Benefits of Electric Road System with charging from below technology to battery electric vehicles

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Summary

This study uses GPS-logged movement patterns of 412 private conventional cars in Sweden to model the potential impacts and benefits of implementing an Electric Road System (ERS) that is designed to be usable also to passenger Battery Electric Vehicles (BEVs). The study inspects the possibility of eliminating stationary charging stations and allowing smaller batteries in BEVs and its economic benefit. The study examines different ERS placement scenarios, charging options and BEV shares. The results show that an ERS makes possible a drastic reduction in the required battery capacities to complete all driving. With only charging at home, the mean reduction in battery capacity is 75%, or to about 14 kWh. An average battery capacity of 87 kWh could eliminate all stationary charging. In Sweden, with an ERS net economic benefits of 29-45 billion € are expected from reduced battery capacities alone, depending on the stationary charging pattern, percentage of cars switching to BEV, ERS placement and ERS charging rate.

Introduction

In Sweden, passenger cars represent about 60% of CO_2 emissions from transport [1]. Electrification of transport, such as switching to electric vehicles, can mitigate these emissions. Currently, for passenger electric vehicles, batteries are the dominant technology. However, for long-haul trucks, batteries are not considered realistic due to the size and weight required [2]. The newly emerged technology electric road system (ERS) transfers electricity to vehicles dynamically while driving on-road, making it a viable solution for electrifying long-haul trucks. The dynamic transfer of electricity can be done through overhead transmission lines or from the road below [3, 4]. Electricity transfer systems that use overhead transmission lines are conductive, with the vehicle connecting to the transmission line through a type of pantograph. Whereas the road-based charging from below (CFB) technologies can either be conductive or inductive. It also has the advantage of also making it possible to charge electric passenger cars, which are precluded for overhead lines for several reasons [3].

Selecting a technology that benefits multiple vehicle types is worth considering especially if the benefits can be expected to cover the expenses or maybe exceed it. For instance, charging passenger battery electric vehicles (BEV) on the road would increase the utilization of ERS infrastructure and therefore improve its value. Most importantly, given that a battery is the most expensive component of a BEV, a reduction in the battery capacity required to meet all driving needs would significantly decrease BEV prices, possibly encouraging more people to buy them [5]. ERS with CFB could possibly also be an alternative to stationary charging, especially for longer trips, by completely relying on ERS to charge the batteries.

Therefore, there is a crucial societal choice to be made for infrastructure for possible electric roads: either the more established overhead technique servicing only the heavy traffic and busses or utilize CFB to include passenger vehicles. To make a deliberate and good choice good assessment is needed. For that purpose, several ERS assessments including BEVs have been conducted earlier on the effect on the BEV charging and battery size due to ERS, such as [6, 7, 8, 9, 10]. However, they were based on general assumptions about the effect of electric roads on BEV charging and battery capacities, which fails to identify the real impact of ERS on individual drivers. Thus, to the best of our knowledge, there has not been any research on the effects and implications of BEV charging on ERS based on real driving of individual vehicles.

Based on individual real movement patterns for representative passenger cars in Sweden, this research aims to investigate specifically the BEV contribution to the viability of CFB on ERS. The research identifies benefits to passenger BEVs by assessing possible reduction in battery capacity with several realistic stationary charging patterns. The research also examines the cost savings of reduced battery capacities and stationary chargers with ERS.

Methodology

The research inspects the expected BEV usage of ERS by modelling individual driving patterns. The research utilizes GPS loggings for 412 cars with data loggings for 30 days or more. Loggings are extracted from the Swedish car movement database [11] measured between 2010-2012. The database contains the use of cars representative in car size and fuel types in Western Sweden, which is considered a representative part for all Sweden in urban and rural areas, city and household size, and population density [12]. The loggings are processed, filtered and projected to the road network. To explore the full potential benefits of ERS, BEVs are assumed to be charged with three stationary charging patterns. A temporal approach is followed to group the trips based on their parking times and considered charging pattern. The first is home-only stationary charging (HSC) where cars are charged at home locations only. The second is home and other stationary charging (HOSC), where cars complement their home charging with other publicly available stationary chargers. The last is no stationary charging (NSC) where cars are charged only on ERS without any complementary stationary charging.

Due to high investment costs, it is reasonable to place ERS on roads with the most traffic, as proposed in previous studies [6, 13, 7, 4, 8, 9]. We investigate large-scale implementation of ERS using road-traffic data (i.e., the average daily traffic, ADT) provided by the Swedish Transport Administration [14]. The European (E) and National (N) roads constitute 4% of Sweden's total road length [14] while encompassing more than 50% of the national vehicle traffic (all traffic, including cars, trucks, and busses, etc.) [10]. In this research, six ERS placement cases that include different lengths and traffic distributions are investigated; all E roads alone, all N roads alone, and also 25%, 50%, 75% and 100% of road lengths of both E and N roads, prioritized by traffic volume (Figure 1).

The research examines E-roads because it is discussed mostly for ERS in other researches [10], and compares it with N roads results. Knowing that E roads and N roads are almost equal in lengths, the traffic shares on each road type are different [10]. E roads only cover about 65% of both E and N traffic shares, while N roads only cover a little bit over 35%. On the other hand, 25% and 50% of both E and N road lengths, cover more than 81% and 95%, respectively, of traffic share on both road types.

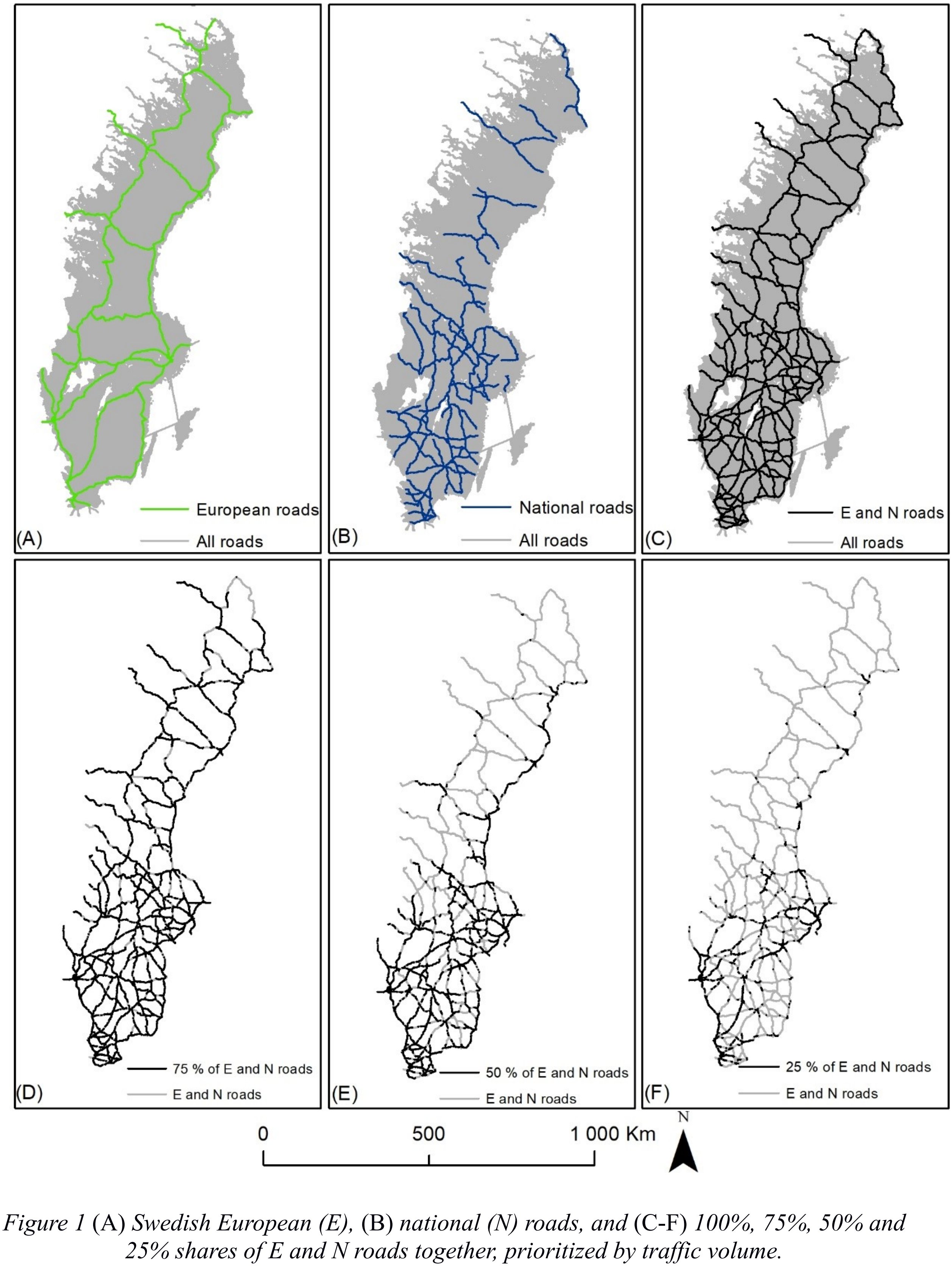

Figure 1 (A) *Swedish European (E),* (B) *national (N) roads, and* (C-F) *100%, 75%, 50% and 25% shares of E and N roads together, prioritized by traffic volume.*

For simplicity, all BEVs are assumed to have an average specific energy use of 0.18 kWh/km, independent of for instance road conditions and traffic, load and weather. This corresponds to the average energy use in a larger Swedish EV trial using VW e-Golf. This research assumes that charging power on ERS increases linearly with vehicle speed. Different ERS charging rates, ranging from *e* to 4*e* in steps of *e,* are inspected to provide insights into the impacts of charging rate. Charging rate *e* maintains the vehicle's battery state of charge (SoC), while higher charging rates recharge the batteries and increase the SoC while driving on ERS roads. The assumptions mean that charging power increases linearly with vehicle speed, and, for example, when driving at 100 km/h, the ERS average charging power to the vehicle is 18, 32 and 72 kW, for the rates *e,* 2*e* and 4*e,* respectively.

Several studies have estimated the ERS infrastructure cost of inductive and conductive technologies for rail ERS in the range of 0.4-2.7 M€/km, including the components for both the electric road infrastructure in both directions and the electricity distribution to the road [10, 4, 15, 16]. Accordingly, we consider two ERS cost estimates: a low estimate of 0.4 M€/km and a high estimate of 2.7 M€/km.

The lithium-ion battery used in a BEV is the most expensive part of the car. The battery current costs are 190-250 $/kWh in 2017- [17, 9, 18, 19]. But it is expected to drop to reach a range of 100-160 $/kWh in 2025-2030 [20, 9]. This research estimates battery price to be 120 $/kWh (~106 €/kWh), between 2025-2030.

The monetary savings from the reduced average battery capacity with ERS considers the battery capacity, BEV shares of vehicles in Sweden, expected battery price and the number of saved batteries per vehicle within a lifetime of ERS. For ERS, a technical lifetime of 35 years is expected, which is like what is typically applied for railway investments [10, 21]. If an electric battery would serve up to 15 years [6], this yields at least two batteries within the ERS lifetime. Therefore, we assume the economic benefits of two reduced battery capacities for each BEV examined.

On the other hand, to account for stationary charging costs two types of chargers are considered, i.e., slow and fast charging points. The research considers €2,000 and €75,000 per slow and fast charger, respectively [22, 23, 24]. The expected lifetime of a charger is about 10 years on average [23], which means that within the lifetime of an ERS at least 3 chargers of each type would be required at corresponding charging locations. Every BEV is assumed to have a slow home charger. Whereas, slow and fast chargers are considered for public charging points. Current EU regulation requires member states to set up policy frameworks that will provide at least one publicly accessible charging point per every 10 BEVs [25], of which 15.3% are estimated to be fast chargers in Sweden [26] and the remaining are slow chargers. Prices of HSC and HOSC stationary charging patterns are calculated accordingly.

Results

ERS utilization

For all modeled cars, the study identifies "Charging Distances" (CDs) as the distance of driving at roads equipped with ERS. Using that, the study identified ERS shares for each ERS placement case as the total CD to total travel distance, see Figure 2. Results show that applying ERS to more road lengths increases the coverage rate. However, even though both E and N roads have equal lengths, their ERS shares are different. More specifically, using 50% of both E and N roads results in higher coverage of ERS distance compared with 100% E or 100% N (Figure 2). This shows the importance of considering both the lengths and traffic while placing ERS. The difference between 25% of both E and N roads and 100% of both E and N roads is not significant. Thus, in the following analysis, we show E&N25 as the main scenario for ERS placement and compare it with E&N100 in the sensitivity analysis.

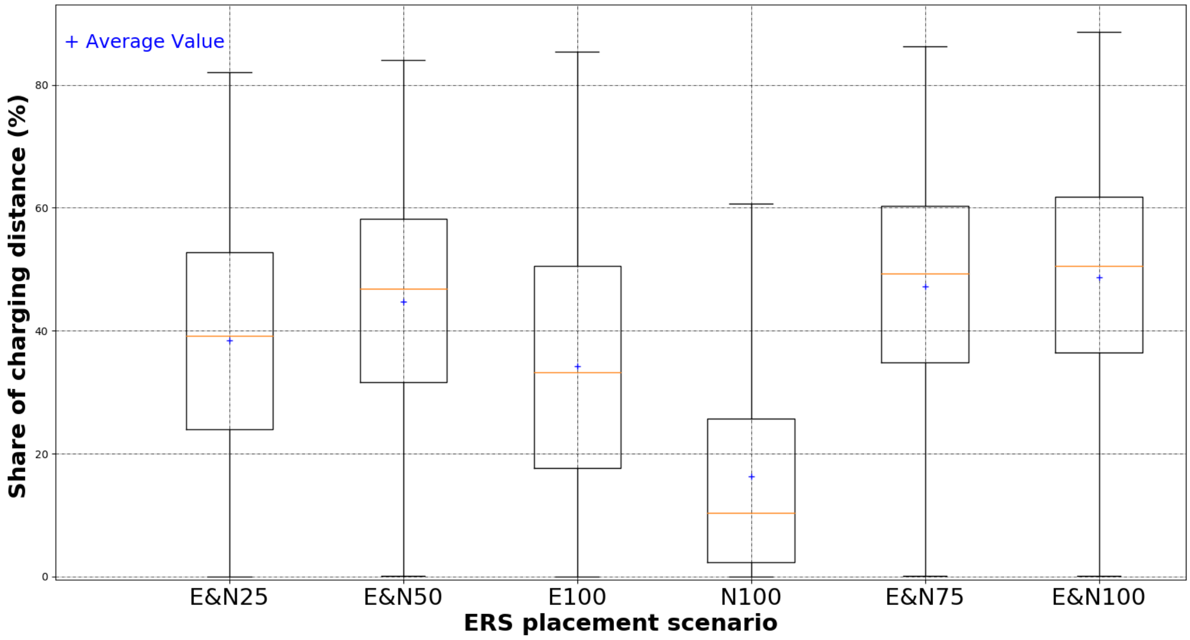

Figure 2 Box plots for the share of BEV charging distance in six ERS scenarios. E&N25, E&N50, E&N75, and E&N100 refer to scenarios with ERS placed on 25%, 50%, 75%, and 100% of both E and N roads, respectively, measured by traffic volume.

Possible reduction in battery capacity

We investigate possible reductions in battery capacities by estimating the required sizes for each individual car to fulfill all driving with and without ERS and considering the three stationary charging patterns. The capacities required to cover all driving, sorted from small to large, are shown in Figure 3. In the absence of ERS, in the HSC scenario, the average capacity to complete all driving is 55 kWh and 95% of the cars require ≤118 kWh battery. For HOSC the average capacity required is around 15% lower at 48 kWh, and 95% of the cars require ≤103 kWh.

Utilizing 25% of E and N roads (2*e*) with HSC yields a mean reduction in battery capacity of 60%, to only 22 kWh. Covering 95% of the cars in this case requires 54 kWh. 100% of E and N roads further decreases battery capacities, but the changes are small, with a mean total reduction of 73%, to 15 kWh. For HOSC, results are very similar to the HSC case. For 25% of E and N roads (2*e*), the mean reduction in battery capacity is 56%, or 21 kWh. Covering 95% of the cars requires 48 kWh in this case. And the mean results for 100% of E and N roads show a small decrease, with mean reduction of 73%. In both stationary charging patterns, increasing charging rate does not impact the reduction in battery capacity significantly.

Comparing the battery capacities while eliminating all stationary charging (NSC) with no-ERS scenario is meaningless; therefore, we are only showing the battery requirements for ERS (2*e*) and ERS (4*e*) cases. NSC requires average battery capacities of 149 kWh with E&N25 (2*e*). Increasing the ERS lengths to E&N100 reduces the average battery capacity to 87 kWh. However, doubling the ERS charging rate to 4*e* decreases the required mean battery capacities considerably by 46-50%. This implies that relying completely on ERS without any stationary charging stations would be facilitated by higher charging rates to keep battery sizes down, but still on average large battery capacities would be required.

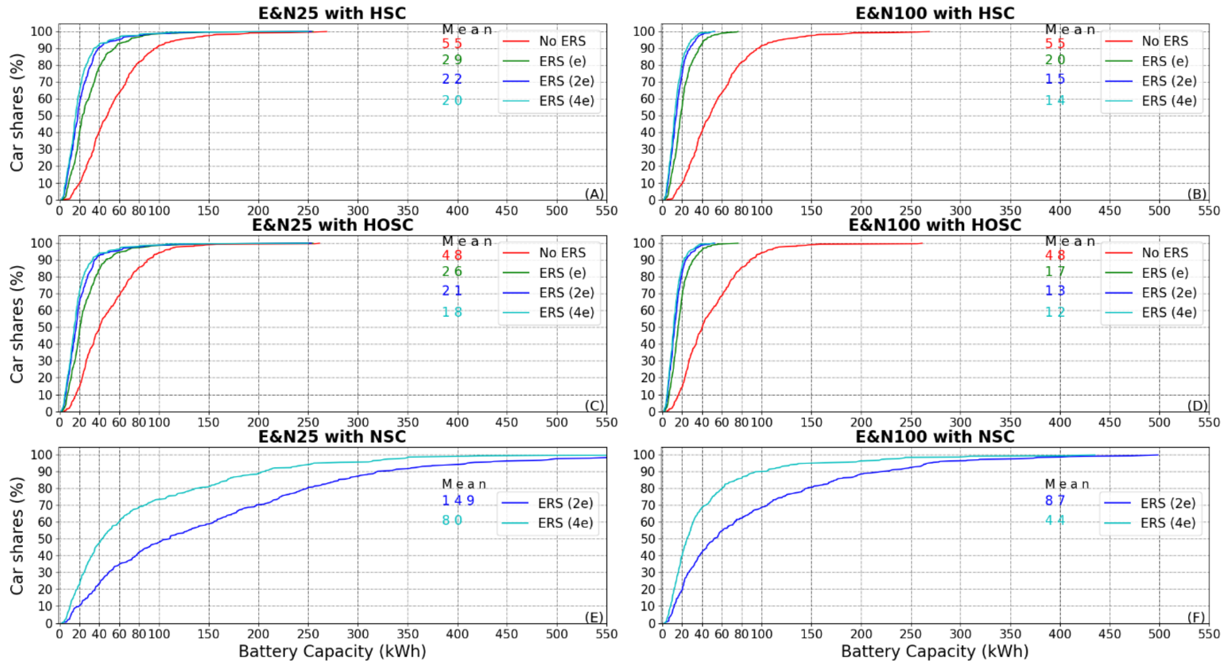

Figure 3 Cumulative share of cars for required battery capacity to cover all driving in the E&N25 case (left) and E&N100 case (right). The numbers in the boxes are the mean battery capacities required to meet all driving trips. HSC: Home-only stationary charging, HOSC: Home and other stationary charging, NSC: No stationary charging.

ERS savings

The economic benefit of reduced battery capacities also depends on the number of passenger cars switching to BEVs. The total number of passenger cars in Sweden is about 4,871,000 [1]. We assume that the modeled cars represent all Sweden's passenger vehicles; thus, all private vehicles in Sweden follow the distributions of reduced battery capacities found in Figure 3. Also, we present savings in two assumed orders of BEV penetration: 1) drivers with the highest battery capacity savings switch to BEV first (optimal), and 2) drivers switch in random order to BEV (random). The two orders ease exploring the boundaries of economic benefits at early stages, the maximum with optimal order and average estimates with random.

The savings resulting from smaller battery capacities as a function of BEV penetration with ERS are shown in Figure 4. The two horizontal lines show the range of ERS cost estimates (low in green and high in yellow). With HSC, implementing 25% of E and N roads results in large net benefits within the range of both ERS costs (Figure 4). Even with high ERS cost estimates, the cost is covered if 15% and 34% of cars switch to BEVs, in the optimal and random scenarios, respectively. For HOSC, given the smaller savings from reduced battery capacities, BEVs have to make up 18% and 40% of the fleet in the optimal and random scenarios, respectively. For 100% of E and N roads, only a low ERS cost would yield positive net savings (Figure 4.B). In both HSC and HOSC, increasing the charging rate does not increase the net savings significantly. However, the HSC has more absolute reduction in battery size and thus higher net savings.

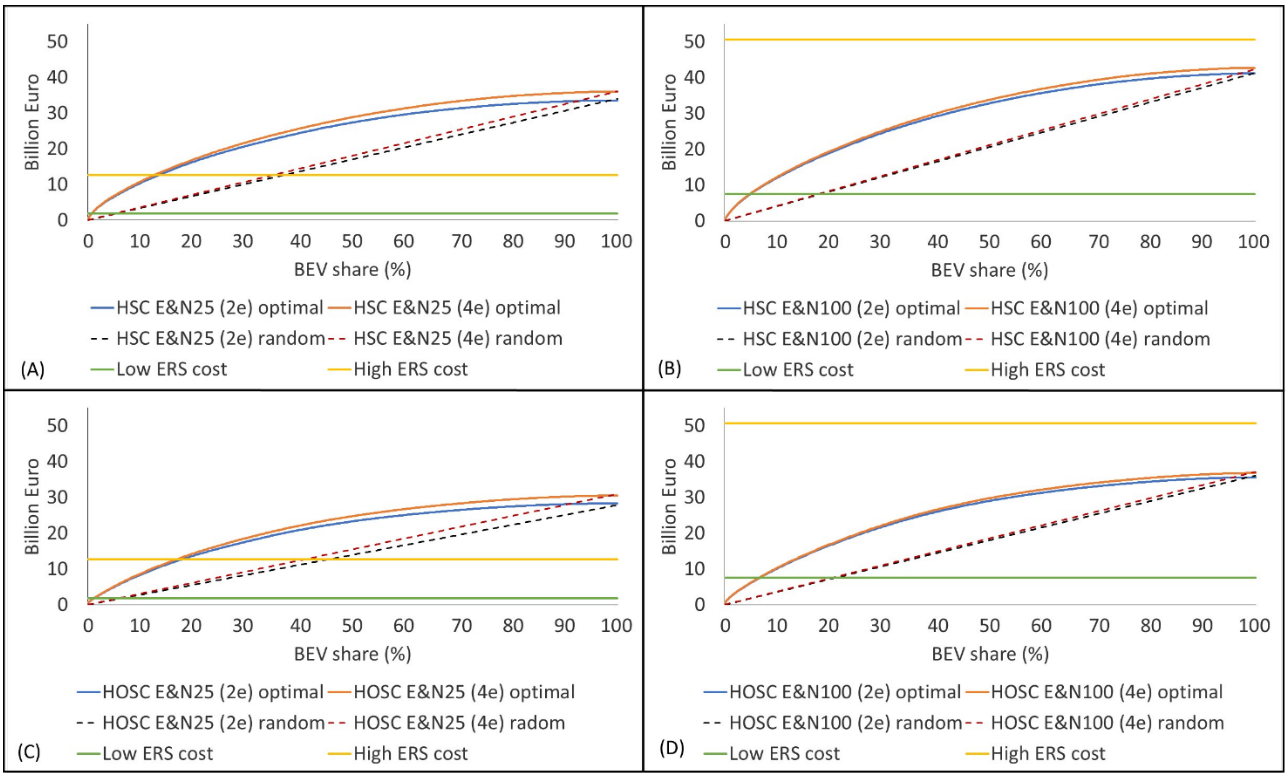

Figure 4 Savings in billion euros from reduced battery capacity required as a function of BEV penetration level with A) HSC and E&N25, B) HSC and E&N100, C) HOSC and E&N25 and D) HOSC and E&N100 with 2e and 4e charging rates.

Without ERS, HSC requires high initial investments in both large average BEV batteries and infrastructure in the form of home chargers. The cost of charging infrastructure for HSC is estimated to be €32 billion for a passenger fleet that is 100% BEV. Compared to that base case, i.e., HSC with no ERS, max net savings of including ERS (4*e*) in each considered charging pattern are illustrated for a 100%-BEV fleet in Figure 5. Only high ERS costs are considered in order to illustrate conservative net savings for each case. With ERS, both HSC and HOSC scenarios require smaller initial investments given the reduction in the average battery sizes. HSC with 25% of E and N roads could provide net savings of €23 billion. Extending ERS to 100% of E and N roads, the higher ERS cost would eliminate the savings from reduced battery sizes, yielding negative net savings. HOSC saves even more from reduced battery size but also requires additional charging infrastructure investments of €20 billion to cover a 100%-BEV fleet. Net savings with HOSC are thus less than for HSC in both placement scenarios. NSC requires BEVs with larger batteries, especially for 25% of E and N roads. Thus, relatively high investments in vehicles are expected at early stages. Reduction in infrastructure costs and battery capacities are not enough to cover high ERS costs in any ERS placement scenario.

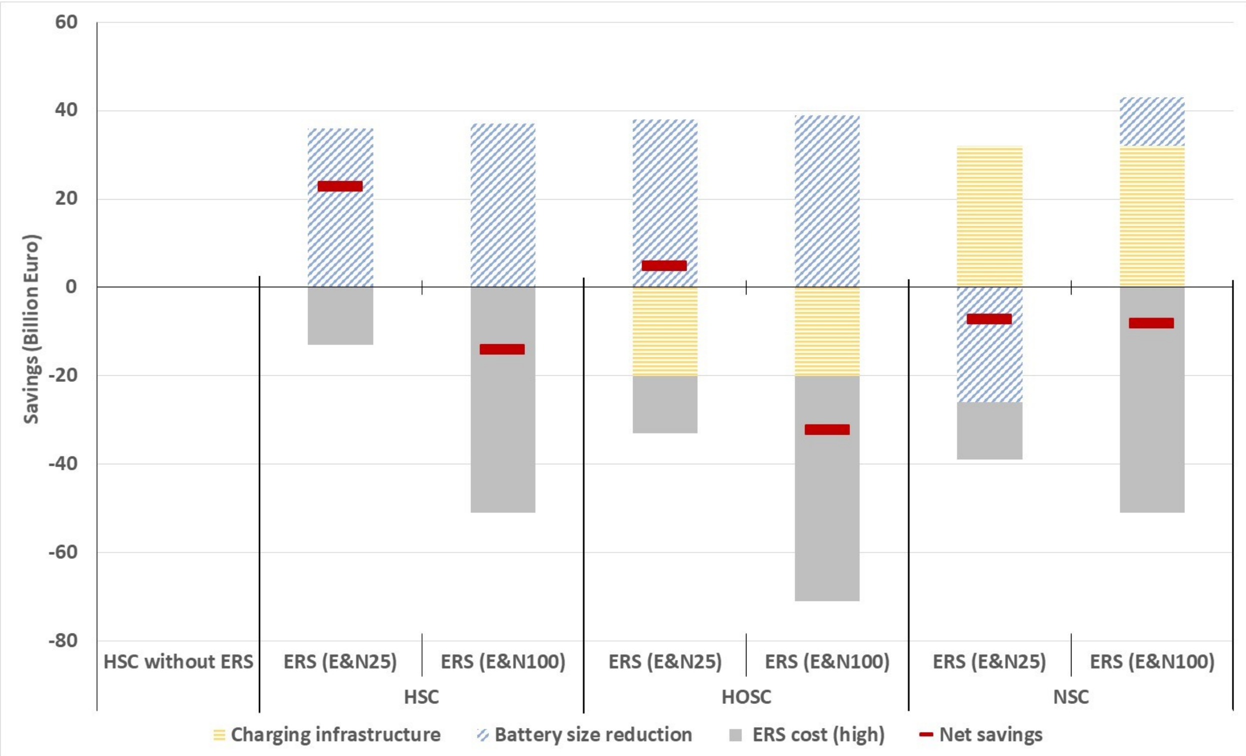

Figure 5 Savings and extra charging infrastructure costs of Home-only stationary charging (HSC), Home and other stationary charging (HOSC) and No stationary charging (NSC) with ERS for 100%-BEV share compared to HSC without ERS.

Conclusion

The research utilizes real detailed driving patterns to investigate the benefits to BEVs from using ERS with technology that allows charging from below. For that, the research exploits GPS loggings of a representative group of cars found in Sweden. The research also proposes different ERS placements scenarios, percentage of cars switching to BEV and ERS charging rates. The research summarizes its results as following. The analysis shows that with ERS, the required battery size to complete all driving is small for most vehicles. The study shows that ERS cover most private vehicle trips with home-only stationary charging and small battery capacities (15-22 kWh). The study shows that public chargers are not needed with small battery capacities as they have insignificant impact on reducing battery capacities. Moreover, all stationary charging could be eliminated for private vehicles with large battery capacities (87-149 kWh).

Among our investigated scenarios, 25% of E and N roads costs about €2-€13 billion and yields net benefits from reduced battery capacities of €23-€34 billion, while 100% of E and N roads costs 4 times more (€8-€51 billion) and could yield negative net savings. The research shows the importance of considering both the lengths of segments covered with ERS and traffic of segments to assure successful coverage daily trips. BEVs with the option to reduce large battery sizes could be targeted in the early stages to maximize benefits. The results show that in most cases the economic benefits from the reduction in battery capacity and charging infrastructure are greater than the associated costs of installing ERS. With ERS, net economic benefits of 29-45 billion € are expected from reduced battery capacities, depending on the stationary charging pattern, percentage of cars switching to BEV, ERS placement and ERS charging rate.

Acknowledgments

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