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Hourly electricity demand from an electric road system – A Swedish case study

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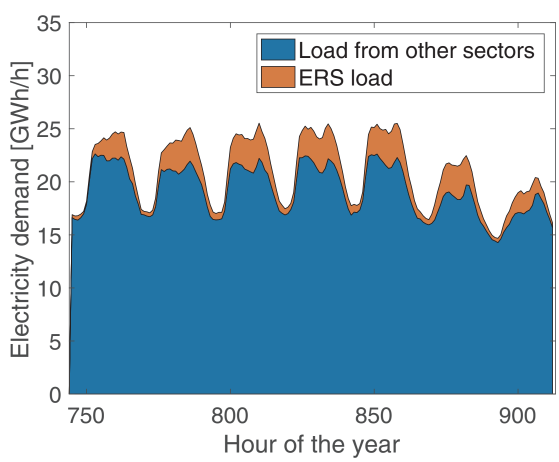
HIGHLIGHTS

- The electricity use on Swedish roads using electric road systems (ERS) is analyzed.
- ERS hourly electricity use coincides with present peaks in the electricity system.
- An ERS could increase the electricity demand of the dimensioning load hour by 4%.
- An ERS could reduce Swedish road-transportation CO_2 emissions by 19%.
- Applying ERS to all Swedish main roads could electrify 50% of annual traffic.

GRAPHICAL ABSTRACT



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ABSTRACT

This study investigates the hourly electricity demand related to implementing an electric road system (ERS) on five Swedish roads with the highest traffic flows that connect the three largest cities in Sweden. The study also compares the energy demands and the CO_2 mitigation potentials of the ERS with the use of carbon-based fuels to obtain the same transportation work, and extrapolates the results to all Swedish European- and National- (E- and N) roads. The hourly electricity demand along the roads are derived by linking 12 available measurement points for hourly road traffic volumes with 12,553 measurement points for the average daily traffic flows along the roads. The results show that applying an ERS to the five Swedish roads with the highest traffic flows can reduce by ~20% the levels of CO_2 emissions from the road transport sector, while increasing by less than 4% the hourly electricity demand on the peak dimensioning hour. Extending the ERS to all E- and N-roads would electrify almost half of the vehicle kilometers driven annually in Sweden, while increasing the load of the hourly peak electricity demand by only ~10% on average.

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1. Introduction

To meet ambitious climate targets, as laid out in the Paris agreement [1] and in the European Union (EU) framework document [2], the transport sector needs to transform its energy supply to non-fossil-based energy carriers. Currently, 95% of the global transport sector uses petroleum, and the sector accounted for 23% of the global greenhouse gas (GHG) emissions in 2015 [3]. Furthermore, while other sectors (e.g., power, residential and industry) in the EU have decreased their CO_2 (and GHG) emissions since 1990, the transport sector has instead increased its levels of CO_2 emissions [4]. The EU aims to reduce the GHG emissions from the transport sector by 60% up to Year 2050 compared to emissions levels in Year 1990, with electrification of the transport sector being proposed as one of the main options for achieving this goal [5]. In Sweden, newly adopted legislation aims to reduce the levels of GHG emissions from the domestic transport sector (excepting aviation) by 70% by Year 2030 (relative to the levels in Year 2010) [6]. In addition, Sweden currently has 98% fossil-free electricity generation [6], which makes electrification of the transport sector an attractive option (although the electricity system is linked to the Nordic and European electricity systems, which means that any effect of increased electrification is dependent upon developments of the electricity systems in the neighboring regions). Today, the electricity generation in Sweden consists of 53% hydro power, 40% nuclear power and 7% from other sources such as wind power and biomass [6]. Several recent studies (e.g. Johansson et al. [7], Fridstrom et al. [8] and Grahn et al. [9]) have lent support to the notion that electrification of the road transportation together with an increased share of renewable electricity generation could play an important role in a future scenario to reduce CO_2 emissions from the transport sector. Taljegard et al. [10] model the electricity system in the Nordic countries and Germany including an increased demand due to an electrification of the transport sector. The modelling results show that if to reach the Swedish climate target for 2050, an increased demand from an electrified transport sector will mainly come from an increased investment and generation of wind power in Sweden.

Electrification of road transport can be achieved using various strategies, including: (i) the use of battery-powered electric vehicles (EVs) that employ static charging; (ii) the use of electricity to produce alternative fuels (e.g., methanol and hydrogen) that can drive vehicles with an internal combustion engine or fuel cells; and (iii) the application of dynamic charging of EVs through an electric road system (ERS). Future development of the road transport sector could consist of a mixture of these technologies and fuels, as it is not yet clear as to which of the options will be the most cost-efficient, and it remains uncertain as to which other preferences will decide the main routes for decarbonizing the transportation sector [7]. ERS provides dynamic power transfer when driving, thereby reducing the size and weight of the onboard vehicle battery without compromising driving range, as compared to using only static charging. To allow driving for 4 h, a heavy truck would need a battery with capacity in the range of 600–800 kWh, which would entail a battery package weighing several tons, assuming the usage of current battery technology. ERS reduces the vehicle cost by decreasing the battery size. However, a large-scale infrastructure, which has a high up-front investment cost, needs to be built in order to supply the vehicles with electricity while driving. In addition, there are challenges to find viable economical business models, agreeing on technology standards, and to accommodate a radical increase in technical, business, and systems complexity [11]. While ERS can be powered either conductively or inductively, to date, full-scale demonstration of ERS on public roads has been limited to conductive systems. The conductive approach offers two different solutions for transferring power from the road to the vehicle: (i) *via* overhead catenary lines connected to a pantograph mounted on top of the vehicle; and (ii) through a conductive rail located in or on top of the road that transfers power to the vehicle *via* a mechanical pick-up arm located underneath the vehicle. The inductive approach transfers power between the road and the vehicle wirelessly through an elongated magnetic coil that is built into the road and connects to a pick-up point in the vehicle. Both the inductive approach and the conductive rail approach can supply with electricity all the main types of conventional road vehicles (i.e., passenger cars, buses, and trucks, with the exception of motorcycles). The catenary overhead lines solution is in current design forms limited to compatibility with buses and trucks due to the elevated positioning of the wires. This study will not examine the effects of different ERS designs, although separate results will be presented for light vehicles (passenger cars and light trucks) and heavy vehicles (buses and heavy trucks).

Electrification of the road transport sector with ERS could impose local or regional constraints on the electricity grid depending on how, when, and to what extent the vehicles are charged. Several studies have been published in recent years describing the demand profiles and impacts of EVs on the electricity system, assuming static charging of passenger EVs (e.g. Jochem et al. [12], Hedegaard et al. [13] and Grahn [14]). However, in the scientific literature, few studies (Grahn [14], Taljegard et al. [15] and Stamati et al. [16]) have investigated the demand profiles of an ERS and the possible impact of an ERS on the peak power demand. Grahn [14] found by modeling the Swedish vehicle fleet that charging at home or/and at work would increase the peak load in Sweden by 1–2 GW, assuming that 50% of the Swedish vehicle fleet comprised EVs. They also predicted that with 50% adoption of passenger plug-in hybrid electric vehicles (PHEVs) in Sweden and assuming that 5 kW of charging power from the ERS are available for all types of trips, a 2–GW peak load from EVs in Sweden would occur daily at 12 pm [14]. Stamati et al. [16] have investigated the electricity demand for a highway in the Netherlands and the possibilities to meet that demand with renewable electricity generated in connection to the road. Taljegard et al. [15] have shown that an ERS load profile that includes the traffic (passenger cars, trucks and buses) on all main roads in Norway would increase the hourly peak power demand on the dimensioning hour of the system by approximately 7%. They have also shown that heavy vehicles account for approximately half of the increase in peak power demand, assuming that both light and heavy vehicles are electrified.

While there have been several other studies focusing on ERS, most of these have focused on the technical aspects related the power transfer (e.g., Wu et al. [17], Villa et al. [18] and Covic et al. [19]) and investment cost, implementation, and maturity aspects (e.g. Connolly et al. [20], Wilson et al. [21], Boer et al. [22], Sundelin et al. [23] and Olsson et al. [24]). There is a lack of studies which investigate the characteristics of the electricity demand from an ERS, and that analyses how this will affect the stationary electricity system, and what are the potential CO_2 savings for road transportation.

The present study investigates the hourly electricity demand when electrifying light and heavy vehicles with ERS on the roads that connect the three largest cities in Sweden. The study also compares the energy demands and CO_2 mitigation potentials of carbon fuels and ERS. A case study of the roads connecting Stockholm, Gothenburg, and Malmö is performed. This part of the Swedish road network (i.e., parts of European roads E4, E6, E18, E20 and National road 40) is 1420 km long and covers 9% of the Swedish E- and N-roads and 0.7% of the total Swedish road network. However, these roads account for 15% of the Swedish yearly vehicle kilometers, 25% of the yearly heavy vehicle kilometers [25], and 19% of annual CO_2 emissions from the Swedish road transportation sector [26]. A new method has been developed in this study that links available measurement points (12 in this study) for hourly road traffic volumes with available measurement points for average daily traffic (ADT) flows (12,553 in this study). Moreover, the method for calculating the hourly demand profiles based on the roads included in the case study are used to estimate the hourly electricity demand for all E- and N-roads in Sweden. The results are, as previously mentioned, presented for all vehicle types combined and for heavy and

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