Several studies and reports have large uncertainties in their estimates of the ERS infrastructure cost because ERS is still an immature technology under development, and results from the different ERS test sites at small scales on public roads are limited [12]. The Swedish Transport Administration estimates several technologies currently being tested in Sweden with a range of 1.2–2.0 M EUR/km for electrifying both directions [49]. However, the German Institute for Energy and Environmental Research estimates the infrastructure cost for catenary ERS in the range of 1.7–3.1 M EUR/km [14]. Other studies and reports estimate inductive and conductive ERS technologies a range of 0.4–2.7 M EUR/km, including the components for both the electric road infrastructure in both directions and the electricity distribution to the road [8,12,22,49,50]. Here, we consider two ERS cost estimates: a low estimate of 0.4 M EUR/km of road and a high estimate of 2.7 M EUR/km of road. The study also assumes, as in Limb et al. [8], that the extra annual operation and maintenance costs associated with road segments of ERS are equal to the operation and maintenance costs of conventional roadways or about 0.01 M EUR/km [51]. Installing this system in both directions on two-way roads yields 4690 km and 18,770 km of ERS for E and N25 and E and N100, respectively.

2.7. Stationary Slow Charging Infrastructure Specifications and Costs

We consider slow chargers corresponding to the simulated stationary charging at relatively long stops (i.e., 10/8+ and 4+ h). It is reasonable that each car has a charger for their overnight parking at or near home. There are also stops of longer duration outside the home, for instance, at summer houses, hotels, etc. On the other hand, there are possibilities to coordinate charging equipment installation in households with more than one car and in large parking lots, keeping the cost down.

In the MixedSC scenario, we assume more chargers per car than HomeSC, where the number of extra chargers is proportional to the extra number of charging events (i.e., 0.425). Many cars are used for daily commuting and demand charging points in the MixedSC scenario. Not all commuting cars park simultaneously, though. The cost of slow charging infrastructure ($C_{slow\ infra,scen}$) is calculated using the following formula:

$$C_{slow\ infra,scen} = V \times k_{scen} \times N_{charger} \times C_{slow\ charger} \quad (4)$$

where k_{scen} is the number of slow chargers per BEV and is set to 1 and 1.425 for HomeSC and MixedSC, respectively. $N_{charger}$, the number of installed chargers in ERS's lifetime, is set to 3, corresponding to an average expected lifetime of a charger of about ten years [52]. In the power simulation, a delivered charging power of 6.6 kW is used, and the corresponding average cost for the slow chargers, $C_{slow\ charger}$, is set to EUR 2000, including equipment and installation [52–54].

2.8. Treatment of Fast Charging

Both slow home and destination chargers can be complemented by fast chargers (FC) for quick charging along the road on long-distance trips. It may occur when stopping for short breaks or at extra stops taken exclusively to fill up the battery. However, we have deliberately not simulated fast-charging events in our simulation. Therefore, there is no effect on the battery sizing or the charging distribution in time and space. The reason for this is due to the ambiguity introduced in how to identify these occasions based on ICE car driving patterns. Further, the dependency on individual charging behavior and the battery sizes introduces an intrinsic contradiction when our main purpose is identifying the necessary battery size to fulfill all driving. However, excluding fast charging is of less importance as long as our results emanate from the comparisons of scenarios and not from absolute values. Excluding fast charging holds especially true for the economic analyses: whatever FC infrastructure, the costs cancel out if the same FC system is assumed in all scenarios.

The possible effect of omitting FC on our results is further elaborated in the Discussion section. Here, we estimate the possible size and cost of an FC infrastructure. An FC system should initially focus on geographic coverage and, later, have enough charging points to keep down the waiting times when the number of BEVs increases. In Sweden in 2018, the need for extra FC stations was estimated to be of the order of 300 to cover (max 50 km between stations) all roads classified as “functionally prioritized roads for long-distance personal transport” [55]. These roads are around 20,000 km and coincide to a large extent with the E and N roads, i.e., the ones suitable for an ERS system. Currently (end of 2021), Sweden has around 99,000 BEVs and 1600 FC charging points with a total capacity of 0.137 GW, comprising a specific FC power of 1.38 kW/BEV [56]. Applying the same driving data set as we do with real FC charging time-of-day data, and a queuing model, Gnann et al. [57] estimated the needed specific FC infrastructure for a larger BEV fleet to be 0.27 kW/BEV assuming charging points of 150 kW each and a battery range of 300 km. For a fleet of 4.9 million BEVs in Sweden, this sums up to nine thousand charging points with a total power of 1.35 GW and a cost of EUR 1.6 billion when assuming an estimated charger cost of EUR 59,000 each [55,57] and three generations of chargers during the ERS lifetime [57]. Thus, we can note that for an FC system, total power and cost are dwarfed compared to slow home chargers, which add up to 32 GW and EUR 29 billion in our HomeSC scenario. We also note that it has lower specific power than the current FC system still in a build-up phase.

3. Results

3.1. Selecting Roads with the Highest Traffic Increases ERS Utilization

The study derives the ERS driving share for each BEV as the percentage of total travel distance on roads equipped with ERS, see Figure 2. Implementing more kilometers of ERS increases the ERS driving share but with diminishing returns. Increasing the ERS kilometers from E and N25 to E and N50 and then to E and N75 and finally to E and N100 increases the average ERS driving share by 6, 3, and 1 percentage points, to reach a maximum of 49%.

The placement of ERS is more important. Even though the total lengths are equal for E and N roads, with almost 50% each, their contributions to the ERS driving share are very different, with N roads performing notably worse. Additionally, E and N50 results in higher ERS driving shares (mean 45%) compared to 100% of E roads alone or 100% of N roads alone. Here, we use E and N25 as the main scenario for ERS placement and compare it with E and N100 in the sensitivity analysis.

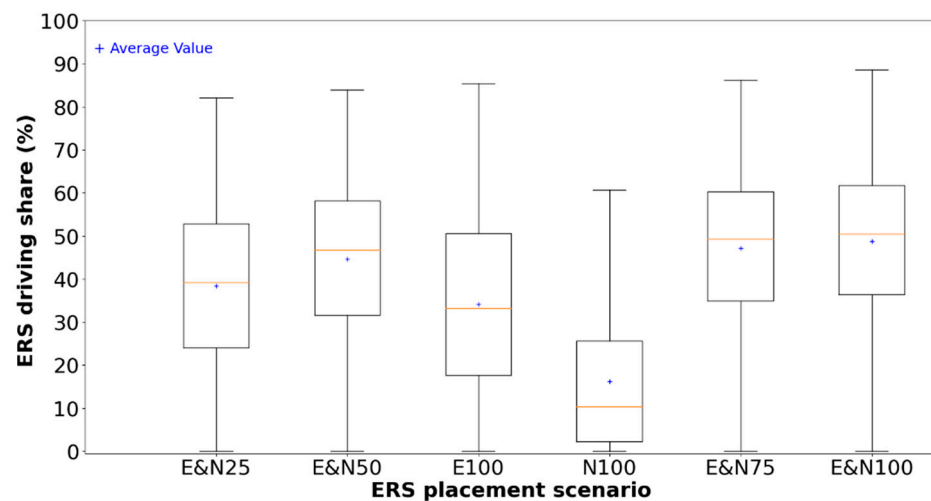


Figure 2. Box plots for the ERS driving share in six ERS scenarios. E and N25, E and N50, E and N75, and E and N100 refer to scenarios with ERS implemented on 25%, 50%, 75%, and 100% of both E and N roads, respectively, measured by traffic volume. E100 and N100 refer to European (E) and National (N) roads only, respectively. The scenarios are ordered according to road length from the shortest on the left to the longest to the right, although E and N50, E100, and N100 have roughly the same road length.

3.2. ERS Utilization Is Not Very Dependent on Annual Travel Distance but Urban/Rural Residence

Urban residents have a higher ERS driving share (54%), on average, compared to rural residents (48%) in both ERS placements, see Figure 3. The ERS driving share is not very dependent on the total driving distance for each car, as suggested by the very low coefficients of determination (R^2) for the regressions. Noticeably, some BEVs utilize ERS sparingly. Even for E and N100, for about 7% of the cars, less than 20% of their total travel distances are on ERS roads. These also tend to have low annual kilometers. On the other hand, cars with high annual driving ($> 40,000$ km/year) have high ERS shares of on average 66%.

3.3. Combining ERS with Stationary Charging Significantly Reduces the Required Battery Range

The study shows the possible reductions in battery range by estimating the required minimum battery range for each vehicle. The battery range required to cover all driving, sorted from small to large, and the median and mean battery range for each case are shown in Figure 4. Reduction in batteries is mainly presented with median values. In contrast, mean values are considered for later economic evaluation. In the absence of ERS, in the HomeSC scenario, the median range to complete all driving is 266 km (Figure 4A). For 95% of the cars to be able to complete all their driving would require batteries with a range up to 655 km, which is greater than currently commercially available (For reference, the battery range for Tesla Model S is about 416–555 km).

Utilizing E and N25 ($2e$) with HomeSC yields a median reduction in battery range of 62%, to only 101 km (Figure 4A). E and N100 further decreases battery ranges, with a median reduction of 71%, to 78 km (Figure 4B). Reducing the charging rate on E and N25 from $2e$ to e yields an increase in the average battery range required by 26%, whereas a doubling to $4e$ decreases the range by only 12% (Figure 4A). For MixedSC, the results are very similar to the HomeSC case; workplace and occasional charging at longer stops (≥ 4 h) do not alleviate battery range requirements.

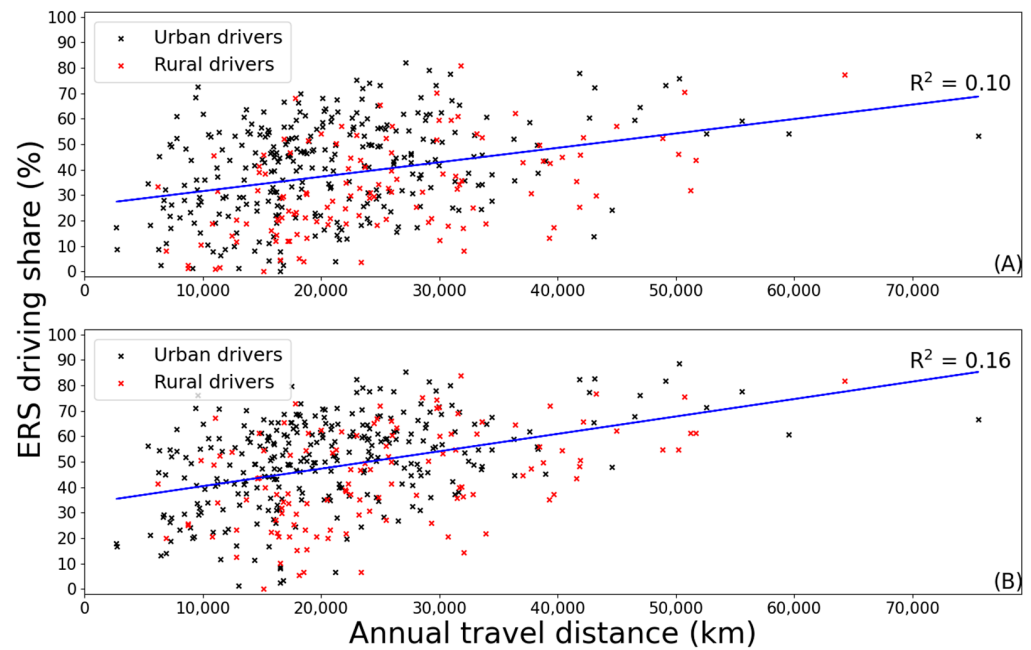


Figure 3. ERS driving shares for individual cars versus extrapolated annual travel distance for (A) E and N25 and (B) E and N100 for urban and rural drivers. Blue lines are the linear regressions for all drivers.

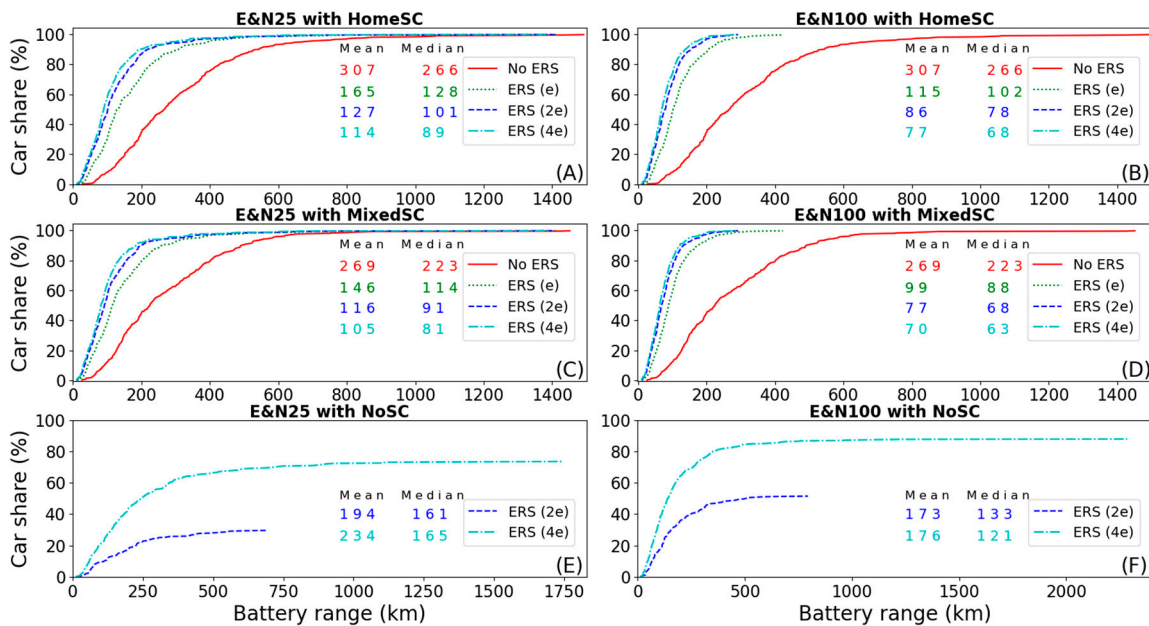


Figure 4. Cumulative share of cars for required battery ranges to cover all driving in the 25% of E and N roads (E and N25) case (left) and 100% of E and N roads (E and N100) case (right). The numbers next to the legend boxes are the mean and median battery ranges required to meet all driving. Note that (E,F) have different scales for x-axis than (A–D). HomeSC: home-only stationary charging, MixedSC: home and other stationary charging, NoSC: no stationary charging.

3.4. ERS without Stationary Charging Is Feasible for Many but Not All Vehicles

Given the observed car movement patterns, without any stationary charging, i.e., NoSC scenario, not all cars can solely rely on ERS. To rely on ERS, the car’s ERS driving share must be at least $1/x$ for an ERS charging rate of x_e . The share of drivers that can completely rely on ERS is 30% and 73% with E and N25(2e) and E and N25(4e), respectively. The share of drivers increases to 52% and 88% with E and N100(2e) and E and N100(4e),

respectively, as presented in Figure 5. Thus, the share of cars that fulfill this criterion increases with the extension, but even more with the ERS charging power. For those cars that can complete all their trips with NoSC, the median battery range requirement is 161 km for E and N25(2e) and 133 km for E and N100(2e). Doubling the charging rate to 4e more than doubles the share of cars that can rely solely on ERS but has minor impacts on the median required battery ranges (Figure 4E,F). The increases in required battery range when home charging is excluded are shown in Figure 5 for E and N25 and E and N100. Relative to HomeSC, NoSC increases the battery requirement by 105 kWh on average or 193% (42–508% for the 5th and 95th percentile) with E and N25(2e) and 135 kWh on average or 234% (38–711% for the 5th and 95th percentile) with E and N25(4e).

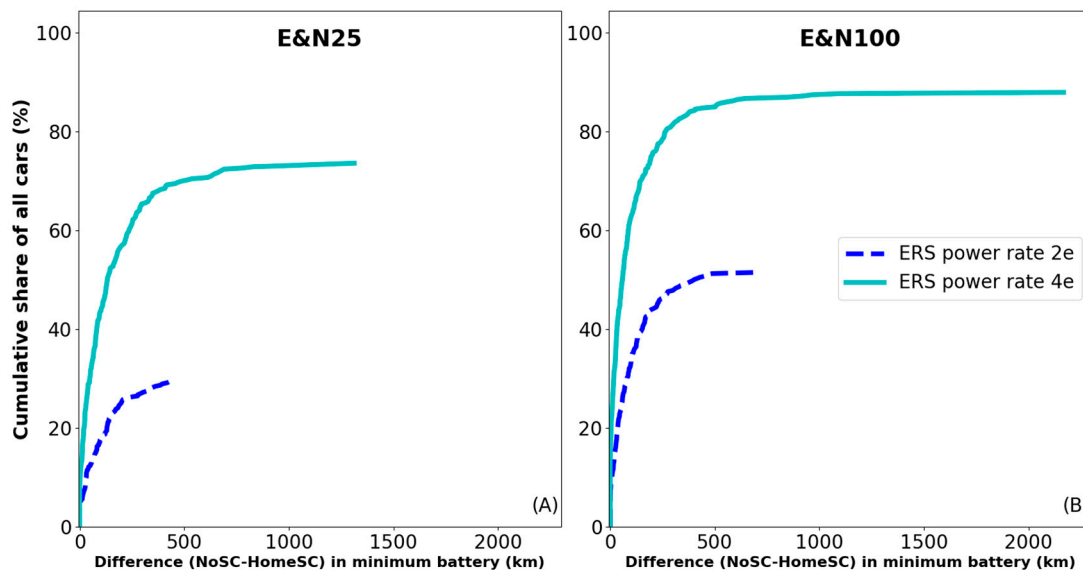


Figure 5. The cumulative share of all cars as a function of the difference in minimum battery range between ERS without and with home-only stationary charging, i.e., between NoSC and HomeSC, respectively. The share in (A) is shown for ERS on 25% of E and N roads (E and N25) while in (B) the share is for 100% of E and N roads (E and N100) for the two ERS power levels 2e and 4e. The cumulative shares are limited upwards by the shares of cars able to fulfill all driving without home charging (i.e., NoSC case).

3.5. Urban Residence Requires Smaller Battery Range

The required battery ranges for urban and rural residents differ. See, for example, Table 1 for ERS (2e). For the E and N25 system with stationary charging, the median battery ranges required by rural residents are 15–18% greater than for urban residents. The relative difference between rural and urban residents increases if the ERS is extended to E and N100. The larger batteries required for rural residents are partly due to the additional annual driving.

3.6. Savings from Smaller Batteries Can Be Sufficient to Recover ERS Infrastructure Cost

For an estimate of the economic benefit of reduced battery ranges, in Equation (2), the study assumes that all private vehicles in Sweden, about 4.9 million [58], follow the distributions of possible reduced battery ranges presented in Figure 4, and have the aforementioned energy use e of 0.18 kWh/km. The resulting savings are illustrated in Figure 6 for the two assumed orders of ERS adoption: (1) economically optimal (using Equation (2)) and (2) random order (using Equation (3)). The two horizontal lines show the range of ERS cost estimates.

Table 1. The median of battery ranges for rural and urban drivers without/with ERS (2e). E and N25: ERS on 25% of E and N roads, E and N100: ERS on 100% of E and N roads. HomeSC: home-only stationary charging, MixedSC: home and other stationary charging.

| Stationary Charging Pattern | ERS | Median Battery Range (km) | | |
|-----------------------------|------------|---------------------------|-----------------|-----------------|
| | | All Residents | Rural Residents | Urban Residents |
| HomeSC | No ERS | 266 | 278 | 262 |
| | E and N25 | 101 | 110 | 93 |
| | E and N100 | 78 | 90 | 70 |
| MixedSC | No ERS | 223 | 227 | 220 |
| | E and N25 | 91 | 98 | 85 |
| | E and N100 | 68 | 76 | 65 |

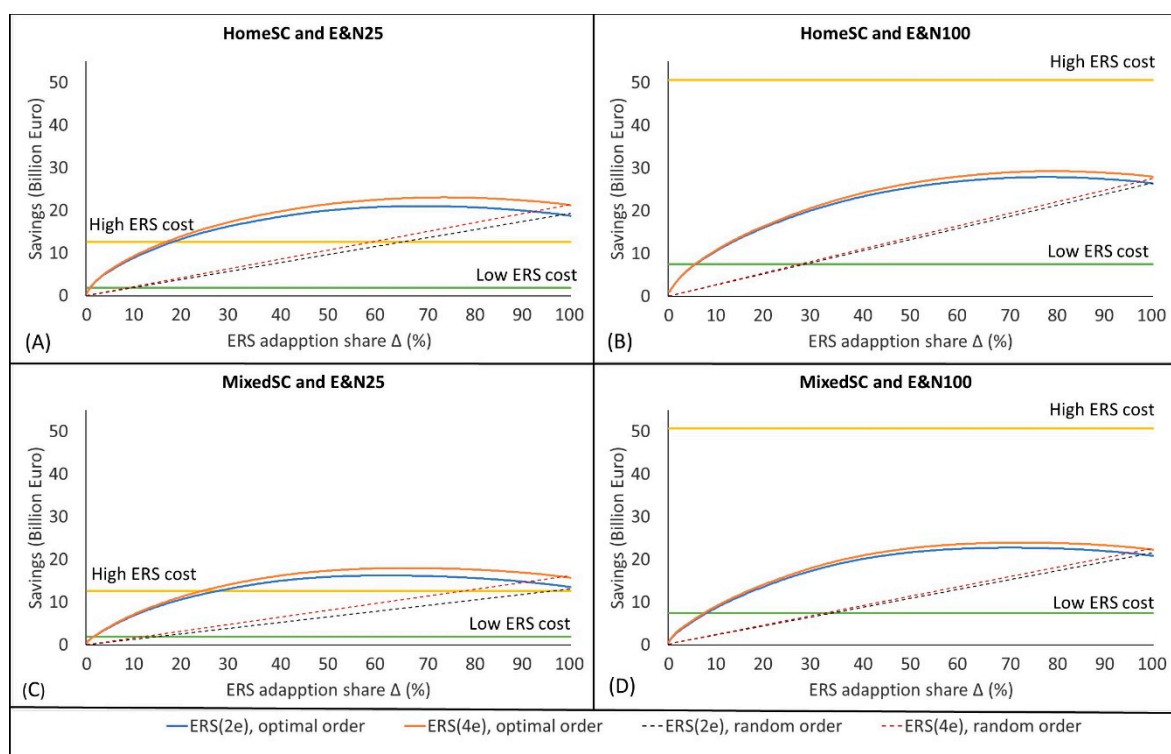


Figure 6. Savings in billion euros during the ERS lifetime from reduction in required battery capacity as a function of ERS adoption share Δ in vehicle fleet with (A) HomeSC and E and N25, (B) HomeSC and E and N100, (C) MixedSC and E and N25, and (D) MixedSC and E and N100, with 2e and 4e ERS charging power rates. The savings are calculated based on Equation (2) (optimal order) and (3) (random order), respectively. HomeSC and MixedSC refer to home-only stationary charging and home and other stationary charging, respectively.

With HomeSC, implementing E and N25 results in considerable net benefits for the whole range of ERS costs (Figure 6A). Even with high ERS cost estimates, the cost is covered if at least 18% and 65% of BEVs switch to ERS in the optimal and random scenarios, respectively. For MixedSC, given the smaller savings from reduced battery capacities, ERS-using BEVs have to make up 27% and 96% of the fleet in the optimal and random scenarios, respectively. The savings from saved batteries are not positive for all BEVs. Certain BEVs would invest more in the pick-up system than they save on battery capacity during the lifetime of an ERS. We estimate that 70% and 62% of the fleet could economically benefit from reduced battery sizes with ERS combined with HomeSC and MixedSC, respectively. For E and N100, only a low ERS cost would yield positive net savings (Figure 6B). In both HomeSC and MixedSC, increasing the ERS charging rate does not substantially increase

net savings. However, HomeSC has a greater absolute reduction in battery size (Figure 4) and thus higher net savings.

3.7. ERS or ERS with HomeSC Would Provide Relatively High Net Savings Compared to Their Costs

HomeSC without ERS requires high initial investments in both large batteries and home chargers. In Figure 7, the net savings in different scenarios are compared to this base case to cover a 100%-BEV fleet. We use the high-cost estimates for ERS to illustrate conservative net savings.

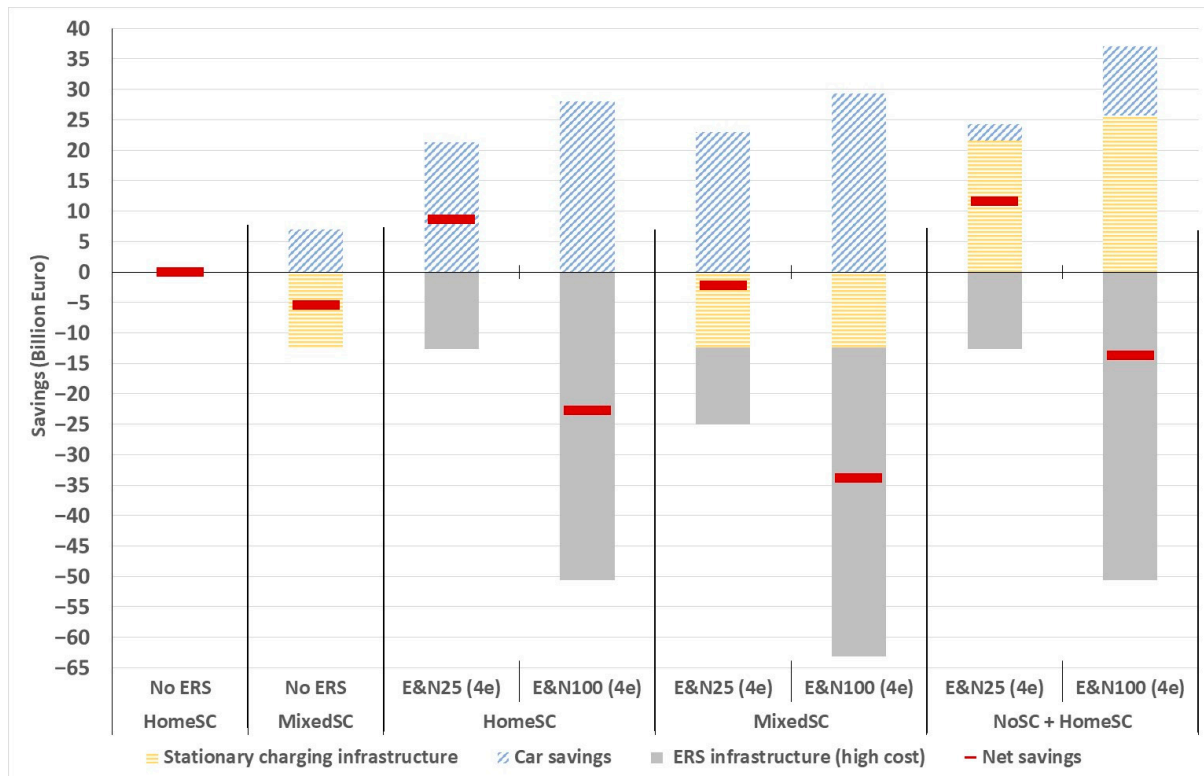


Figure 7. Car and charging infrastructure savings, ERS costs, and the resulting net savings for different combinations of stationary charging and ERS compared to the base case (left), assuming an ERS charging power rate of 4e, the high value for the ERS investment cost, and 100% of the fleet adapted to ERS.

Noticeably, ERS in the form of E and N25 (4e) with HomeSC could provide net savings of almost EUR 9 billion. Extending the slow charging infrastructure to MixedSC requires additional stationary charging investments of EUR 12.5 billion to cover a 100%-BEV fleet. The savings of EUR 7 billion in smaller batteries due to the additional slow charging (without ERS) do not compensate for this investment. With ERS, the costs outweigh the savings.

An E and N25 system with no home stationary charging (i.e., NoSC) for drivers that can completely rely on ERS (i.e., 73% of the drivers) and home charging (i.e., HomeSC) for drivers that cannot rely on ERS (i.e., the remaining 27%) provide the largest net savings or EUR 12 billion, as seen in Figure 7, the second bar from the right. Note that for some drivers who can eliminate home chargers, it is still not optimal to do it. Thus, net savings might be underestimated.

Extending the ERS beyond E and N25 can lead to considerable costs. For example, extending to E and N100 requires additional investment costs of EUR 38 billion but only results in savings of EUR 7–EUR 13 billion from smaller batteries.

3.8. When Drivers Maximize or Minimize Their ERS Utilization

The potential battery reduction with ERS presented earlier was derived by assuming drivers maximized their charging whenever infrastructure is available along their driving and at longer stops. However, for these given minimum battery ranges, car users could still maximize or minimize their ERS/stationary charging shares in place of the other charging option based on their preferences, such as economic considerations.

A significant difference in ERS charging shares is noted when drivers maximize or minimize their ERS utilization. The average shares of ERS charging for BEVs using their minimum vehicle battery ranges (shown earlier in Figure 4) for both extreme cases are illustrated in thick lines in Figure 8. The two extremes gradually decrease with increasing minimum battery ranges due to the reliance on stationary charging for long trips outside of ERS roads.

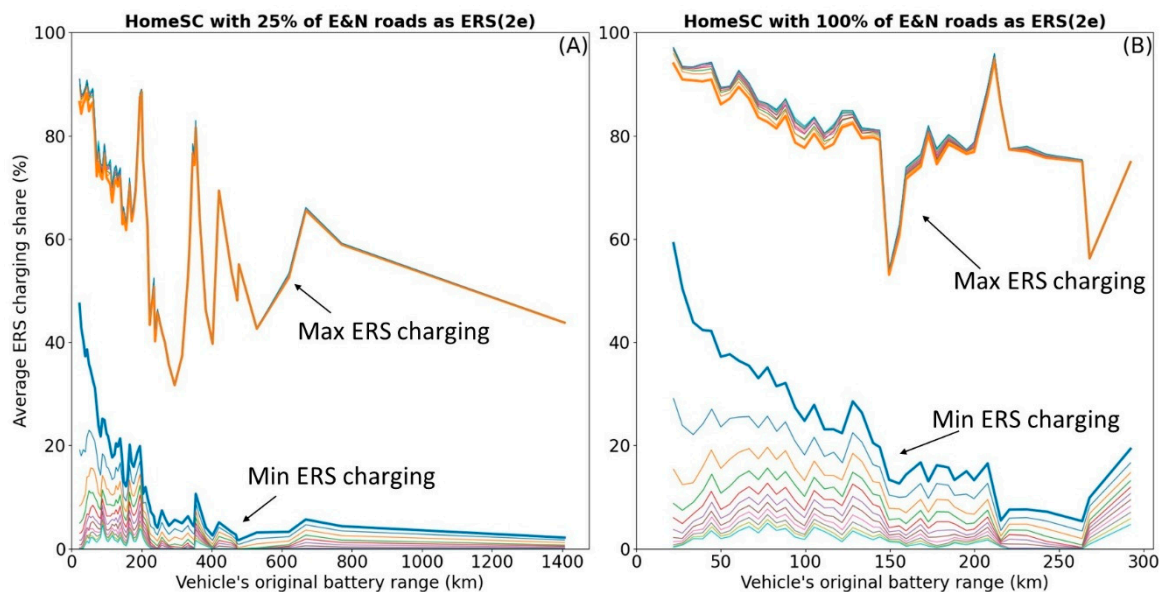


Figure 8. Maximum (thick orange) and minimum (thick blue) average ERS charging shares by minimum vehicle battery ranges given (A) E and N25 and (B) E and N100 and for home stationary charging (HomeSC) scenarios. The effects of increased battery ranges beyond the minimum battery requirement are shown in differently colored thin curves in steps of 28 km (i.e., of 5 kWh at $e = 0.18$ kWh/km).

Car users might utilize greater battery ranges than the minimum required. The effects of increased battery range above the minimum in steps of 28 km (~ 5 kWh at $e = 0.18$ kWh/km) are also given in Figure 8. Maximum ERS charging is insensitive to increased battery ranges, as shown with overlapped lines. However, increased battery ranges significantly influence minimum ERS charging shares, especially starting from small minimum battery ranges. Assuming a lower battery range limit of 111 km (~ 20 kWh), the average minimum ERS charging shares are still around 20% and below. Further, increasing the lower limit to 222 km (~ 40 kWh) reduces the shares to below 10%.

3.9. ERS Reduces Peak Power Grid Consumption by Distributing Charging throughout the Day

Hourly and daily charging patterns for stationary charging alone and both stationary and ERS charging for the main case (i.e., HomeSC and E and N25 (2e)) are shown in Figure 9 with their max–min use. It is assumed that stationary charging starts immediately when arriving. Thus, no flexibility is utilized. In the case of no ERS (i.e., HomeSC only), charging occurs mainly after working hours (i.e., after 16:00) and continues during the night, resulting in the highest charging peak of about 3 GWh/h between 18:00–19:00. With only minimum ERS charging (i.e., max HomeSC + min ERS charging), charging partially shifts

to earlier in the day with the highest peak reduced to 2.2 GWh/h. With maximum ERS charging (i.e., min HomeSC + max ERS charging), the charging is further evenly distributed throughout the day except 1:00–6:00 am, see Figure 9b, and the charging peak is reduced to 1.8 GWh/h, a 40% reduction compared to HomeSC charging only. Moreover, there are considerable differences in demand between weekdays and weekends, see Figure 9. There is less charging on weekends, especially on Saturdays, because vehicles are used less. As a reference, Sweden uses 380 GWh/day of electricity (or, on average, 15.8 GWh/h) in 2019 [59].

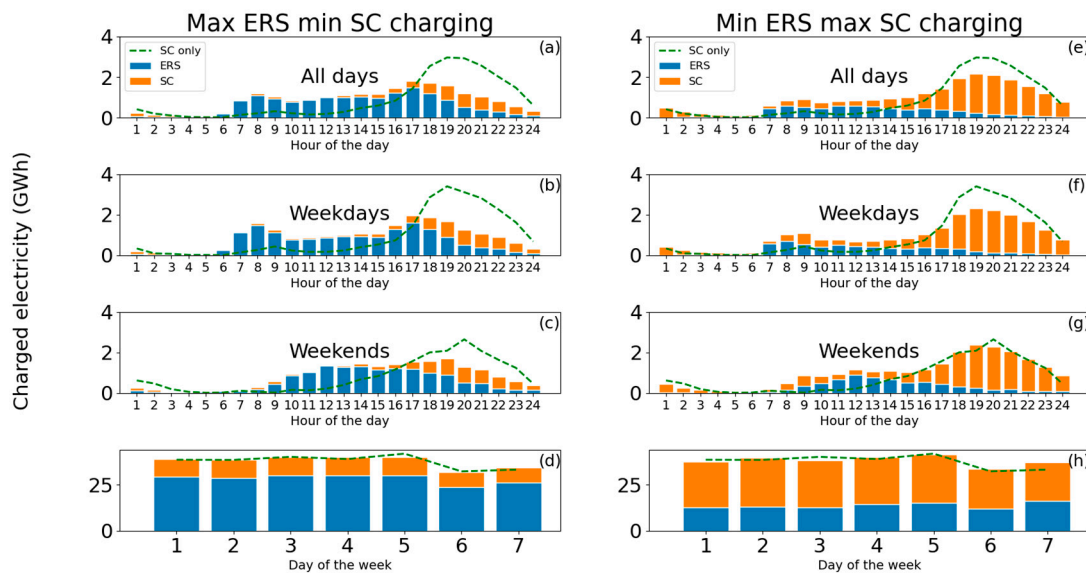


Figure 9. Hourly and daily distribution of EV charging. The dashed line represents the charging with only home stationary charging (SC only). Bars represent charging for E and N25 (2e) with the max ERS min SC charging case (left) for (a) all days, (b) weekdays only, (c) weekends only, and (d) for each day of the week, where 1 corresponds to Monday and 7 to Sunday. Corresponding results for the min ERS max SC charging case is shown in Figure. (e–h) (right). Note that the first three rows have different scales for y-axis than the last row.

4. Discussion

4.1. Data and Analysis

The data and the analysis have limitations and assumptions that can influence the results. The analysis is limited to Sweden, but the methodology could easily be adapted to other contexts in cases where similar data are available. The home location of the surveyed cars in Western Sweden provides a reasonable representative estimate of the potential battery range savings for those parts of Sweden with a relatively high population density. Still, the dataset probably overestimates the potential for other areas, especially for a less extensive ERS. Some regions are not covered as well as Western Sweden; see the placement of E and N25 in Figure 1D. The daily driving distances for drivers in the western region are similar to the Swedish average but differ slightly from counties with sparse population density [60]. Our data comprises private cars $\approx \leq$ eight years old, given that newer cars drive more and take longer trips more often. There is a tendency for higher ERS share with more driving (see Figure 3). Thus, the data may slightly overestimate the possible ERS share of driving for all cars. On the contrary, the limited period of tracking thus probably underestimates the share of cars occasionally driving longer trips and therefore underestimate the possible battery range savings from ERS.

Our simulations yield very small to large battery ranges depending on the driving patterns. However, due to customer preferences, BEVs with very small battery ranges may not appear on the market. On the other hand, our simulations and cost estimates do not include fast charging, resulting in very large batteries covering a few long trips

for some cars. This assumption may also be considered unrealistic. Limiting our analysis to a more realistic range of battery capacities decreases the battery savings. The average battery range saving in the main case scenario, i.e., E and N25(2e) with HomeSC, is 180 km (or 32 kWh) per car, see Figure 4. Limiting the batteries to current BEV market ranges (i.e., 150–500 km), the average battery range savings would decrease to around 120 km or 2/3 of the unrestricted savings. Of the decrease in savings of 60 km, 1/3 depends on the limit upwards and thus can be allocated to the availability of fast charging. Further, concerning the economic effects, an ERS system may decrease the need for fast charging points. However, because the cost of even an extensive fast charging system is relatively low compared to ERS (see costs in Methodology 2.7 and Figure 7), any possible cost saving is also relatively small and will not influence the major results, for instance, as presented in Figure 7. Moreover, the simulated minimum battery capacities are not determined based on an average driving day mostly related to work purposes, but on an occasional longer trip (e.g., on a weekend outing) maybe only interrupted by less than 4 h parking duration. Such long occasional trips explain the insignificant battery requirements reduction in the MixedSC scenario compared to HomeSC.

Most studies on ERS assume energy is supplied at constant power. Compared to such a system, our simulation assumption (partly for simplicity) for energy charging from ERS means that cars driving slowly are charged at a lower power rate than cars driving at higher speeds. This assumption will probably lead to underestimating the potential energy supplied from the ERS and, therefore, underestimating the possible battery savings. In contrast, the economic gains could be even higher. However, the battery savings are also limited by the driving distance to the ERS, limiting our underestimation.

Once again, we have assumed the needed functionality of this technology is in place. Utilizing ERS technology with a high charging rate for BEVs is still a technical challenge. Various companies propose charging powers between 20 and 200 kW for different vehicle types [8,10,28,34,35], which corresponds to roughly between e and $11e$ with our charging rate assumptions (power at 100 km/h). ERS with a high charging rate for BEVs (e.g., $4e$) can further reduce or even eliminate all stationary charging. The focus should then be on technologies that can be used by private vehicles and heavy trucks, i.e., that provide sufficient charging power for heavy trucks while allowing for relatively high charging power for private BEVs. For instance, with charging rates that serve trucks (i.e., charging power of 130–200 kW), current pick-up systems for cars can transfer a charging power of 50 kW [12], which is less than the investigated $4e$ (charging power = 72 kW under our charging rate assumptions).

For wear and longevity reasons, current BEV batteries are often limited in charging power to a C-rate of around 1 to 2 kW/kWh of battery capacity; that is, a full charge will take at least between 30 and 60 min. The saved battery costs in our estimate rely on using very small batteries for some vehicles. For instance, for the E and N25(2e), around 20% of the cars require a battery range below 50 km (~10 kWh), as depicted in Figure 4A. For these batteries, the assumed $2e$ charging power will be around 2C or more. Larger battery ranges could be deployed instead in these cars.

Utilizing the option to lower the ERS investment cost by covering only limited segments of the road will further increase the charging power on these segments if the average delivered power is to be kept constant. Such savings may thus rely on the further development of car batteries to tackle higher C-rates. Of course, restricting the minimization of the batteries will relieve any requirement but also restrict potential battery savings. It may be noted, though, that the development of batteries towards higher C-rates will also help diminish the inconvenience of a competitive fast charging system.

We made a conservative assumption that drivers can adapt to BEV comfortably without changing their driving patterns. Studies on the change in driving behavior from ICEV to BEV are so far limited. A few that exist are hypothetical cases or are limited to early adopters. For example, Karlsson and Karlsson [47,61] examine how multicar households have the option to use, and actually use, a short-range BEV extensively together with a

longer-range car, which also could be a BEV, with no change in the households' travel pattern. Rolim et al. [62] show that ICEV drivers can adapt to BEVs. At the same time, concerns they had before purchasing the vehicles usually go with experience and vehicle use, which suggests that given reasonable prerequisites, shorter battery ranges could be realistic.

The literature is still uncertain regarding infrastructure costs for electrification, especially for ERS and future stationary charging systems. Additionally, given that the charging power will be higher for trucks than cars, the study assumes that including the latter will not affect the decisions about dimensions or ERS costs. Moreover, many companies have tested different inductive and conductive ERS technologies with varying rates of power and different cost estimates. Thus, the study excludes any ERS cost dependency on car charging rates. Future FC and BEV system voltage needs to be adapted to each other. The study considers only the cost of a pick-up system and excludes a DC/DC conversion cost in the BEV. Thus, we assume that the ERS system is adapted to the relevant BEV car voltage. The study does not consider any dependence of road traffic on investment costs of electricity supply, which might not be accurate.

The infrastructure cost figures are deliberately and by necessity crude, but we believe this type of order-of-magnitude estimate provides valuable insights at this stage. The study mainly considers a pickup system cost for conductive ERS technology. Estimates for inductive ERS are of the same size but can be more sensitive to a higher power, for instance, if more than one receiver is used [63]. However, inductive systems are also less developed, and there could be room for enhancement [64]. On the other hand, this research does not consider the economic benefits of ERS to buses and trucks, which can be significant and have been the main motivation for the installation of ERS in the first place.

This study can be extended to examine many other important research/policy questions. E.g., the environmental impact of ERS vs. large batteries and fast SC. A follow-up study examining the carbon footprint impacts of full-fleet electrification of Swedish passenger car travel in combination with different charging conditions, including ERS is already published in [60].

4.2. ERS Placement, Coverage, and Economics

We found that economically it is feasible to utilize shorter ERS distances with high traffic. Among investigated scenarios with stationary charging, E and N25 costs about EUR 2–EUR 13 billion and then yields potential net savings from reduced battery sizes of EUR 9–EUR 19 billion. E and N100 costs four times more (EUR 8–EUR 51 billion) with little additional ERS share of driving and potential savings in battery capacities, see Figures 2 and 7. This finding is consistent with [12], which finds that utilization of E and N25 alone could result in the electrification of 70% of the traffic on E and N roads and 35% of Sweden's total traveled vehicle kilometers.

The electricity amounts and costs are not included in the study on the assumption that the differences between the scenarios are insignificant for the results. The losses in the different charging modes should be relatively low due to the generally high efficiency in the involved electricity transfer and conversion steps. Differences between the charging costs could also appear when considering, for instance, the difference between day and night charging.

Two essential properties of ERS for supplying long-distance trips are its relatively high investment cost and its less scalability with traffic. The high investment raises the cost of coverage of less trafficked roads and economically favors compromise coverage. For comparison, an FC system achieves reasonable coverage at a relatively low cost. Further development is easily and cheaply scalable to charging needs with an expanding BEV fleet by adding more charging points (see Methodology 2.8). As concluded, E and N100 is of the same size and overlaps to a large extent with the roads classified as important for long-range personal traffic and considered the important ones in achieving full coverage of an FC system. Similarly, E and N100 may be about the size of an ERS to achieve enough

coverage for people to find it convenient to buy BEVs with small ERS-adapted batteries. If so, an uneconomically large ERS (see Figure 7) is needed to reap the economic benefits of smaller batteries and, therefore, an expensive substitute for an FC system. Due to the low road coverage from a passenger car fleet perspective, we did not deliberate any ERS with an extension below E and N25, even though this has been considered in the Swedish Transport Agency's plan for ERS rollout for heavy vehicles [65].

The results show that in most cases the possible reduction in battery ranges from complementing stationary charging infrastructure with an ERS leads to lower total costs than without an ERS. This finding is consistent with [15] for Denmark and [8] for the US, which shows that ERS is less expensive than the additional costs of larger battery ranges. However, 30% of the fleet would not benefit economically from such battery capacity reductions when considering the pick-up costs.

Implementing ERS does not guarantee any specific usage of it, nor that the BEVs with minimum battery ranges are chosen [8]. This uncertainty will influence the expected savings and the charged energy on ERS. Many variables could affect a driver's battery and charging preference, e.g., battery prices, annual driving, charging rate, and electricity prices with ERS and stationary chargers [10,28,66]. Suppose ERS charging fees only cover operation and maintenance costs, as with other public transportation projects in Sweden and suggested in the recent public inquiry on ERS regulation [64]. In that case, this could lower the ERS electricity price. However, even with such a scenario, drivers might not completely rely on ERS charging.

The overall business model for the ERS will be crucial. The benefits and costs can be unevenly distributed. The significant economic gain from ERS goes to those BEV owners who can have and accept a smaller battery, while the major capital cost is the ERS investment. The needed addition to the energy price in an FC system to recover investments is relatively high, reflecting a small energy market because most charging occurs at home or other slow chargers. This addition is mirrored in the current price on public chargers of several times the electricity price. An ERS can have a charging share as low as an FC system (see Methodology 2.8 and Figure 8) but is much more expensive for a system with good coverage (compare FC cost in Methodology 2.7 to E and N100 cost in Figure 7). Thus, the needed addition for full investment recovery could be very high for an ERS, and other ways to recover the investment are unavoidable [67]. The specific arrangement for this will significantly influence who bears the costs and benefits from an ERS, especially if the ERS does not have full coverage. ERS shifts evening and night charging to daytime and alleviates the evening peak demand, see Figure 9. However, with smart charging technology and demand shifts to avoid high electricity prices, the actual benefits of ERS might be smaller in the future.

5. Conclusions

This study uses detailed driving patterns of representative individual conventional vehicles to investigate the possible benefits of adding an ERS charging option that can also be used by private passenger BEVs in Sweden. We show that, on average, passenger BEVs utilizing ERS can significantly reduce the battery requirement, although with a considerable spread depending on individual conditions. Considering these potential savings, investment in ERS can lead to an overall cost reduction compared to stationary charging only. Thus, passenger BEVs merit consideration when planning ERS infrastructure for trucks and buses due to the possibly considerable additional societal benefits. However, the uncertainty on to what extent these savings will be realized in the passenger car market and the behavioral effects of specific properties of the ERS realization, such as geographical coverage, business models, time-of-day/flexibility in charging, especially in comparison to alternative ways of supplying passengers BEVs with electricity, need further investigations.

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