EVS29 Symposium
Montréal, Québec, Canada, June 19-22, 2016

Charging strategies – implications on the interaction between an electrified road infrastructure and the stationary electricity system

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Summary

This study uses a vehicle model together with detailed traffic data of the European route 39 in western Norway to estimate how the electricity demand for an electric road system varies with time and location. The aim is to better understand the impact of an electric road system on the stationary electricity system. The results show that the electricity demand for an E39 electric road system is comparable to a larger industry, potentially increasing the peak power demand in the regional electricity system with only a few percent. Yet, if all main Norwegian roads are electrified, or if vehicles can also charge their batteries while driving, there will be a significant (>10%) addition of electricity demand to the current load.

Keywords: power, energy consumption, case study, EV (electric vehicle), environment

1 Introduction

Today, many of the electric cars and trucks are used in densely populated areas for shorter commuting and distribution purposes [1, 2]. An increased driving range for electric vehicles might require a combination of electric road systems and significant charging infrastructure. Therefore, electric road systems (ERS) by means of on-road conductive or inductive power transfer when driving have gained increased interest during the last years [2-6], mainly due to limitations in battery range, expensive batteries and that current battery technology becomes too heavy for some vehicle categories. An ERS can provide direct powering of electric motors and/or be used to charge vehicle batteries while driving. This provides a possibility to reduce the need for large batteries, both for passenger cars, trucks and buses. Dynamic electric power transfer to vehicles can be done either through overhead lines or through conductive or inductive installations in the road [4, 7, 8]. Several ERS systems are under development and currently tested on public roads [3, 5-9].

Electrifying the transport sector will typically only have a limited influence on the total yearly electricity demand for a country [2, 10]. For example, if all worldwide passenger cars were electrified, the electricity consumption would increase with approximately 5% [11]. However, electric vehicles could impose a challenge on the electricity system by enhancing peak loads or causing a new peaks in the load. Different

electrification strategies, for example charging of vehicle batteries at home and/or at work, fast charging stations and ERS, will result in different load profiles, and thus, have different effects on the electricity generation system.

In literature, the impact on power peaks from a large-scale introduction of electric vehicles has been the topic in a number of papers during recent years [12-20]. For example, Göransson et al. [12] have shown that, electric vehicles charged at home or/and at work might increase the peak load. However, they also show that if the charging patterns are delayed a few hours to avoid an increase of evening peak, the vehicle charging could instead be used for peak shaving of the net electricity load. Similar conclusions were made by Weiller [15] and Hadley & Tsvetkova [14], who looked at a large-scale introduction of plug-in hybrid vehicles in the U.S electricity system. Grahn et al. [21] found, by modelling the Swedish vehicle fleet, that if 50% of the Swedish vehicle fleet were electric vehicles, charging at home or/and at work would increase the mean load peak in Sweden with 1-2 GW, depending on the charging strategies.

Although the literature shows the importance of controlled charging in order to avoid an increase of peak generation with a large-scale introduction of electric vehicles, little is known about the variations in the electricity load from an electric road system. Stamati & Bauer [22] have modelled the electric power demand for an average day for a highway in the Netherlands, limited to one vehicle type (passenger cars). Grahn et al. [21] have developed a model which includes stochastic individual driving behaviour, static charging opportunities at parking sites and dynamic charging opportunities along electrified roads (ERs). Grahn et al. show that, with a 50% introduction of passenger PHEVs in Sweden and if 5 kW charging power on the electric road is available at all type of trips, a 2 GW peak load from electric vehicles in Sweden occurs at 12pm. None of the studies have so far included truck and buses in the load curve of an electric road system.

An electric road system can potentially cause local or regional constraints on the grid depending on when and to what extent the vehicles are using the ERS. An ERS also gives the possibility to charge the battery whilst driving, while on-board batteries are used to power the vehicle when passing non-electrified roads. There is a need to investigate the temporal and geographical distribution of the electricity demand from an ERS, in order to understand the impact of an ERS on the stationary electricity system. The aim of this work is to provide an analysis of the geographical and hourly load profile along a coastal highway, passing both urban and rural regions. The work applies a vehicle energy consumption model using the Norwegian European route 39 (E39) as a case study, yielding from which traffic work data is available.

The E39 runs along the western coast from Kristiansand in the south to Trondheim in central Norway; a distance of 1100 km. Large infrastructure investments is planned for the E39 in the so called “Coastal Highway route E39” project [23] and since new road infrastructures have long life times it is of importance to assess different alternatives for future vehicle options. The E39 is also of interest in an energy systems perspective since it passes some of Norway’s main cities, such as Ålesund, Bergen and Stavanger, and since more than half of Norway’s energy intensive industry is located along the road.

Based on the modeling results, the paper discusses (i) the interaction between an electric road system and the stationary electricity system, (ii) electric road system and relation to other electrification strategies, and (iii) an electric road system from the perspective of different vehicle types.

2 Method

A vehicle energy consumption model is formulated and combined with traffic and road data in order to obtain a geographical load profile, as well as, an hourly load profile for the E39, yielding how the electricity demand varies with time and spatial distribution. The amount of electricity that can be regenerated from the road when decelerating or driving downhill, and be feed back to the grid or to charge vehicle batteries is also estimated.

2.1 Vehicle energy consumption model

The energy flows in the operation of vehicles can be expressed in terms of simple algebraic approximations. This road-load methodology was mainly introduced by Sovran and Bohn [24] and mathematical models for

estimating fuel consumption and fuel efficiency for vehicles has been widely used in the literature [25-30]. In this study, a basic vehicle energy consumption model based on overcoming inertia, road inclination, tire friction, aerodynamic losses and regeneration from braking has been formulated.

The energy consumption and power demand for a vehicle driving a certain distance depends on a number of factors, such as the vehicle characteristics (i.e. vehicle mass, drivetrain efficiency, frontal area, etc.), speed, driving behavior, pavement conditions, altitude, and weather conditions. The power to the wheels P_{wheel} and the engine (P_{engine}) for a vehicle in the model is given by:

$$P_{wheel} = v\left(\mathrm{m}\cdot g\cdot \sin(\alpha) + m\cdot g\cdot C_r + \rho\cdot\frac{v^2}{2}\cdot A\cdot C_D + m\cdot a\right) \quad (1a)$$

$$P_{engine} = n_{grid}^{-1}\cdot n_{engine}^{-1}\cdot P_{wheel} + n_{grid}^{-1}\cdot P_{access} \; (1a)$$

where n_{grid} is the power transfer efficiency from the grid to the vehicle including the pick-up, n_{engine} is the engine efficiency including other losses in the vehicle; m [kg] is the vehicle mass; g [$m{\cdot}s^{-2}$] is the gravitational constant; α [$radians$] is the longitudinal slope; C_r is the rolling resistance coefficient; v [$km{\cdot}h^{-1}$] is the vehicle speed limit; ρ [$kg{\cdot}m^{-3}$] is the air density; A [m^2] is the frontal area of the vehicle; C_D is aerodynamic drag coefficient; a [$m{\cdot}s^{-2}$] is the vehicle acceleration level; and P_{access} [W] is the accessory power (such as air condition, heating the coupe, etc.). Table 1 specify the parameters in more detail.

When P_{engine} is negative, for example when decelerating (driving in downhill or reduce speed), some of this negative power can potentially be utilized by charging the battery ($E_{battery}$) or the regenerated energy can be sent back to the grid. The expression for the energy regeneration to the battery:

$$E_{battery} = -(P_{wheel}\cdot n_{battery}\cdot t)\; when\; P_{engine} < 0 \quad (2)$$

where $n_{battery}$ is the efficiency of charging the battery and t is the time [s]. The regeneration potential from recoverable energy consists of kinetic and potential energy and depend mainly on the vehicle configuration, how the vehicle is driven, and on the capacity of the drivetrain. The regenerated power can be stored in a battery and used to overcome, for example air, or rolling resistance in the next segment of the road, or be returned to the grid. Other factors such as driving behavior, slippery road, tire pressure, weather and powertrain configuration that are also affecting the real energy demand are to some extent implicitly included in the parameters in the vehicle model but not varied in a sensitivity analysis. Hammarström et al. [26] estimate ice and snow on rural roads to increase total energy consumption by approximately 1%.

2.2 Traffic and road data

The electricity supply for an electric road system depends on traffic density, penetration level of electric vehicles, power transfer limitations from grid to vehicle, and length of the road, which is electrified. In the simulation of the electricity and power demand for an electric road system, we have assumed the current route and design of E39, a full implementation of an electric road system and a 100% penetration level of electric vehicles. The traffic and road data applied in the calculations are taken from the Norwegian Public Road Administration (NPRA) database [31]. In these statistics, the E39 is divided into 13 300 segments in order to resolve also fine changes (<0.1%) in the longitude slope. The E39 includes a number of mountains passes and tunnels with a total elevation of 650 meters (from 432 meter above sea level to 289 meter below sea level). Figure 1 gives the cumulative length below a certain slope length for E39. As can be seen, the maximum slope is 10%, and half of the cumulative length has a slope of 2% or more. The vehicle speed limit varies between 20-90 km/h with an average speed limit of 80 km/h. There are approximately 70 circulation places along the road, and for those, a speed of 20 km/h is assumed in the modeling. For steep uphill segments, it is not relevant to apply the speed limit since the power needed would exceed the power capacity of the vehicle engine. In these cases, the power to the wheels from the electric motor is set to be the maximum power limit of the electric motor and thereby a decrease in speed is obtained. The average values for the international roughness index (iri) and the mean profile depth (mpd), which have been used in the calculation of C_r, are 1.55 m/km and 0.95 mm, respectively. These are based on detailed measurement carried out by NPRA between 2005 and 2015.

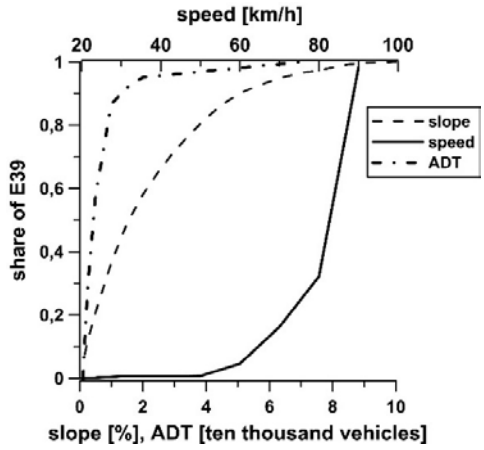

Figure 1: The cumulative length of the E39 below a certain slope, speed and average daily traffic (ADT) based on data from NPRA database.

The annual road traffic volume for E39 is approximately 2 600 million vehicle kilometers for 2014, which corresponds to 6% of the Norwegian road traffic volume. The average daily traffic (ADT), expressed in the average number of vehicles per day, is measured in 770 points along E39, while the hourly traffic for all hours of the year is measured in 70 points. The ADT for each of the 13 300 segments was taken from the closest of the 770 measurement points. Light vehicles is assumed to be vehicles below 5.6 meters and heavy vehicles above 5.6 meters. Figure 2 shows the ADT summed over all vehicle categories (Figure 2a), as well as the ADT and the share of heavy vehicles (Figure 2b) along the length of the E39 route. As can be seen from Figure 2a, there are large geographical variations in the intensity of the traffic flows along E39. On an average day, the traffic varies from less than 1000 vehicles/day in the rural areas to more than 70 000 vehicles in one of the urban areas (Stavanger). But as seen in Figure 1, more than 90% of the road has an ADT lower than 10 000 vehicles. Then there is also a variation on hourly basis, where low traffic hours over the day is only 2% of the rush hour peaks. The reason for the peaks in ADT around the largest cities, such as Stavanger and Bergen, is obviously due to short trips close to the cities, including commuting travels.

Heavy vehicles (heavy trucks and buses) are responsible, on a yearly average, for 12% of the vehicle kilometers on E39, and light vehicles (passenger cars and light trucks) for the remaining 88%. But these numbers varies both geographically (Figure 2b) and with time of the day and time of the year. For example, the heavy vehicle traffic varies on average between a few percent of the traffic during the afternoon to over 30% of the traffic during nighttime (except during holiday).

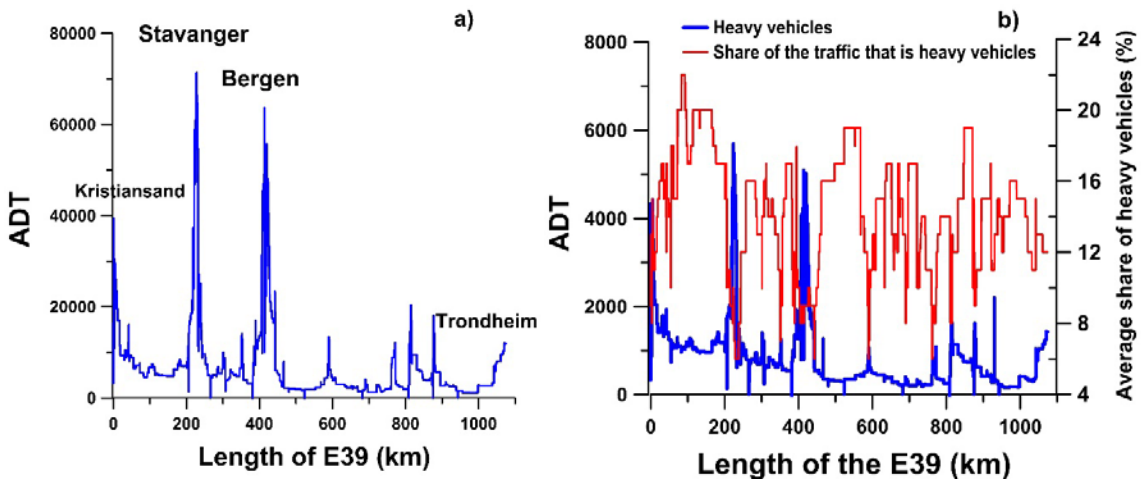

Figure 2: The average daily traffic (ADT) for E39 (a), and the ADT and the daily average share of the traffic that is heavy vehicles (b).

The hourly measurement of traffic data from 2014 has been used to create a profile of how the traffic is distributed over each hour of the year. However, since ADT was measured in about 770 points, the hourly distribution pattern for each of those 770 points was taken from the closest of the 70 hourly measurement points. In 45 of these 70 measurement points, some data is missing for 2014, which has then been replaced by data from the previous year (2013) multiplied with the average traffic increase between 2013 and 2014. In some cases, data was missing for both 2013 and 2014. Then the average value of the corresponding hours from the week before and after, was used to fill in the missing data. In 22 of these 70 measurement points, data were missing for several hundred hours (>200) in a row for both 2013 and 2014, and therefore not possible to fill in missing data, and those points have therefore been excluded from the analysis.

An analysis of the traffic patterns (i.e. distribution of the traffic over the day, between weekdays and between weeks) showed that there was a correlation between traffic density (ADT) and traffic patterns. For example, cities including their surroundings show the following pattern: (i) traffic peaks both in the morning and afternoon, (ii) a larger proportion of traffic during weekdays than on weekends, and (iii) less traffic during school breaks and summer (Figure 3). The situation is somewhat different in the countryside: the traffic during weekdays is still larger than weekends, but the effect is less pronounced, and the holiday traffic are, in most cases, even larger than an average week.

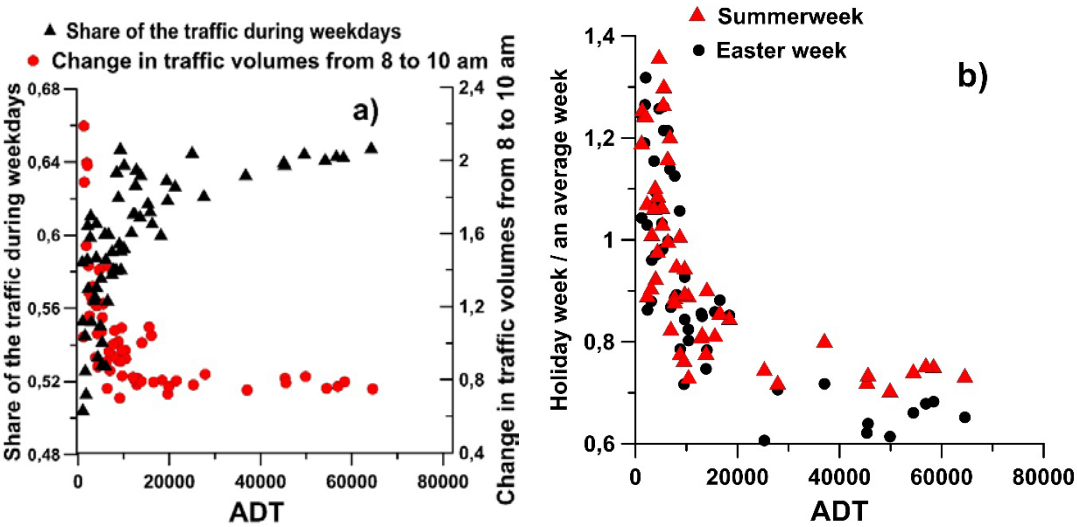

Figure 3: Correlation between the average daily traffic (ADT) and (a) the share of the weekly traffic that occur during weekdays and the change in traffic volumes between 8 and 10 am, and (b), a summer week and an Easter week compare to an average week.

2.3 Vehicle data

Four different vehicle types – passenger cars, light trucks, heavy trucks and buses – are used as a proxy for the Norwegian vehicle fleet, where passenger cars and light trucks are called light vehicles, and heavy trucks and buses are called heavy vehicles. Light trucks are all trucks with a weight of less than 3.5 tons and length of less than 5.6 meters, and the rest of the trucks is then heavy trucks. Table 1 summarizes the vehicle data used in the model. The drivetrain efficiency can be regarded as the averaged conversion efficiency from the grid to traction energy at the wheels, and is assumed to be constant over the drive cycle. Due to spares literature data, we have assumed the same efficiency for both inductive and conductive power transfer, even though the literature indicates that, today, the more immature inductive charging technology has somewhat lower transfer efficiency [4, 8, 32]. In the model, the engine power transfer limit and the regeneration limit are also assumed to be the same for both technologies. The rolling resistance coefficient (C_r) is calculated based on a general rolling resistance model developed by VTI [26], including parameters such as the international roughness index describing the unevenness of the road and the average profile depth, which expresses the macro texture of the road.

Table 1: Values for the vehicle parameters used in the vehicle consumption model [4, 7, 25-28, 32-34].

		Passenger cars	Light trucks	Buses	Heavy trucks
Vehicle drivetrain		electric	electric	electric	electric
Mass [kg]	m	1600	3500	20 000	40 000
Air resistance coefficient[a]	C_D	0.3	0.4 [c]	0.53 [c]	0.53
Area of the vehicle[b] [m^2]	A	2.3	4.2	7.2	9.7
Accessory power [kW]	P_{acc}	1.5	1.5	9	3
Rolling resistance coefficient[c]	C_r	0.012	0.012	0.007	0.007
Acceleration values[d] [m/s^2]	a	1.5	1.5	1	1
Engine efficiency[e] [%]	n_{engine}	90	90	90	90
Battery efficiency[f] [%]	$n_{battery}$	80	80	80	80
Power transfer efficiency[g] [%]	n_{grid}	93	93	93	93
Regeneration power limit [kW]		40	50	200	200
Peak electric motor output[h] [kW]		80	90	300	300

[a] Typical C_D values for trucks and buses are between 0.5-1.1. Passenger cars usually have C_D values around 0.3.[b] For trucks this is about 9-12 m^2 and for passenger cars about 2 m^2.[c] the average Cr for E39 are based on a rolling resistance model by VTI, and measurements of iri and mpd by NPRA.[d] Measurements with instrumented cars in Sweden concluded that vehicle acceleration values above 2 m/s^2 mainly exists for a vehicle speed below 60 km/h. For vehicle speeds between 60-80 km/h and 80–110 km/h, acceleration values are mainly below 1.8 m/s^2 and below 1.25 m/s^2, respectively. [e]consist of the efficiency of the electric motor (95%), inverter (95%), and other losses on board the vehicle (98 %). [F] charging the battery, [g] the efficiency from the 30 kV-grid to the vehicle including the pick-up. [h] the internal combustion engine will cover peaks higher than 300 kW for the heavy vehicles.

2.4 Verification of the vehicle model and assumptions

The study is a simplification in the following ways: (i) an average drivetrain efficiency is used, (ii) no speed reductions due to sharp turns (except circulation places) or traffic congestion, and (iii) an average vehicle type is assumed for each vehicle category. Nam et al. [35] claim that models similar to the one applied in this work have an accuracy within 10% compared to measured values of fuel consumption. Since the aim of this study is to investigate the energy consumption on an aggregated level such error range is considered as acceptable. A comparison with measurements of energy consumption of heavy fuel trucks in Norway by Vestforsk [36] and measurements of the regeneration potential of 447 Swedish passenger cars [28] show that the vehicle model used in this study is within the error range mentioned (10%).

3 Results and Discussion

3.1 Geographical distribution of the electricity demand for E39

The modeling results give that the required power transfer level for a vehicle driving on E39 is on average around 15 kW and 30 kW for a single passenger car and light van, and between 140kW and 120kW for a truck or bus. Table 2 gives the average energy consumption per km (after subtracting any power regeneration from braking/downhill) and the regeneration potential back to the battery or to the grid for the vehicles considered. The majority of the regeneration energy (>85%) comes from potential energy (driving downhill). This is in line with the braking potential for Swedish private cars found by Börjesson and Karlsson [28].

Electric excess power transfer capacity, occurring when the vehicle is not using its full power transfer potential (e.g. below 80kW for light vehicles or 300 kW for heavy vehicles), can be used for charging batteries when driving, and will lead to a higher electricity and power demand from E39. Assuming an electric vehicle charging the battery with a maximum power of 50kW yield on average approximately 1.2 kWh/km of energy available for charging of light vehicles whilst driving.

Table 2: Average electricity demand, regeneration potential and peak power demand for E39

		Passenger cars	Light trucks	Buses	Heavy trucks	All vehicle types
Average electricity demand per vehicle	*[kWh/km]*	0.16	0.35	1.18	1.92	-
Average regeneration potential per vehicle	*[kWh/km]*	0.02	0.03	0.3	0.5	-
Yearly total electricity demand	*[GWh/yr]*	295	140	75	455	965
Yearly total electricity demand	*[MWh/km·yr]*	280	130	70	420	900
Yearly total regeneration potential	*[GWh/yr]*	30	10	25	100	165
Total peak power demand	*[MWh/h]*	140	30	40	130	340

Table 2 also gives the yearly electricity demand and the regeneration potential for an electrified E39, which is 965 GWh/yr and 165 GWh/yr, respectively. This means that in terms of the magnitude of the demand per year, the E39 road can be compared to a large-size industry. Then, charging of batteries when driving is not included, which could increase the electricity demand. The yearly electricity demand and regeneration potential from E39 is, of course, small compared to the overall electricity demand in the nearby region. E39 is located in three electricty spotprice areas (NO2, NO3 and NO5) with a total energy demand of 73 TWh/yr.

Figure 4 shows the spatial distribution of electricity demand and the regeneration potential for a year (Figure 4a) and for the average afternoon peak hour (3-4 pm) (Figure 4b). As can be seen, there is a large variation in the spatial distribution of the electricity and power demand. The most energy intense parts of E39 is of course around the largest cities, such as Stavanger and Bergen, where E39 is used for short trips close to the city areas. City areas have also a larger share of the electricity demand that comes from light vehicles. In urban areas, many light vehicles are driving a short distance on the electric road system and might not need to use the power transfer. Data from the spatial analysis about the local peak demand can be used for the design of the electric road systems and the connection to the local grid, and as a decision basis for which roads that could be preferable to start to electrify. Roads with a large electricity demand, as well as a large number of heavy trucks, should be preferable for electrification, since one can assume that a single electric road system might be used mainly by trucks driving longer distances on the same road.

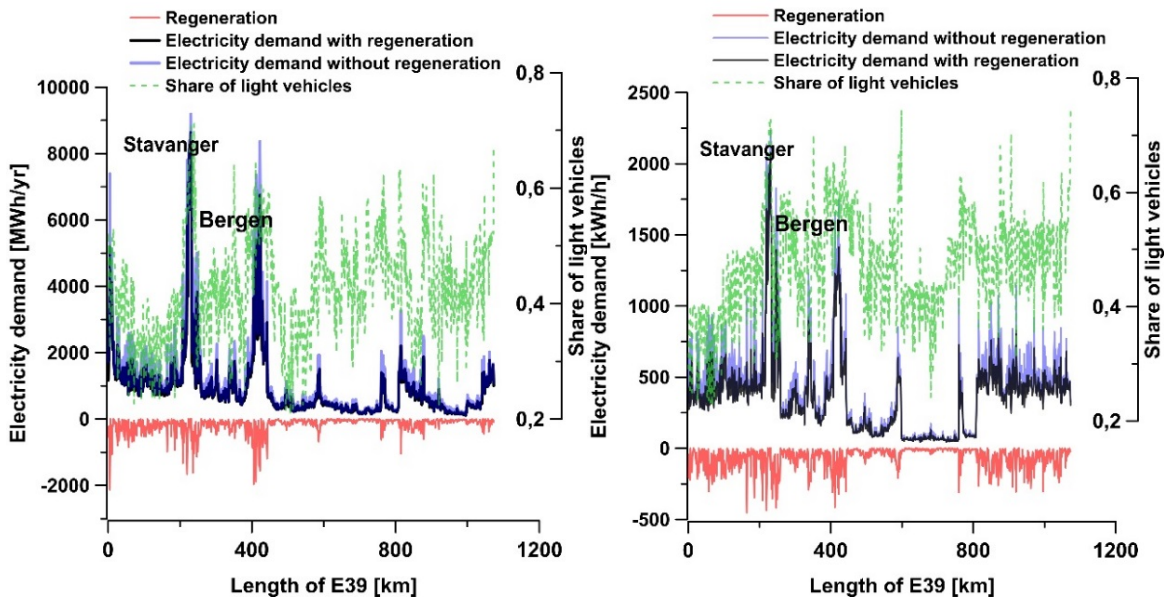

Figure 4: The yearly electricity demand and regeneration potential (a) and the afternoon peak hour (3-4pm) demand (b) for all vehicle types driving on E39 in both direction and the share of the electricity demand that corresponds to light vehicles (dashed line).

3.3 Time distribution of the electricity demand for E39

Figure 5 shows the electricity and power demand for E39 (the sum of the electricity demand of all segments) for each hour of the year, and Figure 6 shows the average daily and weekly distribution. There is a considerable variation between (i) night and daytime, (ii) weekend and weekdays, and working weeks and holiday week, where holiday time is either higher or lower in demand depending on if the road passes cities or country side. The distribution between weekdays and weekends, and over the day, is to some extent different for heavy vehicles compare to light vehicles, as seen in Figure 6. On an hourly basis, the electricity demand varies substantially, where low traffic hour consumption is only 10% of the rush hour peaks in electricity demand (Figure 5 and 6). However, the peaks comes with a predictable and regular pattern, when assuming a behavior and driving pattern similar of today.

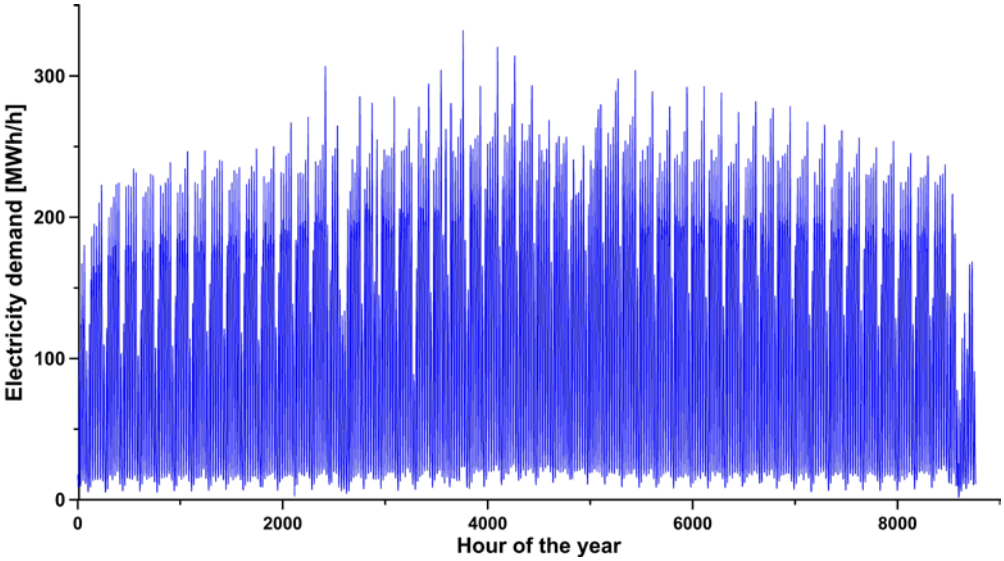

Figure 5: The electricity and power demand (MWh/h) for E39 for each hour of the year.

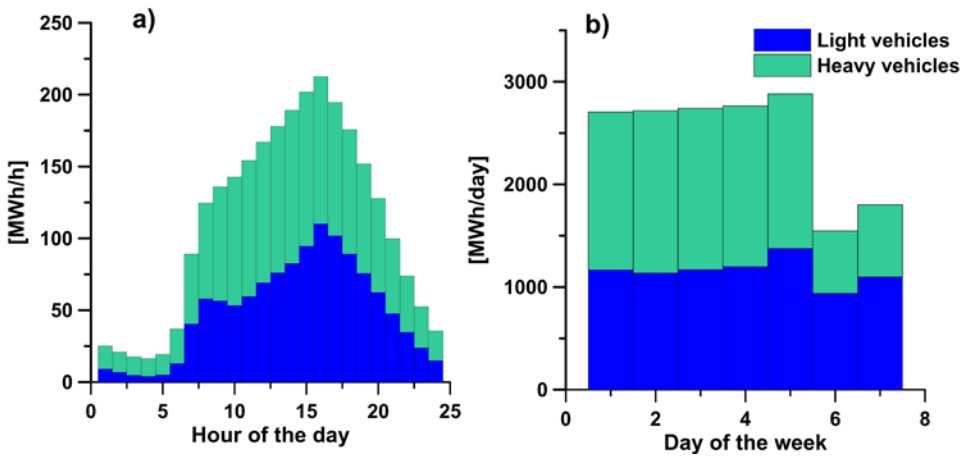

Figure 6: The electrcicity demand for an average day divided between hours of a weekday (a) and between days of the week (b) for heavy and light vehicles.

The electricity demand peaks during daytime, with the absolute highest peak between 3 pm and 4 pm on a weekday, when most people leaves from work (Figure 6). On an average day, the peak power needed is 210 MWh/h, and as seen in Figure 5, the days with highest peak demand is just before summer holiday, then the demand peaks at 340 MWh/h. An electrified E39 would thus increase the peak power demand in regional stationary electricity system with only 2-3%. Thus, with respect to a regional perspective, e.g. western

Norway (electricity price areas NO2, NO3 and NO5), the addition of another 340 MW should not be a major obstacle. But local bottle necks in the grid cannot be out ruled and need to be evaluated in more detail.

The peak demand hours for electricity in the region, which are also traditionally the dimensioning hours of the electricity system in the region, are between 6 and 10 in the morning in January. An electric road system, using electricity during daytime, will add to the peak power of the electricity demand. The peak power demand from the E39 of approximately 340 MWh/h is about 40 times lower compared to the current total peak power demand in the region, i.e.about 13400 MWh/h. Yet, vehicles might enter the road with a not fully loaded battery, and want to charge the battery during the trip, in order to leave the road with a fully loaded battery. This effect will, of course, increase the demand of electricity and power for the road. However, it is difficult to make a reasonable estimation of this effect. If 20-50% of the light vehicles are also charging when driving, which would increase the peak demand from an electrified road up to about 1 GW, the impact on the electrctricity system could become significant. Additionally, heavy vehicles might also charge their battery when driving. Furthermore, the total amount of European and national roads in Norway are 7784 km and 4721 km, respectively. If using the modelled electricity demand (kWh/km) per vehicle for the four different vehicle categories, and applying this demand to the traffic on all European and national roads in Norway, the yearly electricity demand will be 7 TWh/yr, with a maximum peak of 2600 MWh/h, and an average peak of 1600 MWh/h (Figure 7). This means that there will be a approximately 10% increase in peak Norwegian demand for electricity. At that point, an electric road system might have substantial impact on the dimensioning of the electricity system.

3.4 Impact on the stationary electricity system

An implementation of an ERS on all European and National roads in Norway will have a noticeable addition to the electricity demand in Norway, corresponding to eight medium-sized power plants. Figure 7 shows the electricity demand for the peak day in Norway (without electric vehicles or electric road system) and the electricity demand for electric vehicles, assuming 100% electric vehicles, and with different charging strategies; (i) uncontrolled charging (i.e. vehicles are charging their batteries on parking lots, at work and directly at homecoming), (ii) controlled charging at home, and (iii) electric road systems installed on all European (E) and National (N) roads (12 500 km) in Norway. The uncontrolled and controlled charging profiles are taken from Grahn et al. [21] and are multiplied with the number of vehicles in Norway taken from Statistics Norway. Controlled charging at home will lead to a load from electric vehicles during night time (hours 0-7), while uncontrolled charging and electric road systems will add an extra load during daytime (7-23) when the peak hours occur.

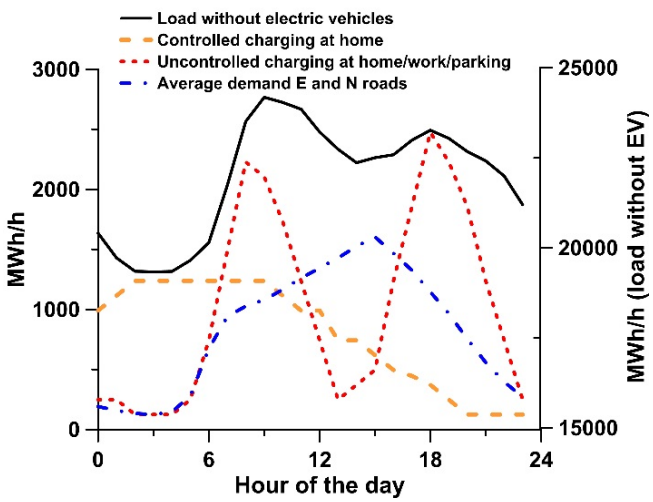

Figure 7. The electricity demand for the peak day in Norway without electric vehicles, and the load from 100 % electric vehicles in Norway using uncontrolled charging at home, uncontrolled charging at home and work, and electric road systems installed on all European (E) and National (N) roads.

An electric road system could smoothen the load curve from electric vehicles compared to only static charging, but an ERS will add to the electricity demand during the daytime when the demand from other sectors is high. The optimal time of the day to charge electric vehicles in order to minimize the impact of an electric road system on the electricity system depends on the design of the electricity system, the possibility for other loads to be flexible and on the system boundaries (e.g. import/export of electricity between regions). Looking from a Norwegian perspective, with Norway as the system boundary, charging electric vehicles at daytime or nighttime does not matter (if not taking potential local bottlenecks into consideration). This is due to the high capacity of flexible power generation, hydro power, in the Norwegian electricity system. If expanding the system boundaries to Northern Europe, the optimum charging strategy will be different due to the high amount of wind power in Denmark and Europe. Then charging the vehicles at night time might be preferable, since this will increase the ability to import electricity to Norway during this time, thus reducing curtailment and /or the competition between baseload and wind power in trading regions, while saving hydropower resources for peak load hours. A considerably higher share of renewables in the Norwegian energy system could make the power demand situation more pressing, since an electric road system is not that flexible.

For light vehicles, ERS in combination with charging at home, could give a possibility to use smaller batteries and still achieve a long drive range. The cost of the extra equipment needed (for example the pick-up) could then be compensated for by a less costly battery. Charging the battery when driving could also decrease the need of fast chargers along the road, and avoid the time it takes to stop and charge. Yet, this will obviously require a well-established network of ERS.

Fast charging at the end destinations or charging at night time will mainly work for light trucks and buses in city areas. If the goal is to achieve a significant electrification of the transport sector, heavy vehicles have few other alternatives than ERS. For long-distance heavy vehicles, also a single electric road system could be of interest, since heavy trucks are driving longer distance on the same route. The heavy vehicles are on average only 12% of the number of vehicles but corresponds to more than 50% of the electricity demand from an electric road system.

4 Conclusions

Electric road systems are today an emerging technology and the role of such technology and its impact on the electricity system need to be evaluated. This study uses a simplified vehicle model together with detailed traffic data of the E39 in western Norway to estimate how the electricity demand for an ERS varies with time and location. In the scenario investigated, we have assumed today's traffic load and present electricity system but with a full penetration level of electric vehicles. The results show that the yearly electricity demand for a European route, like E39, is comparable to a larger industry or the electricity generation from a medium sized power plant. This work shows that an electrified E39 would increase the peak power demand in regional stationary electricity system with only 2-3%. However, if 20-50% of the light vehicles were also charging their batteries while driving at maximum capacity, the peak power would instead increase with up to 8%. Additionally, if extrapolating the results to all European and National roads in Norway, the electricity peak power in Norway would increase with 10%, which is then a noticeable addition to the electricity demand for Norway.

It is shown that the electricity demand for an electric road system shows a regular and predictable pattern, with a peak for an electric road system between 3 pm and 4 pm. An electric road system, using electricity during daytime, will add to the peak power of the electricity demand, which is between 6-10 am in January. The optimal time of the day to charge electric vehicles, to minimize the impact on the electricity system depends on the design of the electricity system, possibility for other loads to be flexible and system boundaries. If using Norway as the system boundary, charging electric vehicles at daytime or nighttime does not matter (except for potential local bottle necks). This is due to the high capacity of flexible hydro power in the Norwegian electricity system. If then expanding the system boundaries to Northern Europe, the optimum charging strategy will be different due to the high amount of wind power in Denmark and Europe. Then charging at night time might be preferable, since that will not add to the peak demand hours.

Acknowledgments

We gratefully acknowledge Klaas Burgdorf and Bjorn Lindenberg at Volvo Cars, as well as Tor Harald Eliassen and Mohammed Hoseini at Norwegian Public Road Administration for valuable input and fruitful discussions, and Norwegian Public Road Administration for financial support.

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References

[1] E. Figenbaum, T. Assum, and M. Kolbenstvedt, *Electromobility in Norway: Experiences and Opportunities*, Research in Transportation Economics, vol. 50, pp. 29-38, 2015.
[2] T. Johansson, *Fossilfrihet på väg SOU 2013: 84.* Stockholm, Statens offentliga utredningar.(1000 s), 2013.
[3] FABRIC, *Feasibility analysis and development of on-road charging solutions for future electric vehicles*, <http://www.fabric-project.eu/>: 19.03.16.
[4] I. Viktoria Swedish, *Slide-in Electric Road System -Conductive project report phase 1*, vol. 1, p. 02, 2013.
[5] Volvo Global, *Global, "Volvo global news - The road of tomorrow is electric*, www.news.volvogroup.com/2013/05/23/the-road-of-tomorrow-is-electric/: [accessed 19.03.16].
[6] Siemens, *eHighway*, http://www.siemens.com/press/en/feature/2015/mobility/2015-06-ehighway.php: [accessed 19.03.16].
[7] I. Viktoria Swedish, *Slide-in Electric Road System - Inductive project report, phase*, 2013.

[8] F. Chen, N. Taylor, and N. Kringos, *Electrification of roads: Opportunities and challenges*, Applied Energy, vol. 150, pp. 109-119, 2015.
[9] Elways, *Elways - Conductive feeding of vehicle in motion*, http://elways.se/?lang=en: [accessed 19.03.16].
[10] L. Fridstrøm and K. H. Alfsen, *Norway's path to sustainable transport*, Institute of Transport Economics, Oslo, Norway 2014.
[11] Ö. Larsson, *Ladda för nya marknader: elbilens konsekvenser för elnät, elproduktionen och servicestrukturer*, VINNOVA, 2010.
[12] L. Göransson, S. Karlsson, and F. Johnsson, *Integration of plug-in hybrid electric vehicles in a regional wind-thermal power system*, Energy Policy, vol. 38, pp. 5482-5492, 2010.
[13] P. Grahn, *Electric Vehicle Charging Impact on Load Profile*, 2013.
[14] S. W. Hadley and A. A. Tsvetkova, *Potential impacts of plug-in hybrid electric vehicles on regional power generation*, The Electricity Journal, vol. 22, pp. 56-68, 2009.
[15] C. Weiller, *Plug-in hybrid electric vehicle impacts on hourly electricity demand in the United States*, Energy Policy, vol. 39, pp. 3766-3778, 2011.
[16] N. Hartmann and E. Özdemir, *Impact of different utilization scenarios of electric vehicles on the German grid in 2030*, Journal of power sources, vol. 196, pp. 2311-2318, 2011.
[17] J. Mullan, D. Harries, T. Bräunl, and S. Whitely, *Modelling the impacts of electric vehicle recharging on the Western Australian electricity supply system*, Energy policy, vol. 39, pp. 4349-4359, 2011.
[18] W.-J. Park, K.-B. Song, and J.-W. Park, "Impact of electric vehicle penetration-based charging demand on load profile," Journal of Electrical Engineering and Technology, vol. 8, pp. 244-251, 2013.
[19] Å. Vatne, M. Molinas, and J. A. Foosnas, "Analysis of a scenario of large scale adoption of electrical vehicles in nord-trøndelag," Energy Procedia, vol. 20, pp. 291-200, 2012.
[20] C. Guille and G. Gross, "A conceptual framework for the vehicle-to-grid (V2G) implementation," Energy policy, vol. 37, pp. 4379-4390, 2009.
[21] P. Grahn, "Electric Vehicle Charging Modeling," 2014.
[22] T.-E. Stamati and P. Bauer, "On-road charging of electric vehicles," in Transportation Electrification Conference and Expo (ITEC), 2013 IEEE, 2013, pp. 1-8.
[23] N. P. R. Administration, "Coastal Highway route E39," ed. http://www.vegvesen.no/Vegprosjekter/ferjefriE39/English: [accessed 19.03.16].
[24] G. Sovran and M. S. Bohn, *Formulation for the Tractive Energy Requirement of Vehicles During the EPA Schedules*, SAE810184, 1981.
[25] T. Sandberg, *Heavy truck modeling for fuel consumption simulations and measurements: Division of Vehicular Systems*, Department of Electrical Engineering, Linköping University, 2001.
[26] U. Hammarström, J. Eriksson, R. Karlsson, and M. R. Yahya, R*olling resistance model, fuel consumption model and the traffic energy saving potential from changed road surface conditions*, 2012.
[27] L. Guzzella and A. Sciarretta, V*ehicle propulsion systems* vol. 1: Springer, 2013.
[28] L.-H. Björnsson and S. Karlsson, *The potential for brake energy regeneration under Swedish conditions*, Applied Energy, vol. 168, pp. 75-84, 2016.
[29] M. Ross, *Fuel efficiency and the physics of automobiles*, Contemporary Physics, vol. 38, pp. 381-394, 1997.
[30] A. Cappiello, I. Chabini, E. K. Nam, A. Lue, and M. Abou Zeid, *A statistical model of vehicle emissions and fuel consumption*, in Intelligent Transportation Systems, 2002. Proceedings. The IEEE 5th International Conference on, 2002, pp. 801-809.
[31] NPRA, *Vegkart*, www.vegvesen.no/vegkart [accessed 19.03.16]
[32] T. R. Laboratory, *Feasibility study: Powering electric vehicles on England's major roads*, 2015.
[33] F. Sprei and S. Karlsson, *Shifting fuels, downsizing or both? The Swedish example*, Transportation Research Part D: Transport and Environment, vol. 18, pp. 62-69, 2013.
[34] T. R. Laboratory, *Feasibility study: Powering electric vehicles on England's major roads*, 2015.
[35] E. K. Nam and R. Giannelli, *Fuel consumption modeling of conventional and advanced technology vehicles in the Physical Emission Rate Estimator (PERE*), US Environmental Protection Agency, 2005.
[36] B. Frakt, *Fuel consumption in heavy duty vehicles.*