A proposed methodology for modelling the combined load of electric roads and households for long-term grid planning

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***Abstract*—The number of electric vehicles (EV) is increasing rapidly, and it is not yet sure how the grid infrastructure will be built, and how this will affect the power system. One option for charging EVs is a dynamic wireless power transfer (DWPT) system, where EVs can charge while driving. This paper presents a methodology for modelling the load from an electric road with a DWPT system and the load from households in an area. A case study for a specific highway section in Norway is also conducted, illustrating the methodology for one substation. The case study shows that the peak loads from the households and the electric road occur at different times both during the year and day. In year 2050, the peak load from the electric road could reach over 6 MW, based on numbers from the Norwegian National Transport Plan. The results from this paper will be of aid in long-term grid planning when considering electric roads in areas with existing load, hence ensuring a socio-economic planning and operation of the power system.**

I. Introduction

The transport sector was responsible for 24 % of the greenhouse gas (GHG) emissions in Europe in 2017. More than 70 % of the GHG emissions in the transport sector was caused by road transport, according to the European Environment Agency (EEA) [1]. Due to the growing need for a more sustainable transport sector, electrification of the transport sector is high on the political agenda all over the world. As a consequence, the number of electric vehicles (EV) is increasing rapidly. In Norway, the country in the world with the highest share of EVs in the car fleet [2], the government has presented several ambitious short-term and long-term goals for reducing the GHG emissions from road transport as a part of the Norwegian National Transport Plan (NTP) [3]. As an example, it is a political goal that all new light vehicles, city buses and commercial vans should be zero-emission vehicles (ZEVs) by 2025. By 2030, all new heavy commercial vans, 75 % of new long-distance buses and 50 % of new lorries should be ZEVs. It is reasonable to assume that a significant share of these ZEVs will be battery-electric.

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Up until today, electric charging of EVs has been dominated by slow and semi-fast charging at home or at work. The development of EVs has also been dominated by electric cars [2]. As EVs are becoming more relevant for other modes of transport, and the need for faster charging time increases, the requirements for EV charging infrastructure become more complex. The development of high-power charging infrastructure, along with increasing battery capacity in EVs, has contributed to increasing the range and applicability of EV technology for all modes of road transport. However, the long charging time and low energy density of state-of-the-art battery technology for EVs are still a challenge when comparing EVs to traditional internal combustion engine vehicles. In order to address this challenge, dynamic charging of EVs on the road has been proposed as an alternative to static charging. In Gotland, Sweden, a 4 km road stretch with charging coils for dynamic, inductive charging has already been built and successfully tested. The road is planned to be used for inductive charging of an airport shuttle [4].

The future charging demand from the transport sector will represent a substantial load to the electric distribution system. The aggregated load from static high-power charging stations with multiple chargers for electric cars is already reaching several megawatts, while the future load from high-power charging stations for electric trucks potentially could reach tens of megawatts. Static charging of EVs presents a load that can be allocated to a specific geographic location and grid location. Dynamic charging, on the other hand, will be more geographically distributed along the road and the associated electric distribution system if the electric road is connected to several substations. The topic of dynamic charging of EVs and the associated aggregated electric load demand is assessed in this paper, along with an analysis of the potential impact on the electric distribution system.

There have been several studies related to this topic, mainly regarding electric road systems (ERS) and more specifically dynamic wireless power transfer (DWPT) systems. An electric road can be conductive or inductive, but in this paper an electric road is defined as a road stretch with inductive coils in

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it. A DWPT system is required to perform dynamic wireless charging for EVs when passing the coils, such as the one illustrated in Fig. 1. The design of DWPT systems is not studied in detail in this paper, as the main purpose here is to study the impact the electric road has on the distribution grid that supplies the DWPT.

In [5], the electricity demand related to implementing an ERS in Sweden was investigated. The study found that the additional load from ERS coincides with the hours when the current load is already high. The authors in [6] did a case study on E39 in Norway and investigated how the energy demand from a road varies over time and with location, and identified the impacts from electrification of the road on the stationary electricity system. Both these studies used numbers for annual average daily traffic (AADT) to find the volume of vehicles along the roads. In this paper, on the other hand, we use actual measurements for a specific area to improve the accuracy of the developed load model. In addition, we propose a method for investigating how the load for a single substation associated with a road segment is affected, rather than studying the aggregated load for the whole road. In this way, the impact of an ERS on the local distribution system can be studied.

The electricity consumption demanded by a DWPT system, and the battery state-of-charge of the EVs, was analysed in [7] for case studies in Spain. Similarly, in [8], case studies in a smart autonomous highway were performed to understand the impact of dynamic wireless charging on grid dynamics. Although the latter study showed that the grid voltages vary significantly due to the ERS, none of these studies investigated how the dynamic wireless charging coincided with existing load in the area. The method proposed in our paper addresses this issue.

A survey of studies related to both dynamic and quasi-dynamic types of wireless charging was done in [9]. The survey covered: a review of terminology, a review of operations and systems issues, and future research directions. The author writes that "(...) systematic studies are required to investigate the effect of wireless charging EVs on the power grid, such as the power demand pattern across time of day or geographical regions, and the relationship between the installation of the wireless charging infrastructure and the power load in the grid.". This topic is directly addressed in our study.

In this paper, a method for modelling the aggregated load profile of a DWPT system based on transport models and measurements is proposed. The variation of the load demand is analysed and compared with regular household loads along the route through calculating a load factor. The method is used on a Norwegian case study, for 2025 and 2050, with different shares of EVs. In our study, we seek to answer the following questions:

- How does the load of an ERS coincide with the existing household load of a specific area?
- How much should the distribution system operator (DSO) expect the peak power to increase for one substation if an ERS is built?
- Should variations in load from dynamic charging, together with the variations in load from existing loads, be considered when dimensioning the power needed for an area?

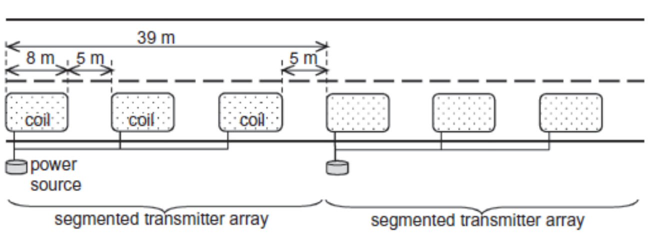

Fig. 1. Assumed layout of the DWPT system (from [7]).

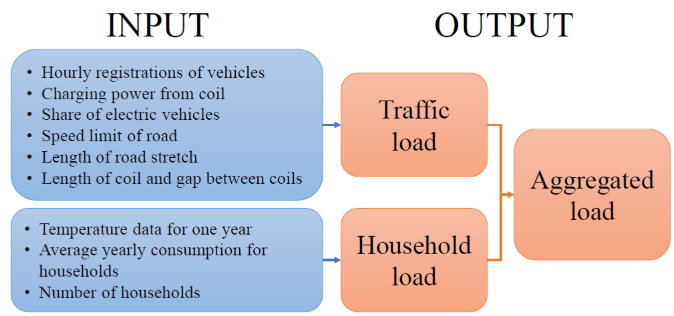

Fig. 2. Overview of input used for creating the aggregated load profile.

II. Method

An overview of the input used for creating an aggregated load profile for traffic and household load is shown in Fig. 2. The hourly aggregated load profile is calculated as described in (1). This hourly aggregated profile corresponds to the aggregated load at the substation level of the area.

$$P_{agg,h} = P_{hh,h} + P_{r,h} \quad , \forall h \tag{1}$$

$P_{agg,h}$ is the aggregated load profile, $P_{hh,h}$ is the household load profile and $P_{r,h}$ is the traffic load profile, for hour h. The subsections below give a description of how the household and traffic load profiles are calculated.

A. Household load profile

The load profiles for existing load in the area are calculated from existing coefficients A and B, based on historical meter data from several customers in Norway. The coefficients are dependent on temperature, made from linear regression on historical meter data and temperature data, and can be found in [10]. They are also different dependent on hour of day, season (winter or summer), day (weekend or weekday), average yearly consumption and customer group (household, industry, etc). In this paper, only the customer group of households is considered. A load profile for a year is calculated as described in (2).

$$P_{hh,h} = (A_h^{D,S} T_{day} + B_h^{D,S}) \frac{E_{input}}{E_{calc}} \tag{2}$$

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$A_h^{D,S}$ and $B_h^{D,S}$ are coefficients A and B, respectively, for day type D, season S and hour h. Coefficient A has the measurement unit kWh/h/°C, while coefficient B has the measurement unit kWh/h. Both T_{day}, the daily average temperature, and E_{input}, the yearly electricity consumption in kWh, are input data. E_{calc} is the yearly electricity consumption calculated from temperature data, as in (3).

$$E_{calc} = \sum_{h=1}^{8760} (A_h^{D,S} T_{day} + B_h^{D,S}) \tag{3}$$

B. Traffic load profile

The traffic load profile for inductive charging while driving is made from hourly measurements of the number of vehicles on the road stretch. The hourly load demand for the electric road, $P_{r,h}$, is calculated as in (4) and (5).

$$P_{r,h} = N_{sim,h} \cdot P_c \cdot S_{EV} \quad ,\forall h \tag{4}$$

$$N_{sim,h} = \frac{L_r \cdot N_{tot,h}}{v_r} \quad ,\forall h \tag{5}$$

P_c is the rated power transfer from the inductive coil in kW and S_{EV} is the share of EVs among the total number of vehicles. $N_{sim,h}$ is the average number of vehicles on the road stretch simultaneously for hour h, assumed to be distributed equally over the hour. $N_{tot,h}$ is the total number of vehicles registered for hour h. L_r and v_r are the length (m) and speed limit (km/h) of the road stretch, respectively.

Since the charging power is related to the battery size of each EV, the charging power may vary between vehicle types. Hence, this should be included in the calculations, if this information is available. In the case of roadside measurements with inductive loops, vehicle types are often divided by length classes, as length is the measured physical property, and not weight. Therefore, we propose to distinguish by vehicle class, exemplified in (6), (7) and (8), by short, medium and long vehicles:

$$P_{short,h} = P_{r,h} \frac{N_{short,h}}{N_{tot,h}} \quad ,\forall h \tag{6}$$

$$P_{med,h} = P_{r,h} \frac{N_{med,h}}{N_{tot,h}} \quad ,\forall h \tag{7}$$

$$P_{long,h} = P_{r,h} \frac{N_{long,h}}{N_{tot,h}} \quad ,\forall h \tag{8}$$

$N_{short,h}$, $N_{med,h}$ and $N_{long,h}$ is the number of short, medium and long vehicles in hour h, respectively. In (9), it is shown how to calculate the maximum possible power transferred to vehicles, P_{max}:

$$P_{max} = N_c \cdot P_c \tag{9}$$

where N_c is the number of coils on road stretch.

C. Load factors

To study the simultaneity of the household load and traffic load over the year, a load factor is defined in this paper as the daily maximum load divided by the maximum load during the year. The two load factors for household and electric road are defined as described in (10) and (11).

$$\alpha_{hh} = \frac{P_{hhmax,d}}{P_{hhmax}} \quad ,\forall d \tag{10}$$

α_{hh} is the load factor for households. $P_{hhmax,d}$ is the maximum hourly household load of day d, and P_{hhmax} is the maximum hourly household load of the year, in kW.

$$\alpha_r = \frac{P_{rmax,d}}{P_{rmax}} \quad ,\forall d \tag{11}$$

α_r is the load factor for the electric road (for all vehicle lengths). $P_{rmax,d}$ is the maximum hourly traffic load of day d, and P_{rmax} is the maximum hourly traffic load of the year, in kW.

III. Case study Lillehammer

The methodology presented in the previous chapter is now illustrated in a case study. The case is a road stretch of the road E6 in Norway, located south of Lillehammer from Vingnes to Vingrom, as shown in Fig. 3. In the case study, it is assumed that an ERS would be installed for lanes in both directions. First, the household load for the area is calculated. Second, the load from the electric road is calculated for two different shares of EVs, corresponding to the prognoses from the Norwegian NTP for 2025 and 2050 [11].

A. Household load profile - Lillehammer

The household load profile is made from information in [12], which gives an overview of the 22 kV distribution grid in the Lillehammer area. The methodology from Section II-A is used, with the following input and assumptions:

- Daily average temperature data for Gausdal, 2019 [13].
- Average yearly electricity consumption for a household: 16,000 kWh (as average in Norway [14]).
- Number of households: 700. Based on a rough estimate of households viewed in [12].

The resulting hourly load for 700 households in the Lillehammer area for 2019 is used for both scenarios described below.

B. Traffic load profile - Lillehammer

Hourly measurements from The Norwegian Public Roads Administration is used to get registrations of vehicles (short, medium and long) for 2019. To create an hourly charging profile for traffic, the methodology from Section II-B is used, with the following input and assumptions:

- Hourly registrations of number of vehicles for Lillehammer Bru in 2019, retrieved from [15].
- Short vehicles are defined as less than 5.6 m, medium vehicles between 5.6 m and 7.6 m, and long vehicles over 7.6 m.
- Length of road stretch: 6.5 km.

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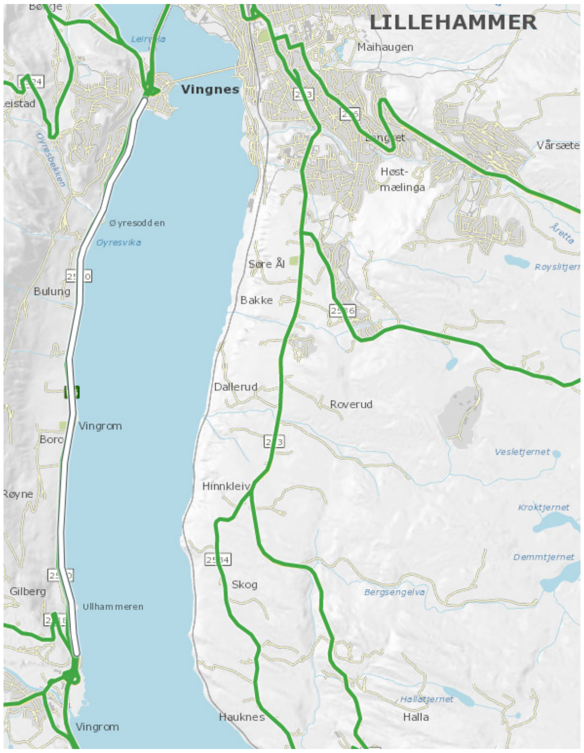

Fig. 3. Roads in Lillehammer area, retrieved from [16]. The road stretch used in the case study is marked in white: Vingnes to Vingrom (ref. 0500 EV6 HP4 m182 - 6391).

- Max. charging power for one coil: 40 kW. Max. charging power for road stretch: 40 MW.
- Speed limit of road stretch: 80 km/h (this is assumed equal to driving speed).
- Length of inductive coils: 8 m. Gap between coils: 5 m (as in Fig. 1).
- For both 2025 and 2050, it is assumed that the traffic pattern and the household load is the same as in 2019.

1) Year 2025: It is assumed that the share of EVs is 39 %, 13 % and 9 % for short, medium and long vehicles, respectively, as estimated in [11] for 2025. Fig. 4 shows the hourly load for the electric road for 2025 for short, medium and long vehicles, together with the household load. Since the expected shares of medium and long EVs are relatively small, they are hardly visible in the figure: long vehicles have a peak load of 63 kW and medium vehicles of 58 kW. The household load has a peak of 2.4 MW, and short vehicles a peak of 2.7 MW. In other words, the ERS will more than double the load in the area. The load for short vehicles is quite even for the whole year, while the household load is much lower during summer, as expected since it is dependent on the outdoor temperature.

In Fig. 6, the load for households and short vehicles for the time period 18.-25. March 2025 is shown in order to better see the variations within a week. Both households and short vehicles have a peak at 8.00 on weekdays, while the higher peaks occur at different times: for households at 20.00, and for short vehicles at 16.00. Both loads are low during the night. During this particular week of March, the short vehicles reach their weekly peak at 16.00 on Friday, and the households four hours later, at 20.00.

2) Year 2050: It is assumed that the share of EVs is 99 %, 98 % and 75 % for short, medium and long vehicles, respectively, as estimated in [11] for 2050. Fig. 5 shows the hourly load for the electric road for 2050 for short, medium and long vehicles. For 2050, the load for medium and long vehicles are more visible in the figure, with long vehicles having a max. load of 527 kW and medium vehicles 434 kW, given the increase in EV share. The load for short vehicles has increased dramatically compared to 2025, having a max. of 6.8 MW, since this road stretch has a large share of short vehicles and the EV share for 2050 is assumed to be 99 %.

C. Load factors - Lillehammer

As described in Section II-C, the two load factors, α_{hh} and α_r, are calculated for the case study. α_r is the same for the different shares of EVs. Fig. 7 shows how the factors for households and traffic vary for 2019. The two loads are not following the same seasonal pattern: α_{hh} is lowest on day 209 (July 28th), while α_r is lowest on day 137 (May 17th) - the Norwegian Constitution day (a public holiday). The load of the electric road is increasing during summer, at the same time as the household load is decreasing. In winter, they change place, and the household load is higher than the electric road.

IV. Discussion and Conclusion

This paper has presented a methodology for modelling the aggregated load profile of a DWPT system based on transport models and measurements. The variation of the load demand was analysed and compared with regular household loads through calculating a load factor. The method was used on a Norwegian case study, for different shares of EVs for 2025 and 2050.

The results from this study aid in quantifying a possible impact from dynamic charging of EVs in addition to existing loads in the power system. However, there are several assumptions that could significantly affect the actual load. For the traffic load profile, there are uncertainties for both travel demand, vehicle properties and charging profile. In our study, we have assumed a uniform distribution of traffic. Due to clustering effects, the arrival of vehicles tends to be exponentially distributed. In more detailed studies, for cases where the road length L_r is short, the variations in arrivals will induce large variations in charging demand. As shown in (5), the speed limit is used as an average speed. Although this might be the case, there might be differences between vehicle classes. For simplicity, we have assumed a constant charging power per vehicle type: short, medium and long. However, the actual value of $P_{r,h}$ might vary and since the technology of DWPT systems is immature, maximum charging power might increase for the coming years.

Fig. 4 and 5 show that the load from an ERS will require large grid investments. The DSO could expect an increase of approx. 2.5 MW for 2025, and approx. 6 MW for 2050, for our case study. It should be emphasized that this is assuming an increase in EVs corresponding to the predictions of [11],

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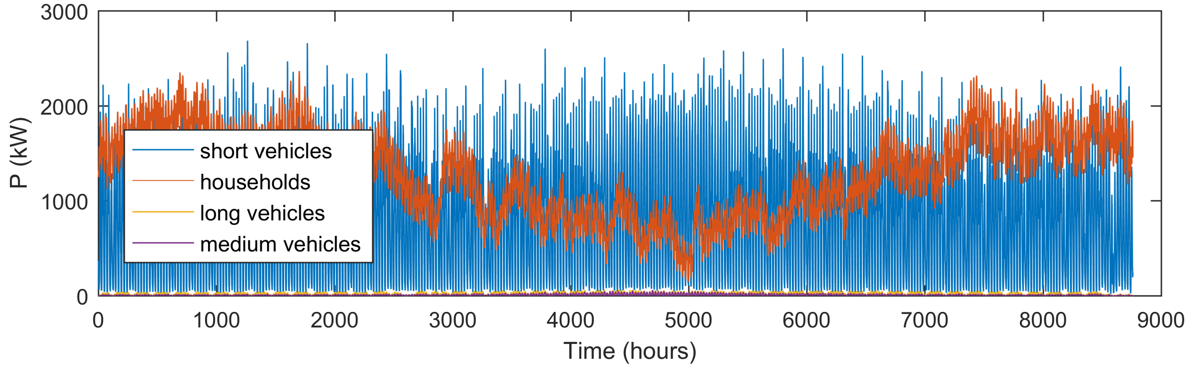

Fig. 4. Load for households, short, medium and long vehicles - 2025.

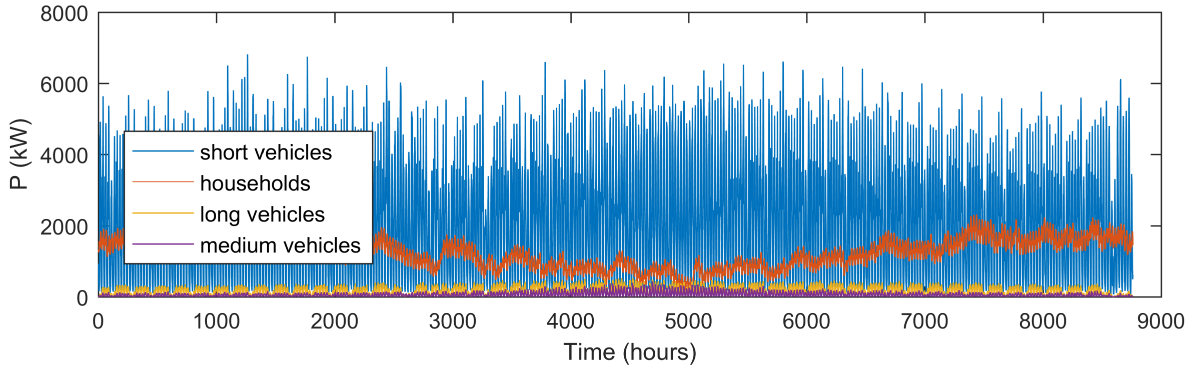

Fig. 5. Load for households, short, medium and long vehicles - 2050.

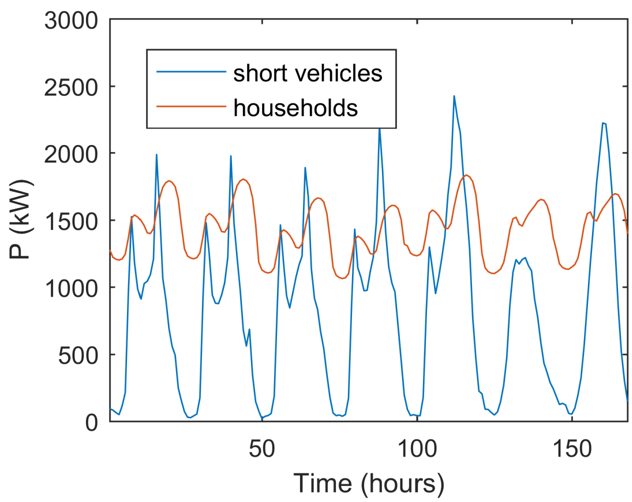

Fig. 6. Load for households and short vehicles for 18.- 25. March, 2025.

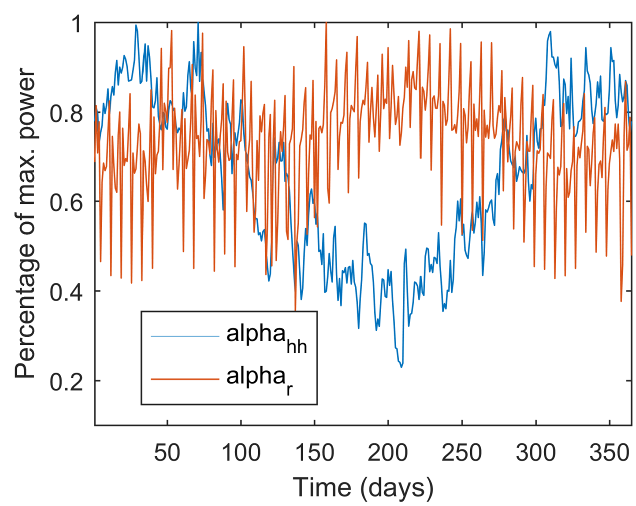

Fig. 7. Load factors for households and traffic for 2019.

that all EVs are charging on the ERS, and a charging power of 40 kW. As Fig. 7 shows, α_r and α_{hh} coincide during spring and autumn, while for winter and summer they are opposite of each other. When planning for an ERS, it might be beneficial to include this seasonal variation, since our study shows that the peak of these two loads are occurring at different times both during the year and within a day. Fig. 6 shows that the households have their peak at 20.00, while the short vehicles (which are the main share of the load from the electric road) have peaks at 16.00.

We have also assumed that all EVs make use of the charging facilities, and although the future EV share is highly uncertain, there might also be a question of cost related to the service of wireless charging. If the dynamic charging turns out to be a more expensive charging service than e.g. static fast charging or home charging, this will influence drivers to not utilise the service even when passing over the DWPT system. This will of course also depend on whether the EV owner has the

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possibility of choosing to accept or reject the charging service. It also underlines the need for a market structure for pricing of dynamic charging on electric roads, and more research on how this will affect the charging profiles.

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