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# Large-scale implementation of electric road systems: Associated costs and the impact on $CO_2$ emissions

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**ABSTRACT**

This study investigates a large-scale implementation of an electric road system (ERS) in Norway and Sweden by identifying: (i) which roads; (ii) how much of the road network; and (iii) which vehicle types are beneficial to electrify based on an analysis of current road traffic volumes, $CO_2$ emissions mitigation potential, and infrastructure investment costs. All the European (E) and National (N) roads in Norway and Sweden were included, while assuming different degrees of electrification in terms of the fraction of the road length with an ERS, prioritizing roads with high-traffic loads. The results show that implementing an ERS already for 25% of the E- and N-road lengths could result in electrification of 70% of the traffic on these roads, as well as 35% of the total vehicle kilometers in Norway and Sweden. The ERS will then connect some of the larger cities with ERS. Installation of ERS on all the E- and N-roads in the two countries would cover more than 60% of the $CO_2$ emissions from all heavy traffic assuming all vehicles run on electricity. For roads with an average daily traffic of >6800 and >1200 vehicles per day, the costs of infrastructure investment are ~0.03 €$_{2016}$ per vkm and ~0.15 €$_{2016}$ per vkm, respectively. Thereby, for roads with high traffic volumes using an ERS, the total driving cost per km using an ERS (0.23–0.55 €$_{2016}$ per vkm) does not seem to be an issue. Light vehicles appear to be important bringing down the ERS infrastructure cost.

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## 1. Introduction

To meet $CO_2$ emission reduction targets in line with the Paris agreement, the transport sector needs to replace fossil fuels with low-carbon options, such as powering the vehicle fleet with electricity generated from renewable sources (European Commission, 2011; Fridstrøm & Alfsen, 2014; Johansson, 2013). However, not only a change to alternative fuels is important for the road transport sector, but also improving vehicle efficiency and improvements in road freight operations and logistics (Mulholland, Teter, Cazzola, McDonald, & Gallachóir, 2018). The literature contains several studies that describe how electrification of the transportation sector could reduce $CO_2$ emissions (e.g. Fridstrøm & Alfsen, 2014; M. Grahn et al., 2009; Johansson, 2013; Kuramochi et al., 2018). A study initiated by the Swedish government on how the transportation sector can be made fossil-free reveals that electrification has the potential to play an important role in reducing the fossil fuel dependence of the Swedish transportation sector (Johansson, 2013). In Norway, a similar study has been conducted by Fridstrøm and Alfsen (2014), who propose large increases in the numbers of electric vehicles (EV) and hybrid electric vehicles (HEV) by Year 2050 to reach Norwegian climate targets. Both Sweden and Norway have currently 98% fossil-free electricity generation (Statistics Norway, 2017a; Statistics Sweden, 2016), which makes electrification of the transport sector an attractive option. Yet, the electricity systems are linked to the Nordic and European electricity systems, which means that the effect from increased electrification of the transport sector will depend on development of the electricity systems also in neighboring regions. It should be a fair assumption that fulfilling the Paris agreement of limiting global warming to well below 2 °C should require the European and global electricity systems to be free of carbon emissions in the long run and, thus, electrification of the transportation sector should be an increasingly attractive option with time.

Electrification of the road transport sector could be achieved through the use of: (i) battery EVs with static charging; (ii) an electric road system (ERS); and (iii) electricity to produce a fuel (such as hydrogen or synthetic hydrocarbons) for on-board use in internal combustion engines. It is not obvious which is the best option, and these three alternatives need to be investigated further (Johansson, 2013). It is likely that the future will bring a mixture of different technologies and fuels,

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both within and between different vehicle categories. ERS with dynamic on-road conductive power transfer (CPT) or inductive wireless power transfer (IPT) while driving has attracted much interest over the past few years (e.g. Chen, Taylor, & Kringos, 2015; Olsson, 2013a). This is mainly due to the limitations experienced with the batteries used for EVs, including limited driving range, high battery cost, and the fact that current battery technology makes EVs too heavy for long-range vehicle categories. The dynamic transfer of electricity can be done through overhead transmissions lines or from the road (Chen et al., 2015; Olsson, 2013a, 2013b). Electricity transfer systems that use overhead transmission lines are conductive, with the vehicle connecting to the transmission lines through a type of pantograph, whereas the road-based technologies can be either conductive or inductive. In the case of a conductive system, the supply of electricity is through a physical pick-up that connects to an electrified rail in the road, whereas in an inductive system, the electricity is supplied *via* a wireless power transfer from a coil in the road to a pick-up point in the vehicle (Chen et al., 2015; Olsson, 2013b). The overhead lines can—at least with current design concepts - only be used by heavy vehicles (i.e., buses and trucks), while the electrified rail in the road and the inductive supply systems can be used by all type of vehicles (cars, buses, and trucks). ERS provides the possibility to reduce the need for large batteries if a shared infrastructure with dynamic transfer of electricity to the vehicles is created. The size of the batteries could be adjusted to, for example, ensure a maximum range of 50 km off-grid driving. However, this would require large-scale implementation of ERS. The ERS technology has been tested on short test tracks (~2 km) on public roads in Sweden, Germany, and USA (Chen et al., 2015). However, to date the ERS technology has not been implemented at scale.

Previous studies in the scientific literature have investigated ERS mainly with respect to technology improvements, e.g., transfer efficiency (Wu, Gilchrist, Sealy, & Bronson, 2012), alignment tolerance of the IPT transformer (Villa, Llombart, Sanz, & Sallan, 2007), and a new three-phase bipolar IPT (Covic, Boys, Kissin, & Lu, 2007). Sundelin, Gustavsson, and Tongur (2016) have studied the maturity of different dynamic power transfer technologies to be implemented at large scale. Some studies (e.g., P. Grahn, 2014; Stamati & Bauer, 2013; Taljegard, Göransson, Odenberger, & Johnsson, 2017) have modeled the electric power demand for roads using ERS. For example, Stamati and Bauer (2013) investigated the possibilities to meet with renewable energy the electricity demand for the highway traffic flow on an average day in the Netherlands. Taljegard et al. (2017) have investigated the spatial and dynamic electricity demand of an ERS in Norway. Chen et al. (2015) have provided an overview of the current state-of-the-art of ERS, presenting the challenges and opportunities associated with ERS. However, Chen et al. (2015) have also pointed out some research gaps, such as the environmental performance of ERS, i.e., the real impact from using ERS to reduce overall energy usage and greenhouse gas emissions. The latter will obviously depend on the fuel mix used to generate the electricity required to power the ERS vehicles. In addition, several reports have also assessed different aspects of ERS (e.g., Boer et al. 2013; Connolly, 2016; Olsson, 2013a; Wilson, 2015). Wilson (2015) has analyzed the feasibility of implementing dynamic wireless power transfer system on the Strategic Road Network in Great Britain. Olsson (2013a) has studied the different cost and technical aspects of implementing an ERS on a highway in Sweden. In the report of Boer et al. (2013), the costs for different powertrains technologies and fuels, including dynamic power transfer, are compared for trucks. Connolly (2016) has compared ERS with oil-driven and battery-electric vehicles in terms of cost, $CO_2$ emissions, and energy. That study concludes that ERS will be more cost-competitive than both oil and batteries in the future due to ERS having lower running costs than oil and the presence of an ERS infrastructure that is shared by many vehicles, thereby enabling the use of much smaller batteries in combination with an ERS.

The new ERS infrastructure will be shared by a large number of vehicles depending on the road traffic volumes (i.e., vehicle kilometers per year, vkm/yr) and the ERS technology chosen (i.e., overhead lines, electric rails or inductive supply). However, implementation of an ERS will require that a new infrastructure is established, which is obviously associated with considerable up-front investment costs. Therefore, it is important to investigate the potential benefits of large-scale implementation of ERS and its role in the transportation system. The aim of this paper is to investigate: (i) the roads, (ii) the extent of the road network, and (iii) the vehicle types that could be beneficially electrified, based on analyses of road traffic volumes, $CO_2$ emissions mitigation potential, and infrastructure investment costs. The study assesses the criteria for roads with the greatest potential for implementing ERS, from both the environmental and economical points of view. The work focuses on Norway and Sweden, and the results are presented in aggregated form for these two countries, except when significant differences between the countries are noted. Sweden and Norway are chosen as a case study mainly due to the access of detailed road traffic data. Access to detailed road traffic data enables thorough analyses of the cost and environmental performance of each road segment. The results may be extrapolations to other countries with different traffic flows and energy prices, and may be used to give a first support to countries with national ambitions to implement ERS technology. More generally, the methods developed and applied in this study can be useful for similar studies performed on other countries. With respect to $CO_2$ mitigation potential, the work focuses on the direct impact from ERS of replacing petrol and diesel and does not use life cycle analysis or consider the emissions associated with the production of electricity and materials (e.g., energy required to produce batteries). Results from life cycle analysis of the carbon emissions of an ERS show that the driving contributed with the largest share of the cradle to grave emissions compared to building the infrastructure (Nordelöf, Björkman, Ljunggren Söderman, & Tillman, 2013).

## 2. Methodology and data

### 2.1. Data on road traffic volumes

A large-scale implementation of an ERS is investigated using road traffic data (i.e., the average daily traffic; ADT) for Norway and Sweden. The data on road traffic volumes were provided by Norwegian National Public Road Administration (NPRA) (Norwegian Public Road Administration, 2016) and the Swedish Transport Administration (STA) (Swedish Transport Administration, 2016). ADT is measured by NPRA and STA for two vehicle categories, light and heavy vehicles, where all vehicle types above 3.5 tonne are classified as heavy vehicles. Four vehicle types are assumed: passenger cars, light trucks, buses and heavy trucks. In the present study, mainly road traffic statistics from years 2015 and 2016 were used and no projections of future traffic flows were considered. The road types included, have been classified into European and National roads (referred to as E- and N-roads), which is the same classification used by NPRA and STA. The following E-roads pass through Norway and/or Sweden: E4, E6, E8, E10, E12, E14, E16, E18, E20, E22, E39, E45, E65, E69, E75, E105, E134, and E136. Figure 1 shows a map of all E- and N-roads in Norway and Sweden.

Table 1 lists statistics on the: (i) road distances; (ii) road traffic volumes; and (iii) $CO_2$ emissions for the E- and N-roads, as well as all roads in the national road network in Norway and Sweden. Based on the numbers in Table 1, approximately 45% of the vkm/yr is driven on E- and N-roads, even though these roads account for only 8% of the Swedish and 12% of the Norwegian total road distances. Heavy vehicles make up only ~13% of the vkm/yr but are responsible for ~45% of the $CO_2$ emissions from the road traffic on E- and N-roads.

Figure 2 gives the distribution of the ADT, i.e., the average number of vehicles per day moving along the E- and N-roads and all other roads (i.e., all roads other than E- and N-roads), aggregated for Norway and Sweden. As shown in Figure 2a, there are large variations in the ADT for the E- and N-roads, although roughly 80% of the E-and N-road length has an ADT of <10,000 vehicles and 40% of the road length has an ADT in the range of 1000–5000 vehicles. For the heavy vehicles in Figure 2b, more than 70% of the road length has an ADT of <1000 vehicles and less than 40% of the road length sees 250 vehicles per day. Compared to all other types of roads, the E- and N-roads have a higher share of road length with ADT >1000 vehicles (Figure 2). In terms of kilometer of road length, all the other types of roads have more kilometers with ADT between 1000 and 5000 than the E- and N-roads. However, all other road types, such as county roads and private roads, are not considered further in this analysis.

### 2.2. Data on road traffic $CO_2$ emissions

Table 1 shows the total emission from all E-and N-road segments aggregated and are taken from Statistics Norway (2016) and Statistics Sweden (2015). The $CO_2$ emissions per road segment have been calculated using data on (i) $CO_2$ emission factors shown in Table 2, (ii) ADT for each road segment and vehicle category, and (iii) the share of the vehicle category "light vehicles" that are passenger cars and light trucks and the share of the vehicle category "heavy vehicles" that are buses and heavy trucks (Table 2). Thus, the $CO_2$ emissions are obtained as

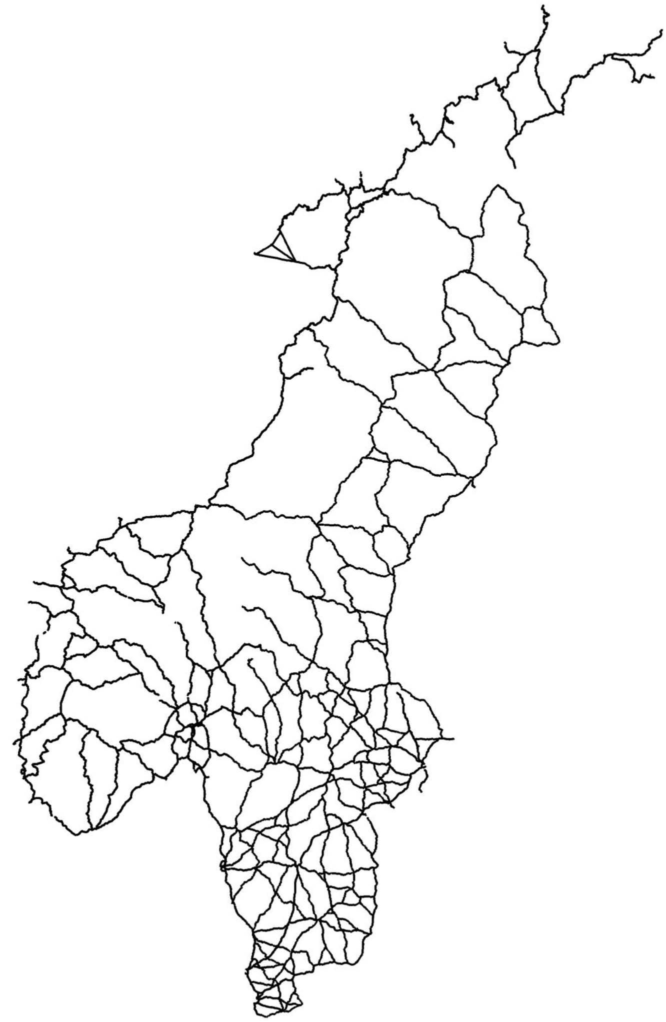

Figure 1. All roads that are classified as European and National roads (E- and N-roads) in Norway and Sweden.

$$\begin{aligned} EM_{c,rs,vt,yr} &= Ef_{c,vt} \times \ ADT_{c.rs,vc} \ \times days \ \times share_{vc,vt} \\ &\forall \ c \in C, \ rs \in RS, \ vt \in VT, \ vc \in VC \end{aligned} \quad (1)$$

where $EM_{c,rs,vt,yr}$ is the $CO_2$ emissions per country (c), road segment (rs), vehicle type (vt) and year (yr); $Ef_{c,vt}$ is the $CO_2$ emission factor per country (c) and vehicle type (vt); $ADT_{c.rs,vc}$ is the average number of vehicles per day per country (c), road segment (rs) and vehicle category (vc); *days* is the number of days per year; and $share_{vt,vc}$ is the share of the vehicles type (vt) in each vehicle category (vc).

In Sweden, data on the $CO_2$ emission factors for the different vehicle types seen in Table 2 are calculated from the total $CO_2$ emission per vehicle type divided by the numbers of driven kilometers for each vehicle type (Saxton, 2016). In Norway, the emissions factors for diesel- and petrol-fuelled vehicles for four vehicle categories are taken from Holmengen

**Table 1.** Road distances, traffic volumes, and road traffic $CO_2$ emissions (Norwegian Public Road Administration, 2016; Swedish Transport Administration, 2016).

| | | Road traffic volume [Mvkm/yr] | | $CO_2$ emissions [kt$CO_2$/yr] | |
|---|---|---|---|---|---|
| | Road distance [km] | All vehicles | Heavy vehicles | All vehicles | Heavy vehicles |
| *Norway* | | | | | |
| European (E-)roads | 6830 | 14,820 | 1900 | 3880 | 1840 |
| National (N-)roads | 4100 | 5340 | 510 | 1300 | 560 |
| E- and N-roads | 10,960 | 20,160 | 2510 | 5180 | 2400 |
| All roads | 93,300 | 44,250 | 4400 | 10,330 | 4020 |
| *Sweden* | | | | | |
| European (E-)roads | 7320 | 25,640 | 3590 | 6760 | 3042 |
| National (N-)roads | 8940 | 13,340 | 1734 | 3440 | 1480 |
| E- and N-roads[a] | 16,250 | 38,980 | 5460 | 10,200 | 4490 |
| All roads | 216,400 | 83,970 | 7557 | 19,310 | 6370 |

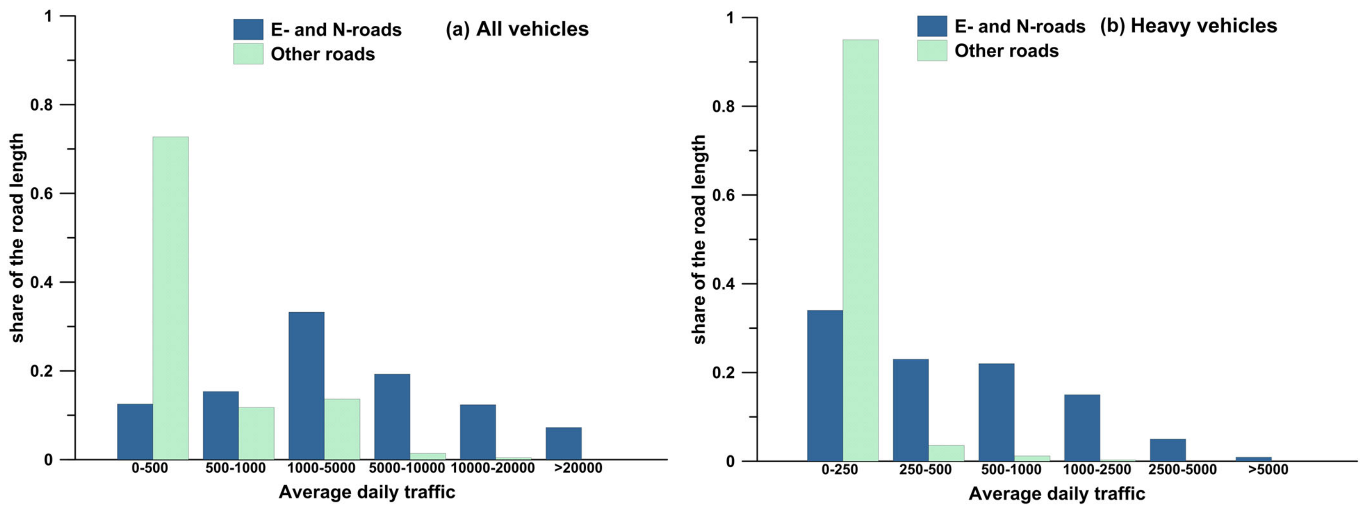


**Figure 2.** Distribution of the average daily traffic, i.e., average number of vehicles passing per day, aggregated for Norway and Sweden. Data shown are for European and National roads (E- and N-roads) and for all other road types (excluding E- and N-roads) for all vehicle types (a) and for heavy vehicles only (b).

and Fedoryshyn (2015). The emissions factors for Norway are thereafter adjusted to reflect that in Norway: (i) light vehicles comprise 36% petrol cars, 46% diesel cars, 1% petrol-driven light trucks, and 17% diesel-driven light trucks; and (ii) heavy vehicles comprise 77% diesel-driven trucks and 23% diesel-driven buses (Holmengen & Fedoryshyn, 2015). In Table 2, the average shares of biofuels (18% for Sweden and 4% for Norway) are included in the emission factors. Given the current composition of the Swedish electricity system and the development of renewable electricity sources, a fully decarbonized electricity system is assumed, resulting in zero $CO_2$ emissions from vehicles that use ERS. Thereby, this study is investigating the potential of a large scale deployment of ERS.

## 2.3. Data on vehicle and electric road system infrastructure costs

Table 3 shows the infrastructure costs for building ERS from different sources found in literature. The cost of investment in infrastructure needed for an ERS remains uncertain, with a broad range of costs reported in the literature, as seen in Table 3 (Olsson, 2013a, 2013b; Wilson, 2015). The large cost uncertainty found in the literature is mainly due to that experiences from the different ERS technologies are limited to test sites and at small scale (up to 2 km) on public roads. All costs in Table 3 are for

**Table 2.** Carbon factors for $CO_2$ emissions from road traffic in Norway and Sweden (Holmengen & Fedoryshyn, 2015; Saxton, 2016).

| | g$CO_2$/vehicle kilometers | | Share of light and heavy vehicles | |
|---|---|---|---|---|
| | Norway | Sweden | Norway | Sweden |
| Cars | 152 | 167 | 0.82 | 0.88 |
| Light trucks | 186 | 181 | 0.18 | 0.12 |
| Buses | 774 | 678 | 0.23 | 0.21 |
| Heavy trucks | 956 | 963 | 0.77 | 0.79 |

electrification in both directions, including the components both for the electric road infrastructure and the electricity system network to the road. The infrastructure investment cost depends, for example, on the infrastructure components included in the cost analysis, the need to develop a new electricity network, and the type of ERS chosen (i.e., overhead lines, ground level transmission or inductive power transmission).

The investment needed in new grid capacity (included in the costs presented in Table 3) affects the total investment cost; it will be highly site-specific and vary between roads. The need for investment in the electricity gridwill depend on the peak-load of the road and this has been examined for two different cases by Olsson (2013a). The first case is an example of a heavy-traffic road segment in Sweden with a peak load of 6.7 MW/km (for traffic in both directions), while the second case is a road that has a peak load of

**Table 3.** Electric road system (ERS) infrastructure costs from different sources found in the literature.

| Literature sources | Type of ERS technology | Orginial ERS infrastructure cost | ERS infrastructure cost [M€$_{2016}$ per km][a] | Comment |
|---|---|---|---|---|
| Ranch (2010) | Overhead lines | 10 MSEK/km | ~1.01 | The cost estimates are based on costs from projects building trolleybuses and railways in Sweden. |
| Boer et al. (2013) | Overhead lines<br>Inductive | ~2–3 M€/km<br>~2–3 M€/km | ~2.04–3.06 | The cost estimates are assumed to be the same for inductive and overhead lines. |
| Asplund (2017) | Rail | 4 MSEK/km | ~0.40 | Elways is a company developing conductive ERS rail technology. |
| Olsson (2013a) | Rail | 9–11 MSEK/km | ~0.89–1.09 | The cost is excluding installation costs, engineering costs or safety studies. |
| Olsson (2013b) | Inductive | 26–50 MSEK/km | ~2.56–4.92 | They both show pessimistic and optimistic costs including cost reductions due to technology improvements. |
| Wilson (2015) | Inductive | 1.9–3.2 M£ | ~2.19–3.24 | They costs are excluding the cost for grid connection, which is estimated to cost 0.4–0.5 M€$_{2016}$ according to Wilson. |
| Sundelin et al. (2017) | Conductive (both overhead lines and rail) | 5–17.5 MSEK/km | ~0.48–1.67 | The report gives cost from pessimistic estimations to potential future costs. |

[a]All currencies are expressed in Euro for year 2016 using ONADA Historical Exchange Rates (i.e., currency exchange of 0.097 €/SEK and 1.14 €/£in Year 2016). All the values are also being recalculated from the year given in the report to year 2016 to account for consumer price inflation based on the Harmonized Indices of Consumer Prices (accessed on May 20, 2017). If no date is given, the year of publication of the article or report is used.

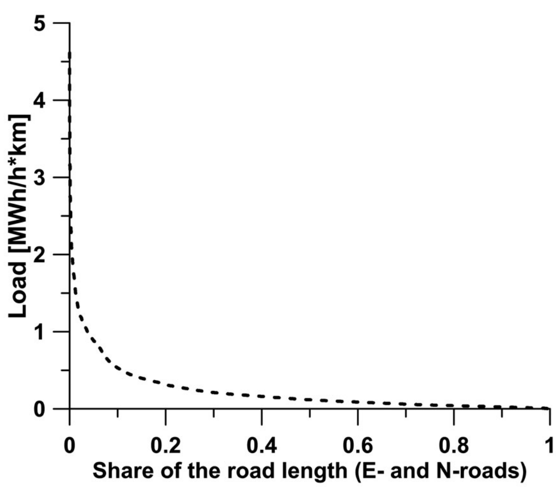


**Figure 3.** The hourly average load per kilometer during peak-traffic hour for all European and national roads (E- and N-roads) in Sweden and Norway combined, assuming that the electric road system is used by all vehicles with a traffic volume similar to that existing today.

0.7 MW/km but that is dimensioned with a security factor of 2, i.e., 1.4 MW/km. The cost for the connection and reinforcement of the electricity network is reported by Olsson (2013a) as 20.7 MSEK/km (~2.1 €$_{2016}$/km) in the first case assuming a road with high peak load (6.7 MW/km). In the second case in Olsson (2013a), assuming a low peak load (1.4 MW/km), the grid is reported to instead cost 7.2 MSEK/km (~0.73 €$_{2016}$/km). The 3-fold higher cost for the higher load case is mainly due to the need for extra reinforcement of the 130-kV grid and for new substations to meet the power requirements (Olsson, 2013a).

Figure 3 shows the hourly average load per kilometer during the peak-traffic hour (i.e., 4–5 pm) for all the E- and N-roads in Sweden and Norway combined, assuming current traffic volumes and patterns and that all vehicles (both heavy and light vehicles) are using the ERS. In order to calculate the load per kilometer, average vehicle consumption values of 0.16, 0.36, 1.29, and 2.24 kWh/km for passenger cars, light trucks, buses, and heavy trucks, respectively, are assumed (Taljegard et al., 2017). As shown in Figure 3, less than 3% of the E- and N-road lengths have an hourly average load during peak hour that exceeds 1 MWh/h per km. Heavy vehicles make up approximately half of the total load per kilometer shown in Figure 3. There is a somewhat higher load per kilometer for Sweden than Norway due to Swedish roads having a higher ADT. The share of the road length with load of more than 1 MWh/h per km lies mainly in the vicinity of larger cities, such as Gothenburg, Oslo, Bergen, and Malmö, where the roads are mainly used for shorter commuting trips to and from work.

Due to the uncertainty of the infrastructure investment cost and that this study does not investigate a specific road, we have chosen to investigate three cost levels: 0.4 M€$_{2016}$/km (level 1), 1.1 M€$_{2016}$/km (level 2), and 2.7 M€$_{2016}$/km (level 3). The maintenance cost is estimated to 1–2.5% of the initial infrastructure investment cost (Boer et al., 2013; Olsson, 2013a). The annualized infrastructure investment costs (including maintenance) for the three costs levels are then 26,000 €$_{2016}$/km, 68,000 €$_{2016}$/km, and 167,000 M€$_{2016}$/km. The calculation of the annualized infrastructure cost is based on a technical lifetime of 35 years (which is similar to what is typically applied for railway investments) (Hjortsberg, 2018) and a discount rate of 5%. The cost calculations in this study are from a societal perspective and a common discount rate is then in the range 3–7% (see e.g. Brynolf, Taljegard, Grahn, & Hansson, 2017). Considering the overall uncertainties in costs of ERS, we find it of no use to calculate with different discount rates or refine cost calculations with respect to possible difference in life time between different components. The uncertainty in the infrastructure cost of ERS is mainly due to the fact that ERS is still an immature technology under development. The allocation of the ERS infrastructure cost can be done in different ways for example: (i) per vehicle kilometer of driving at the road using an ERS and (ii) per kWh of energy used while driving on the ERS. The results presented in this study uses cost per vehicle kilometer.

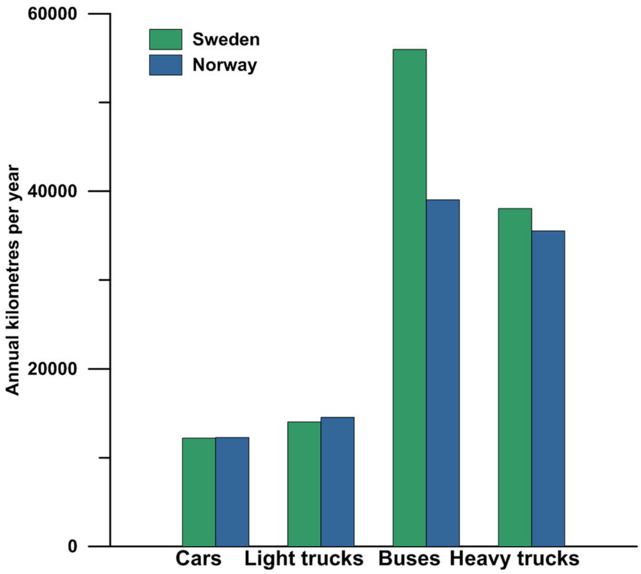


**Figure 4.** Average annual vehicle kilometers per type of vehicle driven in Norway (Statistics Norway, 2017b) and in Sweden (Statistics Sweden, 2017).

Figure 4 gives the yearly average driving distance per vehicle type in Norway and in Sweden based on statistics (Statistics Norway, 2017b; Statistics Sweden, 2017). It is clear that the distance driven each year by an average passenger car (~12,200 km) is approximately one-third of the average for truck or bus (~35,000 km). The results of a study conducted by Kullingsjö and Karlsson (2012), who investigated the individual traveling patterns of passenger car drivers in the region of Västra Götaland, show that more than 95% of the trips are shorter than 50 km. By analyzing the data from individual drivers, Kullingsjö and Karlsson (2012) have also shown that approximately 33% of the vehicle kilometers per year are driven during trips that are longer than 50 km. However, individual driving patterns will determine the exact amount of trips and distance using an ERS but since no such data are readily available for trucks this study is limited to ADT data.

The vehicle costs associated with using an ERS include the costs for: (i) the pick-up system installed on the vehicle; and (ii) electricity use per km, see Equation (2).

$$\mathrm{VC} = \frac{\mathrm{An} \times \mathrm{Invcost}}{\mathrm{vkm}} + \mathrm{Elprice} \times \mathrm{FC} \tag{2}$$

where VC is the vehicle cost per kilometer; An is the annuity factor; Invcost is the pick-up investment cost; vkm is the vehicle kilometer per year; Elprice is the electricity price; FC is the fuel consumption per kilometer.

If the vehicle is using the electric motor and battery also outside the ERS road network, the pick-up system will be the only additional cost to use the ERS. The pick-up system for a truck has been estimated in the range 50 kSEK (i.e. 5000 €$_{2016}$) by Olsson (2013a) to 8000 €$_{2016}$ by Boer et al. (2013). If the vehicle is an hybrid vehicle and the electric engine are used only when using the ERS, the extra vehicle cost for a truck (i.e., pick-up system, electric engine and battery) has been estimated to ~25,000 €$_{2016}$ depending on the assumed battery size and price (Boer et al., 2013).

A much lower pick-up system cost for passenger cars and vans can be expected, since these will only need a power transfer rate of ~50 kW instead of ~200 kW. For a passenger car, a pick-up system cost of ~10 kSEK (1010 €$_{2016}$) is assumed in the present study. The annualized costs for the pick-up system to be used in trucks and passenger cars are 770 €$_{2016}$/yr and 130 €$_{2016}$/yr, respectively, calculated with a discount rate of 5% and life-times of 8 years (truck) and 10 years (passenger car). The annualized cost per vehicle kilometer for the pick-up system is the cost divided by the driving distance per year using the ERS (Figure 5). The electricity cost is assumed to be 0.16 €$_{2016}$/vkm for a truck and 0.02 €$_{2016}$/vkm for a car (based on an electricity price of 0.07 €$_{2016}$/kWh and average consumption levels (in kWh/vkm) of 2.24 for a truck and 0.16 for a passenger car (Taljegard et al., 2017)).

The vehicle cost per vehicle kilometer (as defined in Equation 2) is in the range 0.2–0.4 €$_{2016}$/vkm for a truck using an ERS for between 3500 km and 35,500 km per year, as seen in Figure 5a. In Figure 5a, the pick-up system cost is included for the truck, but not the electric engine and the battery. The corresponding cost for a truck, if also including the full hybrid system (i.e. adding the cost of battery and electric engine), is 0.26–1.28 €$_{2016}$/vkm. Thereby, one can assume that a truck needs to drive large part of the yearly distance on an ERS if only using the electric drivetrain when driving on an ERS. The total vehicle cost for passenger cars is in the range of 0.03–0.13 €$_{2016}$/vkm when using an ERS for between 1200 and 12,300 km per year (Figure 5b). For a truck (assuming only the pick-up system) driving longer than 35,500, the additional vehicle cost for using ERS per kilometer will be almost the same as the electricity cost per kilometer, as seen in Figure 5. A similar result can be seen for passenger cars with a high driving distance, although not as pronounced as for the heavy trucks.

## 3. Results

### *3.1. Traffic volumes*

Figures 6 shows the the relationships between the shares of the E- and N-road lengths with an ERS and the shares of the E- and N-roads' vehicle kilometers with ERS for each vehicle category (all, light, heavy). Vehicle category *All* is heavy and light vehicles combined. Figure 7 shows the same as Figure 6 but as share of the total national vehicle kilometers on all roads on the y-axel (and divided into E and E- and N-roads). The results presented in Figures 6 and 7 are based on ADT data for each road segment in Sweden and Norway, where a certain share of the road length is electrified resulting in a corresponding share of the vehicle kilometers being electrified with ERS. Thus, this assumes that all vehicles use ERS on these roads. In Figures 6 and 7, it is assumed that the roads with most traffic are electrified first. A low share of ERS in Figure 6 means that only roads with the busiest road traffic are electrified. As is evident in Figure 6, applying ERS on 25% or 50% of the road length of the E- and N-roads will cover approximately 70% and 85%, respectively, of the traffic volumes on these roads. The steep curve seen in Figure 6 for the kilometers with the busiest traffic indicates that implementing an ERS on the E-

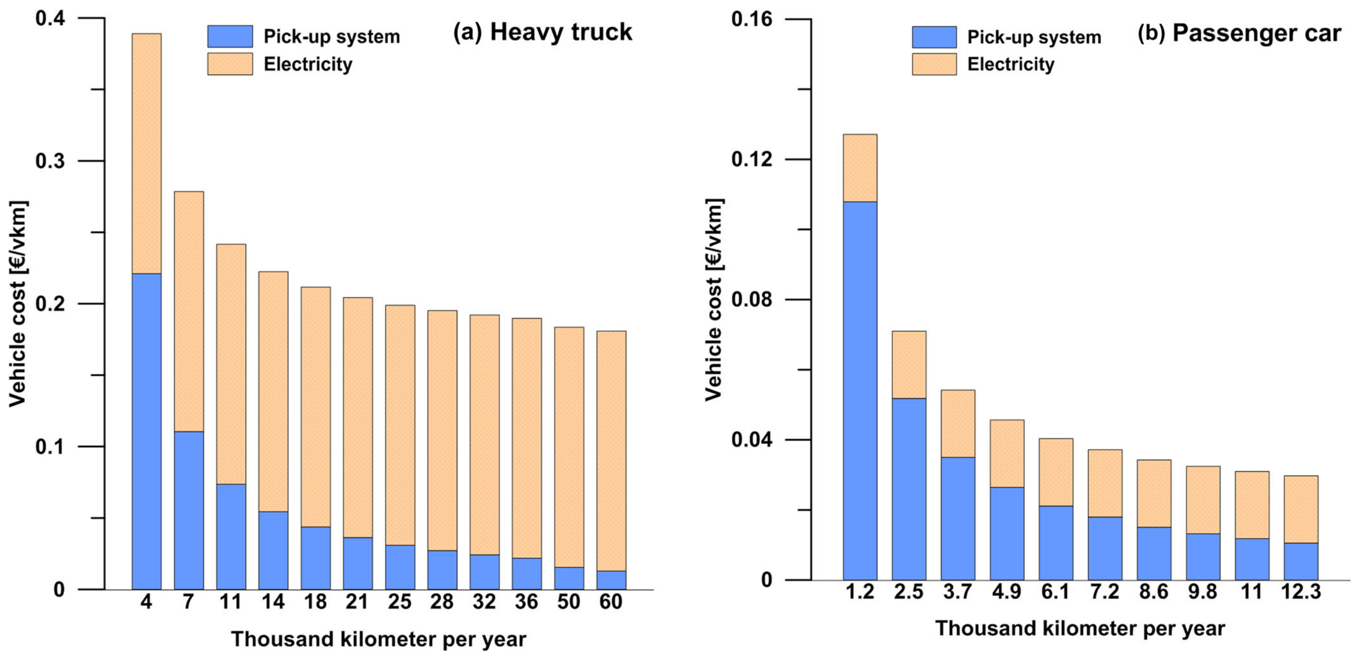


**Figure 5.** Vehicle costs divided into cost for pick-up system and electricity for a truck (a) and a passenger car (b) assuming different driving distances on an electric road systems.

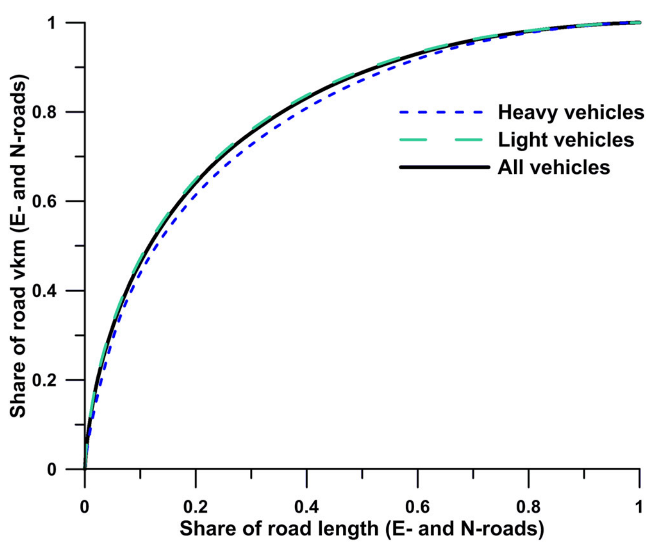


**Figure 6.** The shares of European and National road (E- and N-road) length with ERS and the corresponding shares of the E- and N-roads' vehicle kilometers, aggregated for Norway and Sweden.

and N-road network with lower traffic volumes will only cover an additional ∼15% of the traffic volumes on these roads. As seen in Figure 6, there are significant differences in traffic volumes between the different parts of the road. Figure 6 presents the results for E- and N-roads aggregated, although the graph exhibits the same pattern if one presents the E- or N-roads separately.

The reason for showing also the E-roads separately in Figure 7a is that these are the roads that have been discussed mostly for ERS. As shown in Figure 7a, full implementation of an ERS on E-roads, assuming that all the vehicles using the road today will also use the ERS, would lead to electrification of approximately 30% of the total national road traffic volumes (i.e., vehicle kilometers from both light and heavy vehicles). For heavy vehicles, full implementation of ERS on E-roads will lead to electrification of approximately 45% of the total national vehicle kilometers driven by heavy vehicles in Sweden and Norway, as shown in Figure 7a.

Figure 7b shows that approximately 55% and 30% of the vehicle kilometers of light and heavy vehicles, respectively, are driven outside the main E- and N-road network, for example, on county and private roads. ERS will make a significant difference if the ERS is limited to the busiest roads for both countries, since electrifying 25% of the busiest E- and N-road lengths will result in electrification of 45% of all heavy traffic and 35% of the total national vehicle kilometers, as depicted in Figure 7b.

### 3.2. $CO_2$ emissions

Figure 8 shows the shares of E- and N-road lengths with ERS and the corresponding road traffic $CO_2$ emissions from E- and N-roads for Norway (Figure 8a) and for Sweden (Figure 8b). If there is no ERS implemented, the road traffic $CO_2$ emissions correspond to today's emissions, while if all traffic on E- and N-roads are using ERS these emissions are equal to zero, as seen in Figure 8. Approximately 10 $MtCO_2$ (in Sweden) and 5 $MtCO_2$ (in Norway) are emitted annually from road traffic on E- and N-roads today (Figure 8). Figure 9 shows instead the shares of E- and N-road lengths with ERS and the shares of the total national road traffic $CO_2$ emissions for light and heavy vehicles in Norway (Figure 9a) and in Sweden (Figure 9b). From Figure 9, it is clear that the mitigated $CO_2$ emissions increase dramatically with road share until approximately 20%–40% of the road length is covered by ERS, for both light and heavy vehicles. Using an ERS on 40% of the Norwegian E- and N-roads with the highest $CO_2$ emissions would save 33% and 46% of

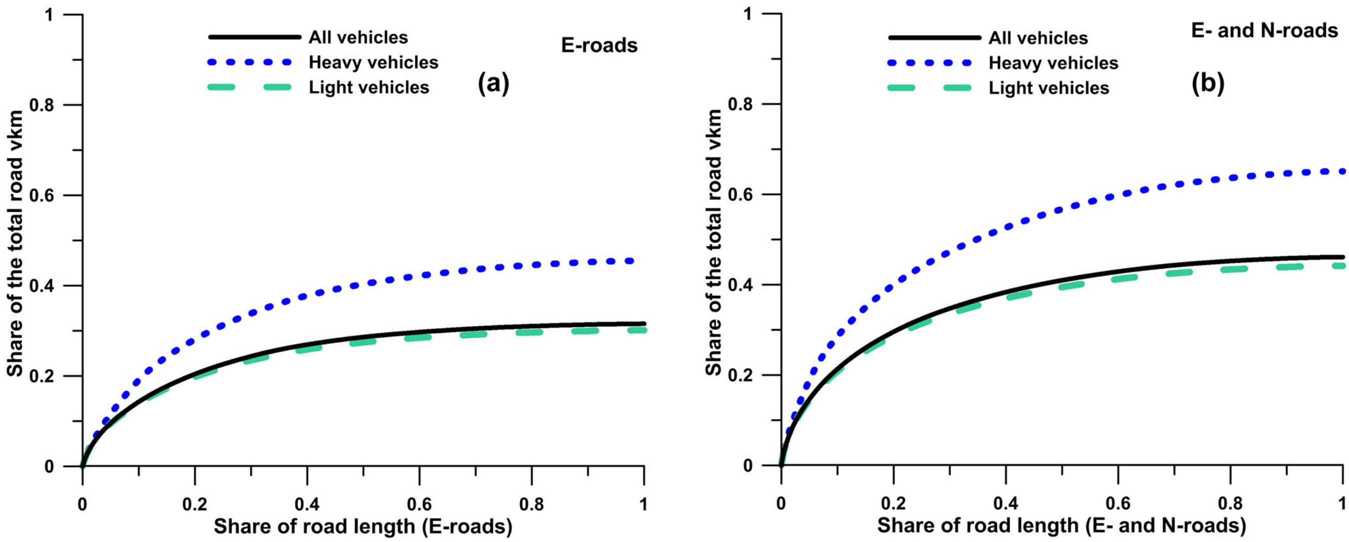


**Figure 7.** The share of European road (e-road) length with ERS (a) and the share of European and National road (E- and N-road) length with ERS (b) and the corresponding shares of the total national road vehicle kilometers, aggregated for Norway and Sweden.

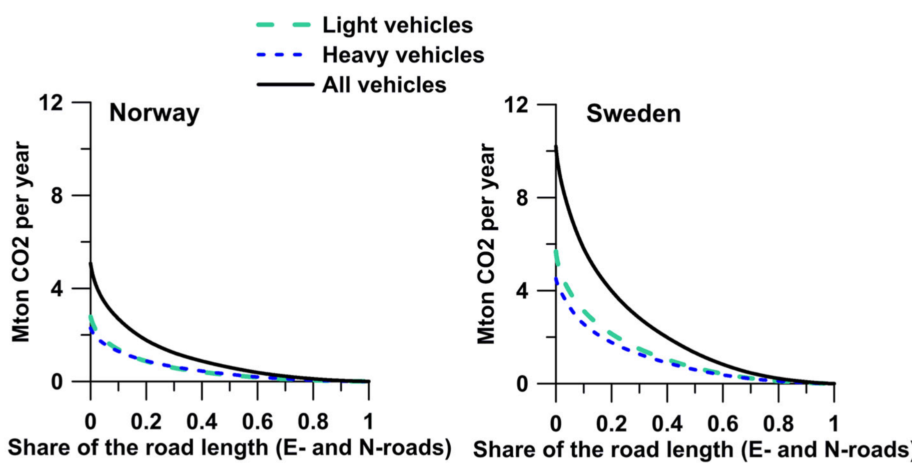


**Figure 8.** Shares of the European and National road (E- and N-road) lengths with ERS and the corresponding road traffic $CO_2$ emissions from E- and N-roads for all vehicles, light vehicles and heavy vehicles in Norway (a), and in Sweden (b). The reference level on emissions was obtained from today's emission level.

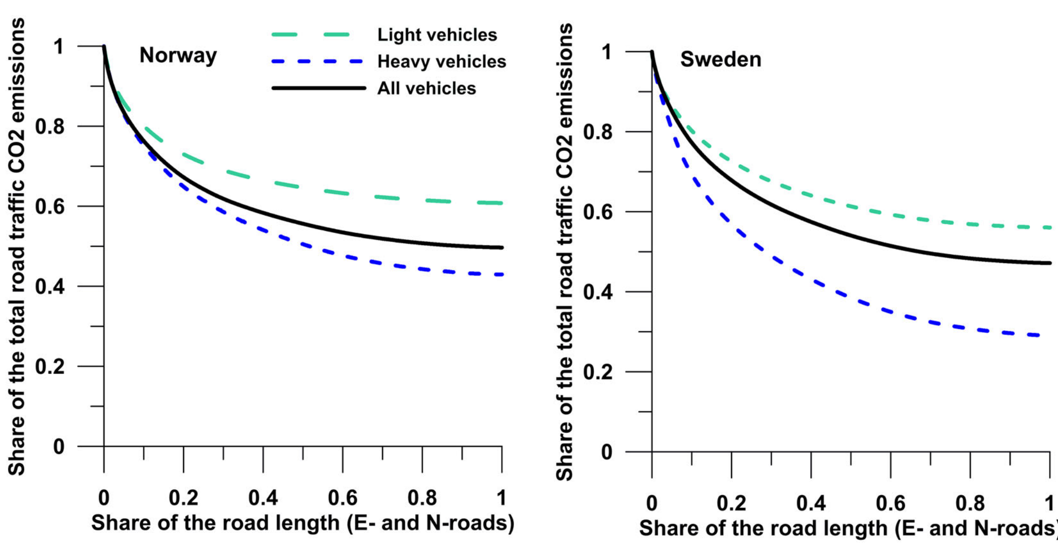


**Figure 9.** Shares of the European and National road (E- and N-road) lengths with ERS and the shares of the total national road traffic $CO_2$ emissions from light and heavy vehicles in Norway (a), and in Sweden (b). The reference level on emissions was obtained from today's emission level.

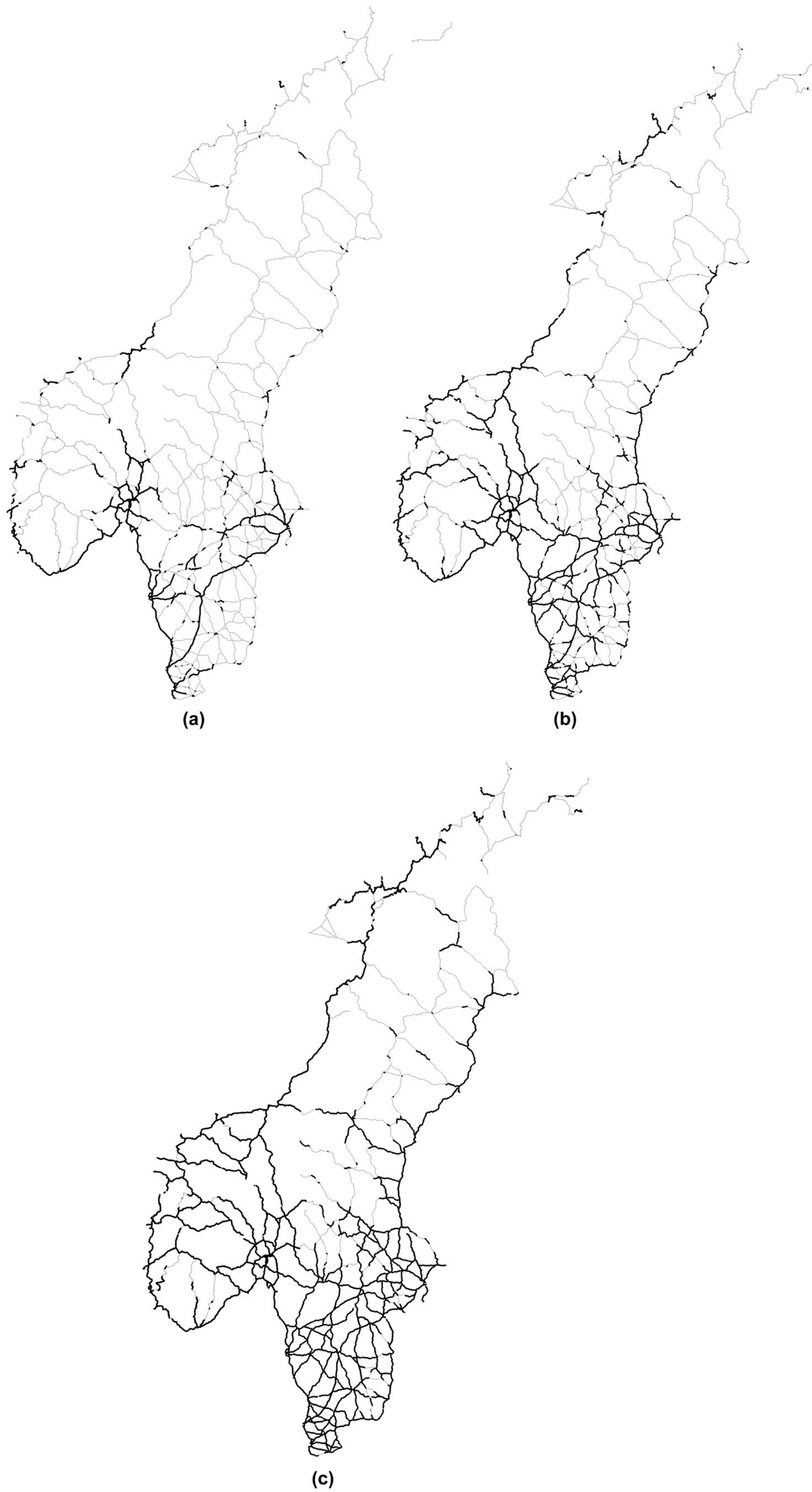


**Figure 10.** The 25% (a), 50% (b), and 75% (c) shares of the European and National roads (E- and N-roads) in Sweden and Norway with the highest $CO_2$ emissions from road traffic.

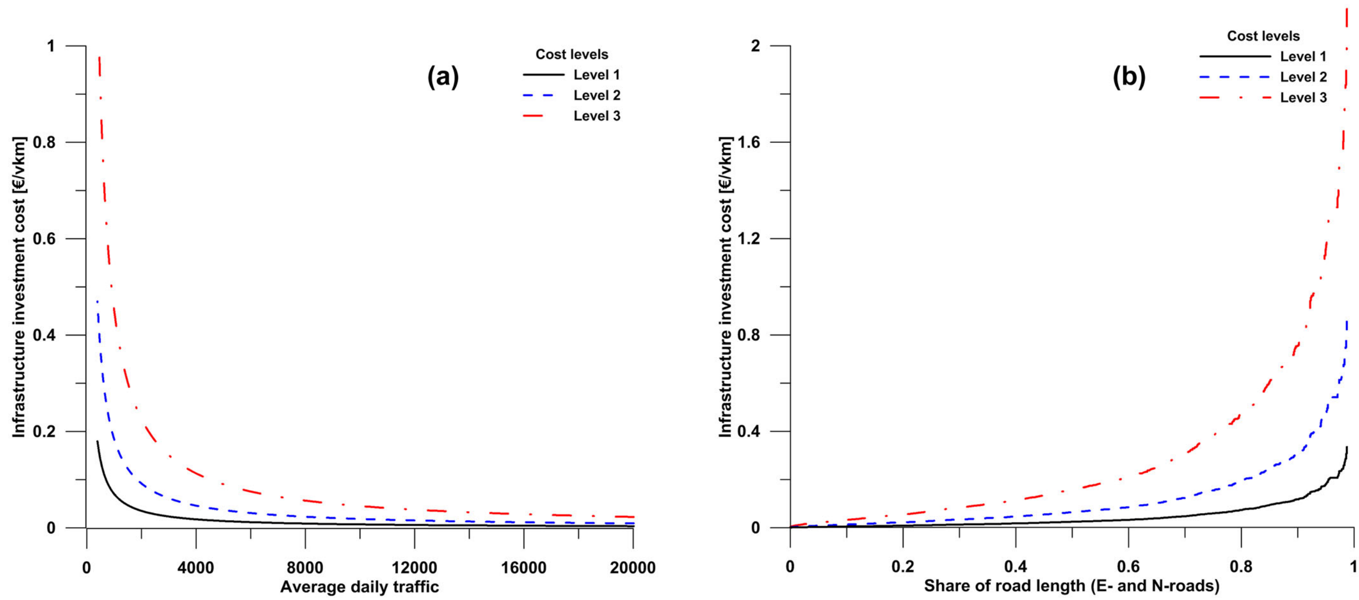


**Figure 11.** ERS infrastructure investment costs per vehicle kilometer for all vehicles and three cost levels applied in this work, as a function of the number of vehicles per day for the average daily traffic (a), and for the share of the European and National road (E- and N-road) length (b).

the total Norwegian emissions from light vehicles and heavy vehicles, respectively. In Sweden, a higher proportion of the transportation by heavy vehicles is done on E-and N-roads, which means that using an ERS on 40% of the E- and N-roads would save 36% and 55% of the total emissions from light vehicles and heavy vehicles in Sweden, respectively. As shown in Figure 9, an additional increase in the use of ERS with 40%–80% coverage would save only a few more percentage points of the total national road emissions. Therefore, electrifying those roads that have a high traffic intensity seems to be crucial for ensuring that ERS implementation is efficient from the $CO_2$-mitigation perspective (according to Figures 8 and 9). Full implementation of ERS on all E- and N-roads would mitigate (at a maximum) around 60% of the Norwegian and 70% of the Swedish $CO_2$ emissions from heavy vehicles, and correspondingly, 40% of the Norwegian and 45% of the Swedish emissions from light vehicles (Figure 9).

In Figure 10, 25%, 50%, and 75% of the E- and N-roads with the highest $CO_2$ emissions from road traffic are illustrated with black lines. ADT values (including both light and heavy vehicles) of around 6800, 3100, and 1200 correspond to the E- and N-road lengths of 25%, 50%, and 75%, respectively. For heavy vehicles, the 25%, 50%, and 75% of the E- and N-road lengths with the highest ADT have ADT values of 900, 400, and 200, respectively. The portions of the E- and N-road network with very high $CO_2$ emissions can be found in the vicinity of cities (Gothenburg, Oslo, Bergen, Trondheim, Malmö, etc.), where the roads are mainly used for shorter trips commuting to and from work. As shown in Figure 10, implementation of an ERS on 25% of the road length includes also parts of the main road network that connects the larger cities in both Sweden and Norway, for example, the triangle of Stockholm, Gothenburg and Malmö and the Oslo region with Kristiansand, Bergen and Stavanger. If an ERS is used for 50% of the Swedish E- and N-road length, it will include ERS also on more of the road network in the northern parts of Sweden and Norway, the west coast of Norway, and the southeast coast of Sweden. The roads with the highest $CO_2$ emissions (see Figure 10) are also the roads with the highest vehicle kilometers per year, with some exceptions where the road network has a higher share of heavy vehicles per day, for example, the E39 between Stavanger and Bergen and the E4 between Stockholm and Malmö. The exceptions are due to the fact that heavy vehicles and light vehicles are emitting different amounts of $CO_2$ per vehicle kilometer, since fuel consumption per vkm is more than 10-fold higher for heavy vehicles than for light vehicles. For heavy vehicles, the roads with the highest emissions levels are mainly those lying outside the larger cities, although they also include several kilometers of roads between some medium-large cities, as well as the E6 between Malmö and Gothenburg.

### 3.3. Infrastructure investment cost

Large-scale implementation of an ERS on 25% of the E- & N-roads (approximately 6800 km) would necessitate a total investment cost in the range of 2700–7500 M€$_{2016}$, assuming an investment cost of 0.4–1.1 M€$_{2016}$ per kilometer. Figure 11 shows the infrastructure investment costs per vehicle kilometer for three cost levels as a function of ADT (Figure 11a) and the share of the E- and N-road length (Figure 11b). In Figure 11, no adjustments have been made for the fact that heavy vehicles are using more energy per vehicle kilometer than light vehicles.

The infrastructure investment cost per vehicle kilometer increases dramatically for roads with a low ADT as expected. Thus, electrifying roads with an ERS that just uses heavy vehicles will increase the cost per vehicle kilometer for a road compared to using an ERS for both heavy and light vehicles. When the average daily traffic is less than 500 vehicles per day, the cost increases rapidly (Figure 11a). For roads with an average daily traffic of more than 500 vehicles per day the infrastructure investment cost is 0.14 $€_{2016}$/vkm for the level 1 and 0.36 $€_{2016}$/vkm for the level 2 cost levels (Figure 11a). Approximately 90% and 50% of the E-and N-road length if including all vehicles and heavy vehicles, respectively, have a traffic volume of at least 500 vehicles per day.

For roads with an average daily traffic of >6800 and >1200 vehicles per day (corresponding to 25% and 75% of the E- and N-road length assuming all vehicles use ERS), the costs of infrastructure investment are 0.03 $€_{2016}$/vkm and 0.15 $€_{2016}$/vkm, respectively, assuming cost level 2. These numbers can be compared with the total driving cost per kilometer per truck (i.e., the vehicle cost plus the ERS infrastructure cost per vkm) amount to 0.23–0.55 $€_{2016}$/vkm, and the cost of the current most-cost-efficient alternative, diesel, of approximately 0.68 $€_{2016}$/vkm. Only ~20% of the E- and N-road length has a traffic volume of more than 1200 heavy vehicles per day. So, the infrastructure cost will be much higher than 0.15 $€_{2016}$/vkm for more than 50% of the E- and N-road network if including only heavy vehicles, as seen in Figure 11a.

The vehicle cost for a passenger car using an ERS has been estimated to be 0.05 $€_{2016}$/vkm when using an ERS for driving 1200 km per year (which is approximately 30% of the average yearly driving distance). The total driving cost per vkm for a passenger car (i.e., vehicle cost plus the ERS infrastructure cost per kilometer) using the ERS for 30% of the yearly driving distance on a road with an ADT of at least 6800 and 1200 vehicles per day are then 0.08 $€_{2016}$/vkm and 0.2 $€_{2016}$/vkm, respectively. The diesel cost for a passenger car is estimated as 0.1 $€_{2016}$/vkm.

For roads with an average daily traffic between 3100 and 1200 vehicles, the $CO_2$ abatement cost is estimated to be in the range 105 to 230 $€_{2016}$/ton $CO_2$, which corresponds to approximately 0.02–0.04 $€_{2016}$/vkm for passenger cars and 0.1–0.2 $€_{2016}$/vkm for heavy trucks.

## 4. Discussion

The analysis conducted in this work includes all the E- and N-roads in Norway and Sweden, assuming different degrees of electrification in terms of the fraction of the road length with ERS. Large-scale implementation of ERS on 25% of the E- and N-road lengths in Norway and Sweden (approximately 6800 km) would require a total infrastructure investment of 2700–7500 $M€_{2016}$, assuming an ERS investment cost of 0.4–1.1 $M€_{2016}$ per kilometer. It should be stressed that these costs are uncertain, as the literature reports more than double this cost for the less-mature inductive power transfer technology. However, for a large fraction of the E- and N-roads in Norway and Sweden, the infrastructure investment cost per vehicle kilometer is low compared to the vehicle cost. For roads with an ADT of less than 500 vehicles, the investment cost per vehicle kilometer for the ERS will most likely be a large part of the total driving cost per kilometer for a truck assuming that all vehicles are using the ERS. However, for roads with an ADT of >1000 vehicles, the infrastructure cost per vehicle kilometer will be low compared to the vehicle cost per kilometer for a truck and for a passenger car. The profitability of building an ERS depends of course on the cost of alternative drive trains and fuels, although the results of the present study reveal that for roads with an ADT of at least 1200 vehicles using an ERS, the total driving cost per km for a truck (0.23–0.55 $€_{2016}$/vkm) does not seem to be an issue, as compared to current most-cost-efficient alternative, diesel, of approximately 0.68 $€_{2016}$/vkm. Approximately, 20% of the E- and N-road length has a traffic volume of heavy vehicles that exceeds 1200 vehicles per day. Yet, further research to compare cost for ERS with other alternative solutions, such as fuel cell vehicles and battery vehicles, is needed.

The implementation of a large-scale ERS will require considerable up-front investment costs. If only looking at the infrastructure investment cost per vehicle kilometer, including all types of vehicles, light vehicles also appear to be important to in bringing down the cost. However, heavy vehicles are emitting more $CO_2$ per vehicle kilometer, which makes the infrastructure investment cost per mitigated $CO_2$ approximately the same for light and heavy vehicles. In the present study, no projections of future traffic flows were considered since this would require a transport modeling, considering different modes of transportation in addition to ERS and this is outside the scope of this work. Yet, it can be concluded that the traffic volumes for all road transport, especially road transport of goods, are projected to increase until 2030 (Johansson, 2013) which should make ERS a more attractive option since ERS would has the potential to take a large share—if not all—of such increase.

If one wishes to implement an ERS system so as to cover 25% of the road length in Norway and Sweden with the highest $CO_2$ emissions, then some of the larger cities, such as Gothenburg, Stockholm, Malmö, Oslo, Kristiansand, Bergen, and Stavanger, as well of course the cities along the roads between these cities, will be connected by an ERS. The ERS will in such a case not be used for passenger or goods transportation on roads north of Stockholm in Sweden and north of Trondheim in Norway, as well as, on roads in the southeast of Sweden (except for shorter distance outside some larger cities), owing to lower traffic volumes on those roads. In the case of large-scale implementation of an ERS (i.e., more than 25%), road types other than the E- and N-roads, e.g. county roads, may need to be considered, since some of those roads have higher ADT values than the E- and N-roads with the lowest ADT values. Full implementation of ERS is, of course, unlikely and these data are provided simply to demonstrate the future potential of an ERS for the electrification of road transportation of people and goods.

An important issue is the willingness of the owners of the different vehicle types to use the ERS rather than using their vehicle batteries or combustion engines/fuel cells. Overhead lines represent an ERS technology that can only be used by heavy vehicles (i.e., buses and trucks), while the electrified rail in the road system and the inductive supply can be used by all types of vehicles (cars, buses, and trucks). Choosing an ERS technology that can be used by all vehicle types will of course reduce the infrastructure investment cost per mitigated tonne of $CO_2$. However, as mentioned above, a higher ADT value is typically reached in the direct vicinity of cities, where the highway is used mainly for shorter commuting trips to and from work. The cost for the extra vehicle equipment needed to enable use of the ERS needs to be economically attractive and less than the cost of a small battery for such commuting vehicles. A vehicle that is driven long distances each year on an road with ERS will benefit from the low running cost of using electricity instead of petrol/diesel/biofuels or bearing the alternative cost of buying a car with a larger battery. Passenger cars are driven approximately 12,200 vkm/yr, and according to the analysis performed in this study, these cars would have the potential to use E- and N-roads for on average approximately 45% of their driving distance. A study of the individual traveling patterns of passenger car drivers in the Swedish region of Västra Götaland found that approximately 95% of the trips were shorter than 50 km and 33% of the vkm/yr were driven during a trip that was longer than 50 km (Kullingsjö & Karlsson, 2012). In the present study, we have not included in the analyses either the individual driving patterns of passenger cars or the individual willingness to pay for using ERS rather than an alternative, such as a large battery, car pooling or renting a car for those trips that are longer than the battery range. Passenger cars using ERS for trips longer than the battery range would most likely need a larger network of ERS to reach a higher share of the yearly driving with ERS. Heavy vehicles are currently driving >35,000 vkm/yr, mostly (~70%) on E- and N-roads. In addition, heavy vehicles are to a greater extent than private cars, driven in the style of a shuttle service, which could facilitate the introduction of an ERS on certain routes.

The results of the present study are very similar for Norway and Sweden, despite the fact that these two countries differ, for example, in terms of the number of total road kilometers, topography, and road quality. Relative to the European (EU-28) average, Sweden has a lower share and Norway has a higher share of freight transport on the road. The understanding of the influence from different factors like traffic flows, vehicle and infrastructure costs per kilometers from this study, gives a good platform for extrapolation to other countries. However, although some general conclusions may be drawn, each national context needs a detailed analysis. There may be possibilities to extrapolate the present results for all E- and N-roads in Europe. However, Sweden and Norway differ from most other European countries when it comes to, for example, traffic volumes per kilometer. This, since most European countries have a higher population density and, consequently, a larger share of roads with higher traffic volumes. Thereby, the infrastructure cost per vehicle kilometer is higher in Sweden and Norway than the European average. On the other hand, Sweden and Norway have lower electricity prices than most European countries. Also, infrastructures with high upfront costs like ERS are more challenging for countries with low GDP per capita. More research is needed to further investigate ERS in an intercontinental European perspective.

The present work does not consider the detailed outline of ERS, i.e., the initial steep increase seen in the number of vehicle kilometers covered with an increased share of the road length with ERS. The traffic volumes (i.e. ADT) are not the only parameter to consider when assessing an implementation plan of roads to electrify with ERS. Also, the willingness to use the ERS is important to consider and to investigate this, individual driving data rather than data on ADT, is needed. Thus, the roads with high-density traffic close to big cities may not be the first to be electrified, since they only cover a short total distance and are mainly used for commuting, and this can be handled effectively by using battery-powered vehicles, as previously discussed. Instead, selected busy city-to-city connections might be equipped with ERS initially. However, the present study does not include a cost analysis of local bulk transport routes, which may for a specific operator prove attractive to equip with ERS.

Although ERS has been tested on public roads, it will still require several more test projects on public roads before being implemented on large scale in Sweden and Norway. Further development and a realization of ERS on large scale will need strong governmental policy support, since market forces alone will not deliver the needed impetus (International Energy Agency, 2017). Sweden and Norway have already today a clean electricity system, but this is not the case for many other countries. An electrification of road transport through ERS requires also a decarbonization of the power sector in order to reach the $CO_2$ mitigation potential presented in this study.

## 5. Conclusions

The results of the present study show that an ERS that encompasses already 25% of the total E- and N-road length would result in electrification of 70% of the traffic on these roads and 35% of the total national vehicle kilometers traveled in Norway and Sweden. In such a case, some of the larger cities in Norway and Sweden, and of course also the cities along the roads between these cities, would be connected by an ERS. Approximately 10 $MtCO_2$ and 5 $MtCO_2$ per year are emitted from road traffic (on E- and N-roads) in Sweden and Norway, respectively. Full implementation of ERS would mitigate up to 60% and 70% of the total heavy traffic $CO_2$ emissions in Norway and Sweden, respectively, and 40% and 45% of the total $CO_2$ emissions from light traffic, respectively. If the ambition is to electrify more than 55% of the light vehicles with ERS, other road types, such as county roads and private roads, would also need to be included in the ERS. However, full implementation of ERS is highly unlikely, so these figures are only provided to show the maximum potential for the electrification *via* an ERS of the road transportation of people and goods. The cost estimations in this study shows that for roads with an average daily traffic of >6800 and >1200 vehicles per day (corresponding to 25% and 75% of the E- and N-road length assuming all vehicles use ERS), the costs of infrastructure investment are 0.03 $€_{2016}$ per vkm and 0.15 $€_{2016}$ per vkm. Thereby, on those roads the total driving per vkm using ERS for a truck and a passenger car can be comparable with, for example, the driving cost for a diesel vehicle today. Further detailed studies on busy city-to-city connections and local bulk transport routes is needed since those roads are more likely to be equip with ERS initially.

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