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Electrical Infrastructure Design Methodology of Dynamic and Static Charging for Heavy and Light Duty Electric Vehicles

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Abstract: Full electrification of the transport sector is a necessity to combat climate change and a pressing societal issue: climate agreements require a fuel shift of all the modes of transport, but while uptake of passenger electric vehicles is increasing, long haul trucks rely almost completely on fossil fuels. Providing highways with proper charging infrastructure for future electric mobility demand is a problem that is not fully investigated in literature: in fact, previous work has not addressed grid planning and infrastructure design for both passenger vehicles and trucks on highways. In this work, the authors develop a methodology to design the electrical infrastructure that supplies static and dynamic charging for both modes of transport. An algorithm is developed that selects substations for the partial electrification of a highway and, finally, the design of the electrical infrastructure to be implemented is produced and described, assessing conductors and substations sizing, in order to respect voltage regulations. The system topology of a real highway (E18 in Norway) and its traffic demand is analyzed, together with medium-voltage substations present in the area.

Keywords: electric vehicles; electric trucks; heavy duty vehicles; catenary charging; fast charging stations; inductive charging; grid planning; highway electrification

1. Introduction

Electrification of the transport sector is central to meeting the Paris Climate agreements. In the Declaration on Electro-Mobility, parties recognized the need to electrify at least 20% of all the road transport vehicles by 2030 [1]. Currently, Heavy Duty Vehicles (HDVs) account for less than 5% of road vehicles in the EU, but are responsible for about a quarter of the total CO_2 emissions from road transport [2], and one-third in Germany [3]. The electrification of HDVs present challenges different from passenger vehicles such as high power demand, longer distance traveled compared to EVs. Truck fuel efficiency has stagnated in the last 20 years [4] and emissions have increased by 15% between 1990 and 2014, with Nordic countries increasing their fleet sizes faster than average. Future demand of long-haul transport is also expected to grow further: in Norway, the freight sector is expected to grow by 35–40% by 2040 [5]. For these reasons, the European Parliament is setting short-term targets on new HDV fleets (including specifically large lorries and heavy trucks) in order to lower their emission performance standards by 15% in 2025 and 30% by 2030 compared to 2019 [2].

Currently, the standards for high-power chargers have been developed up to 600 kW with a growing interest in mega-chargers up to 1 MW [6]. With battery sizes that range from 300 kWh up to 1 MWh [6], charging time is a major problem for the electrification of HDVs. The introduction of a large battery can reduce maximum payload, −20% for a 825 kWh battery, also negatively affecting the available space for goods [7]. On the one hand, the market of electric batteries is experiencing a process of constant innovation, especially in terms of energy density; on the other hand, given the climate goals to be reached globally, it is highly recommended that the use of batteries be minimized, freeing up storage capacity for the overall electrification of the energy system and potentially decreasing its societal costs [8]. For electrification to be realized for both LDVs and HDVs through plug-in charging, mega-chargers have to be built along main corridors for HDVs in addition to normal FCSs for LDVs. An alternative solution for the electrification of HDVs, especially on long-routes transport networks, is represented by dynamic charging: conductive, based on catenary charging, or inductive. This possibility shows the need to investigate how the electrical infrastructure can be designed, through these technologies, to electrify both passenger vehicles, indicated from now on as Light Duty Vehicles (LDVs), and HDVs on highways.

The authors of [9] assessed the demand and costs for Great Britain electrification due to dynamic inductive charging for both LDVs and HDV, analyzing different kinds of transport networks, including rural areas and motorways. In [10], the authors assessed the cost-effectiveness of the implementation of plug-in and dynamic technologies (catenary and inductive) depending on the traffic flow. In [11], the authors compared the energy and the power demand of plug-in, dynamic, hydrogen, and power-to-fuel electrification strategies for a real case study (the E39 highway in Western Norway).

To the best of the authors' knowledge, the present article represents the first work that details a comprehensive methodology to support power system planners in designing charging infrastructure on highways, taking into account both static, inductive, and catenary charging technologies together with real data. The developed design procedure focuses on grid planning, implementing a geospatial analysis which makes use of Open Street Maps (OSM) for the localization of substations and the analysis of the transport network. Differently from [11], the methodology described in this article simulates realistic plug-in charging of electric vehicles and provides a data-driven approach to locate and size the electric infrastructure for different charging technologies. In fact, a limitation of [11] is that static charging is used only by LDVs and vehicles are charging only the energy consumed while driving, with no estimation of initial and final State of Charge (SoC), which greatly affects the energy demand on the plug-in charging infrastructure. Three different electrification scenarios are considered:

- Static: LDVs and HDVs charge at static charging stations located along the highway.
- Inductive: LDVs and HDVs are supplied by dynamic inductive charging infrastructure along the route.
- Hybrid: LDVs charge at static charging stations, and HDVs are supplied by the dynamic catenary charging infrastructure.

These three scenarios are considered for a highway route (E18 in Norway) that passes through both rural and urban areas.

The presented paper has the following structure: Section 2 introduces charging technologies, with particular focus on dynamic technologies; Section 3 reports, in detail, the methodology developed to design the charging infrastructure from a grid planning perspective; Section 4 shows the results of the implementation of the Methodology on a real case study: outcomes are described and visualized both spatially and analytically; Section 5 describes the overall conclusions and contributions of the paper.

2. Charging Technologies

Charging technologies for Electric Vehicles (EVs) can be classified according in the following three main categories:

Plug-in chargers Most of the chargers are slow private chargers connected to the low-voltage network. A large part of the publicly accessible fast chargers presents power characteristics suitable for passenger vehicle charging, but chargers for HDVs are increasing sensibly in the last years, with power that ranges from 150 up to 400 kW. It follows that Direct Current Fast Charging (DCFC) stations with rated power designed for high-power electric trucks on highways can be directly connected to the medium-voltage grid [12].

Inductive charging In an inductive charging system, energy is transferred wirelessly through the magnetic field: the scheme resembles the magnetic pairing of a transformer, where a transmitter coil beneath the asphalt of the road represents the primary side, and a receiver coil located beneath the vessel of the car represents the secondary side. Coils and switches below the surface of the road energize small road segments (1–50 m) when a vehicle is positioned above them. The scheme resembles the magnetic pairing of a transformer, where a transmitter coil beneath the asphalt of the road represents the primary side, and a receiver coil located beneath the vessel of the car represents the secondary side. Alternating Current (AC) electricity is usually supplied through power inverters at 400V AC. Inductive technology is assessed to be characterized by higher costs than other alternatives, but allows both LDVs and HDVs to charge without the installation of a pick-up element. AC electricity is supplied through inverters usually at 400V AC.

Catenary charging The catenary charging scheme resembles the one of a DC railway power supply, although sizing the catenary system can result in being more complex than for trains: factors such as time schedule and distances between HDVs cannot be regulated as easily as for trains/metros. The complexity of the load demand from the aggregation of several trucks, with different conditions of slope, distance between each other, etc., will not be analyzed in depth since it is not in the scope of the article. Traction substations typically include transformers and uncontrolled 6 or 12 pulse diode-based rectifiers, or in some cases, an AC–DC bi-directional converter. Despite the fact that they do not generate imbalances, they can generate high harmonic pollution. Bi-directional converters can be installed as substitutes for or in parallel to rectifiers to take advantage of the energy regenerated during breaking or downhill segments and to inject electricity back into the grid [13].

Static plug-in charging is the dominant technology to charge EVs: in 2019, charging stations surpassed 7 million units [12]. Dynamic technologies, on the other hand, are less widespread: inductive charging technology is still characterized by a low TRL (3–4), and conductive charging based on catenary has achieved TRL 7 in 2018, and it is expected to reach TRL 8–9 in 2020, since there are no major technical constraints to hinder its development [14]. Several pilot projects are in place in small fragments of highways in Sweden (2 km), California (1.6 km), three field trials in Germany with the most advanced pilot ELISA (5 km) and, finally, a catenary infrastructure to be constructed in Northern Italy (6 km in the short term and up to 62 km) with the integration of PV panels along the highway [15]. Siemens and involved partners (Scania, road operators etc.) implemented those electrification projects with hybrid trucks equipped with small batteries (around 20 kWh). With an average consumption of 2.24 kWh/km, the trucks would not be able to reach 10 km of full electric autonomy [11]. Taking into account this limiting factor, pilots were designed with a concept of full, 100% electrification of a particular stretch selected for tests. At the same time, the market of long-haul full electric trucks is experiencing a rapid change: the market expects products such as Tesla Semi (Long range up to 965 km) or BYD T9 (already available with more than 200 km of full electric capacity) [6] and are opening up to new possibilities in terms of electrification concepts and designs. Independently of the chosen technology, whether inductive or conductive, the layout of the system from the High Voltage (HV) grid to the side of the road is the same: a series of distribution substations transforms the electricity to the Medium Voltage (MV) level (typically 20–30 kV) and transfers it along the road through a feeder. Finally, transformers called traction substations convert it to the low-voltage side that supplies the elements on the road. The level at which both systems are run presents the drawback of requiring high currents in the lines, increasing voltage drops and forcing planners to install low-voltage elements relatively near to each other. For example, Siemens implemented pilot schemes in which catenary traction substations are placed at 2 km one from each other, although having declared that the maximum distance can be increased up to 10 km [14]. Few papers have investigated the impact of the implementation of catenary technology on the energy system and its impact on the sustainability of the transport sector. The authors of [16] make use of a market diffusion model to forecast electric truck penetration and an energy system model to quantify the added demand and cost-optimal investment in power system from the long-term implementation of catenary charging across Europe. The peak load would increase by 2%, while electricity demand would grow by 3% by 2040. The authors conclude that even with no added renewable sources in the power system, the increased efficiency of electric engine would still drive down transport emissions, and by up to 10% by 2040 in Nordic countries considering optimistic scenarios. Similarly, the authors of [17] quantify, through a detailed life-cycle analysis (LCA), that as long as electricity production is not coal-based, life-cycle emissions, inclusive of the infrastructure, are lower for electric trucks using catenary charging. The greenhouse gas (GHG) payback time is mainly dependent on the traffic: the more HDVs that are passing an electrified road, the lower the payback time. This result is also confirmed in [18], which quantified reductions in CO_2 emissions of up to 55% by electrifying 40% of national and European main highways in Sweden.

3. Methodology

3.1. Preliminary Design Considerations

The design scheme of the charging infrastructure depends on several factors, such as the regulatory frameworks of the country or the region where the infrastructure is built, the actors involved in the infrastructure development and operations, and finally the distance of the highway from the electrical network.

A first fundamental design choice must be made as to whether a new dedicated distribution grid is put in place or the charging infrastructure is fed through an extension of the existing grid. In the first case, planners should evaluate the distance from the existing transmission grid (420–300–220 kV) or regional grid (145–132–66 kV) to the highway to locate points of the supply connections and decrease the length of the supply cables as well as the costs of the infrastructure. In the case that the design choice is implementing an extension of the grid, the MV substations in the proximity of the road are listed and characterized in terms of their distance from the highway through a proximity analysis. Moreover, the load profile of these substations should be assessed by adding the mobility electrical demand on top of the existing base load (for residential or industrial uses) in order to verify that the load increase does not lead to an overload of the transformer. These parameters, distance and load profile, can serve as a basis for the selection of the optimal substations for the electrification.

At the same time, it is relevant to highlight that the load assessment can be difficult to realize: in fact, transformer data must be anonymized due to privacy and security concerns. For the purpose of this paper, the methodology used implements an extension of the grid.

A second design choice takes into account whether to electrify the whole highway stretch or to implement a partial electrification strategy. In [19], the authors suggest that an ideal scheme should present electrified stretches between 24 and 64 km depending on the traffic flow, with an overall Electrification Ratio (ER) of 50%, which is the optimal ER in order to minimize the total cost of batteries and infrastructure.

3.2. Vehicle Energy Consumption Models

In order to assess the demand of the electric mobility, two energy models were implemented: a static model that estimates the energy supplied by the Charging Stations (CSs) and a dynamic model for both the catenary and inductive charging technologies.

3.2.1. Static Energy Model

The energy that is supplied through plug-in charging is calculated by running a simulation in which each vehicle entering in the highway is characterized in terms of the following parameters:

- Length of travel l_t [20].
- Driving direction d.
- Initial state of charge entering the highway SoC_i [20].
- Battery capacity E_{bat} [20]
- Fuel economy f_e [18] [km/kWh]

All parameters are randomly selected from specific ranges, shown in Table 1. Thus, the EVs entering the highway do not follow a stochastic process, as proposed in [21]. As it is possible to note, the initial state of charge is characterized by a time-dependency in order to better reflect the mobility patterns of drivers for each vehicle. In fact, it is assumed that drivers that start their journey during the night-time until midday have made use of slow home-charging, thus entering the highway with a considerably high state of charge. However, drivers who are starting their journey during the rest of the day are characterized by lower values of state of charge, since it is assumed their travel is starting from the workplace or other locations that do not usually offer charging stations.

Table 1. Characterization of mobility parameters.

		Range	
	Time (h)	**LDV**	**HDV**
l_t (km)		25/125	120/400
d		−1/+1	0.63
SoC_i	0–12 12–24	0.6/0.8 0.3/0.5	0.6/0.8 0.3/0.5
E_{bat} (kWh)		15/25	54/180
f_e		5	0.45

The charging pattern implemented in the static model follows a few basic assumptions:

- A vehicle needs to be recharged if its SoC goes below a minimum level of 20%: below this value, the driver will experience charging anxiety and will charge at the nearest charging station in its driving direction.
- Once the EV has reached its energy demand at the static charging station, a new energy demand will be selected from a random range. The minimum of this interval corresponds to the amount of energy necessary to complete the specific journey of the car. The maximum value is the energy necessary to reach 80% of the battery capacity, where the charging current decreases due to the chemical characteristics of common vehicle batteries [22].
- Plug-in charging stations are assumed to be characterized by a maximum capacity of 50 kW for LDVs and 400 kW for HDVs.

Further information on the share of electric vehicles and the static charging station infrastructure is given in Section 3.3.1.

3.2.2. Dynamic Energy Model

The energy model implemented for the calculations of the dynamic energy demand is analogous to the one used in [11]: the power to the wheels is calculated based on factors shown in Table 2. Moreover, the regenerative breaking potential should be evaluated in order to assess the demand along the route (especially for HDVs due to their high inertia).

Table 2. Dynamic Energy model: parameters characterization.

	LDV	HDV
Mass (kg)	1500	40,000
Air resistance coefficient	0.3	0.63
Front area of the vehicle (m^2)	2.1	3
Average speed (km/h)	80	80
Acceleration values (m/s^2)	1.5	1
Rolling resistance coefficient	0.012	0.007

3.3. Charging Infrastructure Scenarios

Three main charging scenarios are discussed, and a corresponding design methodology is proposed.

The static scenario, as the name may suggest, makes use of the Static Energy Model for both LDVs and HDVs. The inductive scenario solely uses the Dynamic Energy Model for both LDVs and HDVs as a basis for the Substation Selection Algorithm. Finally, in the Hybrid Scenario, both energy models are used: firstly, the dynamic energy demand of HDVs is calculated and used as an input for the substation selection algorithm. Successively, static energy demand of LDVs is calculated and distributed along the substations selected.

3.3.1. Static Scenario

In the static scenario, the energy model described in Section 3.2.1 is implemented for both LDVs and HDVs, and a visual overview of the Static Methodology is provided in Figure 1.

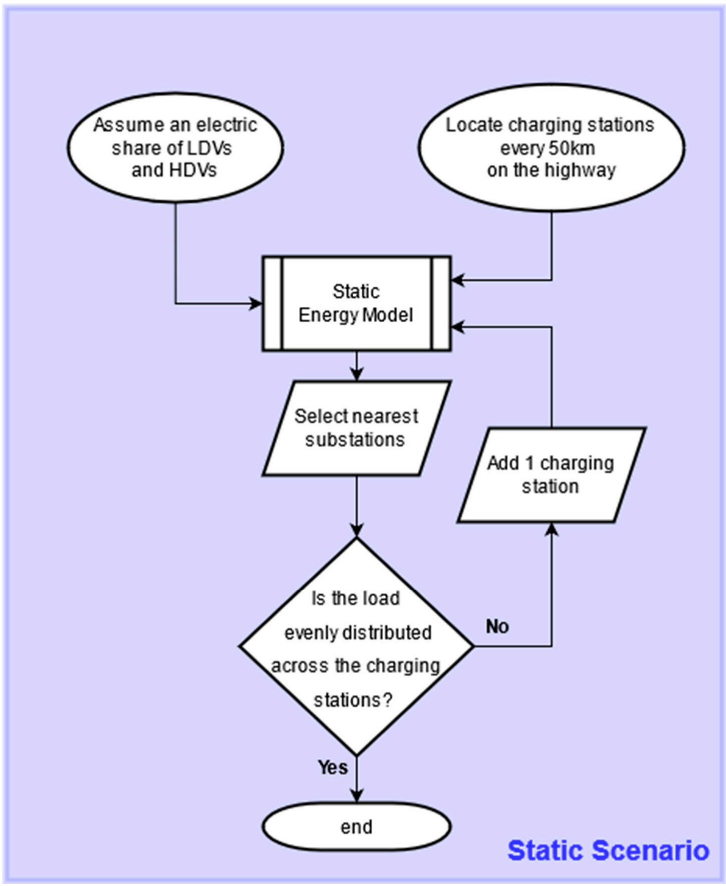

Figure 1. Methodology for the static scenario.

- As a first step, it is necessary to assume a share of electric vehicles to be electrified: based on current policies, it is expected that in 2030, up to 25% of all road transport vehicles will be electric. In order to meet global climate goals, this percentage should increase up to 45% [12].
- The locations of the charging stations are defined based on heuristics: charging stations were located every 50 km in line with the recommendation of the European Joint Research Center. It is stated that for every highway direction, a maximum distance of 60 km would provide adequate infrastructure [23]. The first charging station is located on the stretch in order that its distance from the entry point of the road is below 50 km, and the following stations are located along the highway applying a space interval of 50 km.
- A first load assessment is carried out to detect if the traffic demand is split between the stations in an even way. If the simulation output shows one or multiple stations that are loaded substantially more than the average station along the highway, because of the traffic conditions, then another charging station is added in order to flatten and distribute the demand.

3.3.2. Inductive Scenario

The main contribution of the proposed methodology is represented by the Substation Selection Algorithm (SSA) (in Figure 2), which is characterized by the following steps. The inductive infrastructure is visualized in Figure 3.

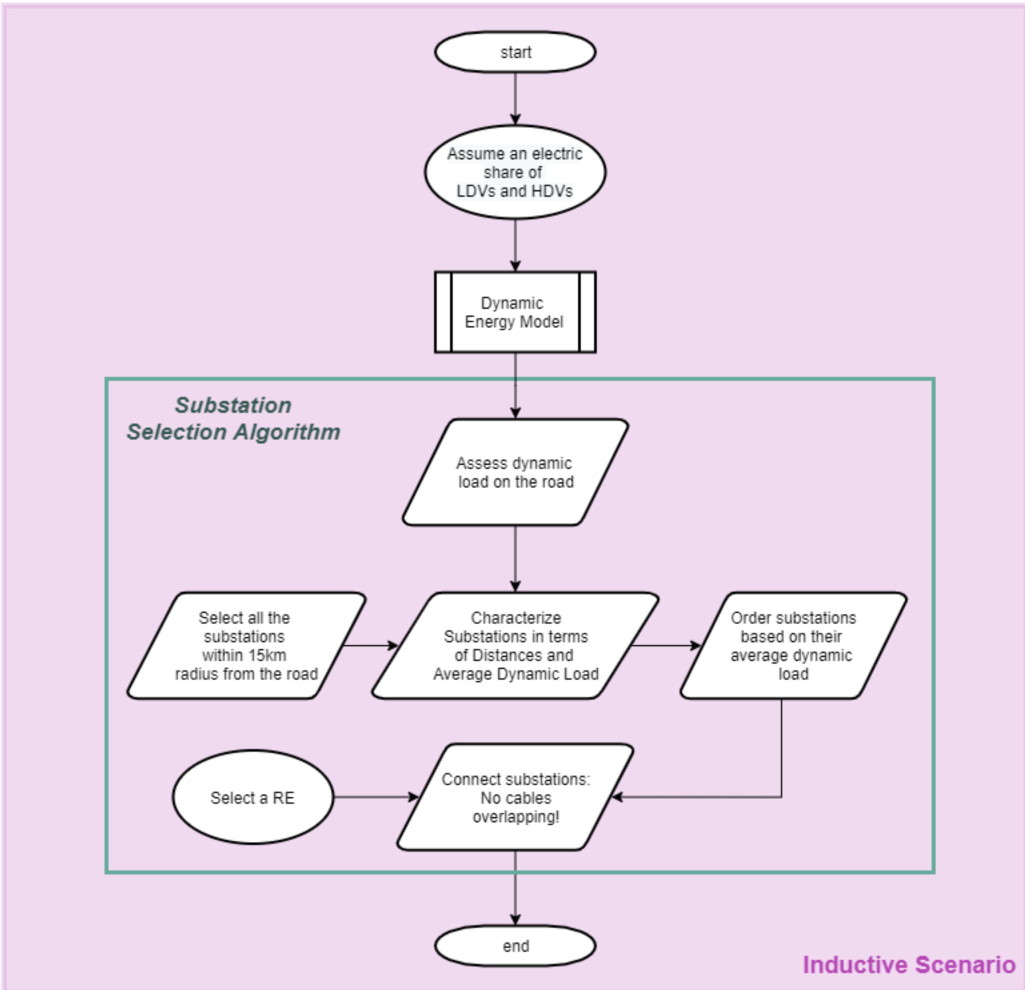

Figure 2. Methodology for the inductive scenario.

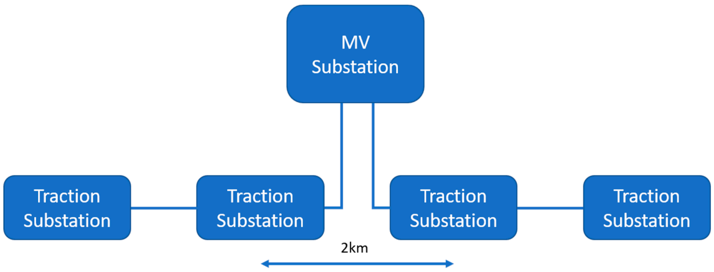

Figure 3. Illustration of the Inductive Infrastructure.

- The Dynamic Energy Model produces an energy demand output along the highway, which depends mainly on the varying traffic flow.
- Medium-Voltage Substations in the near proximity of the highway are selected. The minimum requirements in order execute this step are the geospatial coordinates of the substations, and the voltage level of the transformer.
- The euclidean distance of a particular substation from the highway is defined as d_h. As a first step, d_h is calculated for all the substations. Secondly, two cables are stretched from each of them, as illustrated in Figure 3. Depending on the position at which the substations are located, and the traffic load present on the highway stretches, the length of the cables that are electrifying the highway will change due to voltage drop limits. The distance between the first traction substation supplied by the MV line and the last one is defined as d_e. It is important to highlight that given a substation at distance d_h from the highway and keeping all other factors constant (voltage level, type of cable, load on the cable etc.), we can say that d_e and d_h are in a relationship for which their sum remains constant. Thus, if d_h is increased, d_e decreases. This factor is central in the catenary design due to regulatory and economic disadvantages such as voltage drop, losses, and cabling costs. In [24], the authors state that taking into account a MV grid in the range of 11–22 kV that supplies only a catenary system, the maximum distance allowed for voltage regulations should be in the 10–20 km range. At the same time, increasing the line voltage (e.g., up to 30 kV) allows the length of the electrification stretch to be increased.
- Each substation is characterized by the energy it should hypothetically provide if it was part of the dynamic infrastructure. Substations are then sorted: the order reflects a trade-off between proximity to the highway and traffic level.
- One by one, the algorithm connects the substations to the highway, starting from the one which is characterized by the highest load. A condition in the algorithm ensures that cables do not overlap each other.
- The algorithm ends when a chosen share of the highway has been electrified, which is named the Rate of Electrification (RE).

In Figure 4, it is illustrated how the selection algorithm operates: substations are selected from the OSM dataset within a range of 15 km from the highway. In the inductive scenario, both light and heavy duty vehicles are charged while driving, therefore:

- The Dynamic Energy Model is used to calculate their energy demand
- The SSA described in this chapter is applied

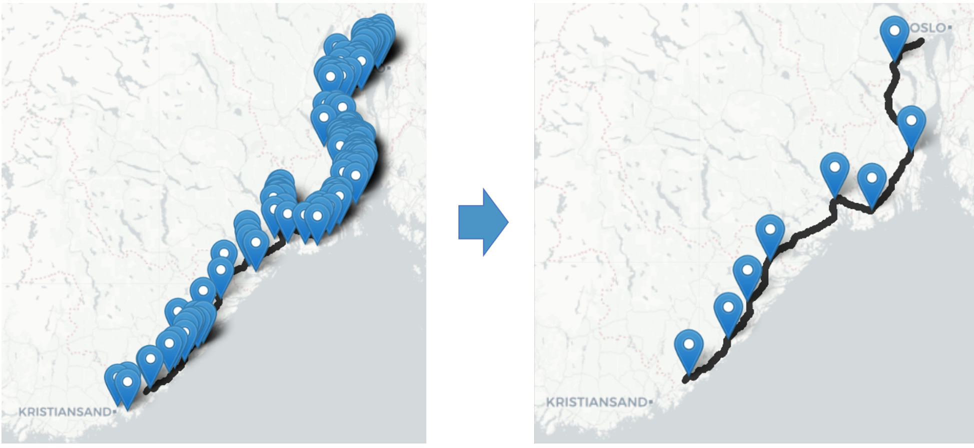

Figure 4. On the left, substations in proximity to the highway. On the right, the result of the SSA.

In Table 3, the efficiencies and distances [24] of traction substation (or charging stations for plug-in scenario) are presented.

Table 3. Characterization of the charging infrastructure.

	Efficiency	Distance (m)
Inductive	0.77	2000
Catenary	0.77	2000
Plug-in	0.73	50,000

Efficiency refers to distribution, charging and electrical engine efficiency combined, as in [11].

3.3.3. Hybrid Scenario

- The algorithm implemented for the selection of the substation for the hybrid scenario is the same as in the inductive scenario, with a small difference: only HDV traffic is taken into account for calculations, as shown in Figure 5.
- Finally, the selected substations receive on the spot the energy demand from LDVs charging at plug-in stations.

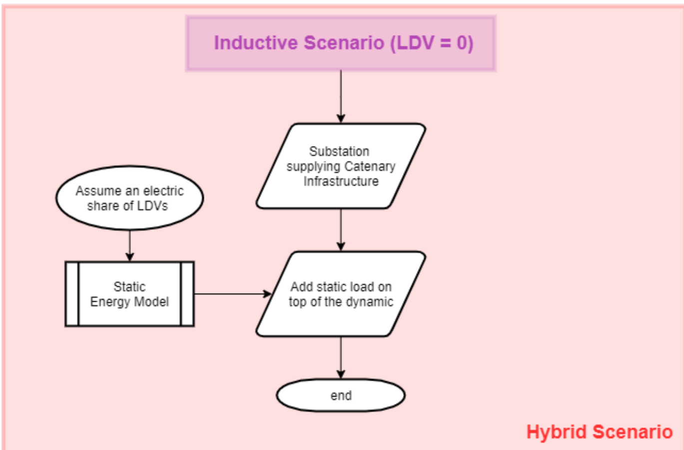

Figure 5. Methodology for the hybrid scenario.

For power flow calculations, it is assumed that the charging station is located at the nearest point from the distribution substation on the highway, supplied by one of the cables stretching from it, as is shown in Figure 6.

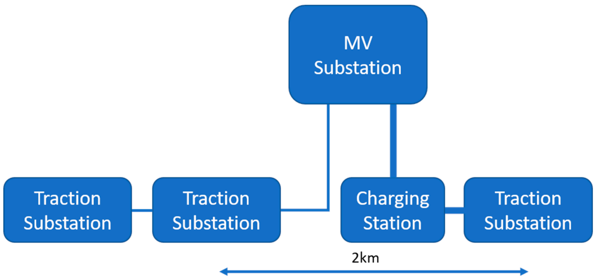

Figure 6. Illustration of the hybrid infrastructure.

4. Case Study: Electrification of E18

The methodology described in this paper is applied to a stretch of the E18 highway in the south of Norway, stretching for 278 km from Kristiansand to Oslo, and is heavily used for freight transport. The highway is already hosting a Fast Charging Station (FCS) in Langrønningen [25], and more chargers are going to be installed on the stretch (Tesla superchargers in Grenstøl [26]), which highlights the electrification potential of the highway.

4.1. Design

The inductive and hybrid scenarios are designed for the worst-case scenario: voltage drop is calculated in Pandapower in the worst hour for the most loaded substation. The recommendation for planning of Norwegian MV grids is to set the limit on maximum voltage drops at 5%.

4.2. Input Data

For this study, there are three main categories of data that were used to apply the methodology presented:

- Traffic. Inspired by [27], data of the hourly passing vehicles was downloaded from [28] for the year of 2019, for both HDVs (over 7.6 m of length) and LDVs (below 5.2 m), for a total of 35 measuring stations across the highway. In Figure 7, the spatial and temporal dependencies of the data input are presented.
- Electric Infrastructure. The geolocations of the substations connecting the high-voltage to the medium-voltage grid were downloaded from the Open Street Maps dataset [29]. Then, a proximity analysis was implemented in order to filter only substations that were at a maximum distance of 15 km from the highway.
- Road Infrastructure. A graph of the highway is downloaded from Open Street Maps to follow distances and design the charging infrastructure with accuracy. The altitude profile of the road has been evaluated through Google Maps—from the analysis of the altimetrical profile, it is concluded that the contribution of regenerative breaking can be neglected. In fact, less than 1% of the road share is characterized by slopes over 2%.

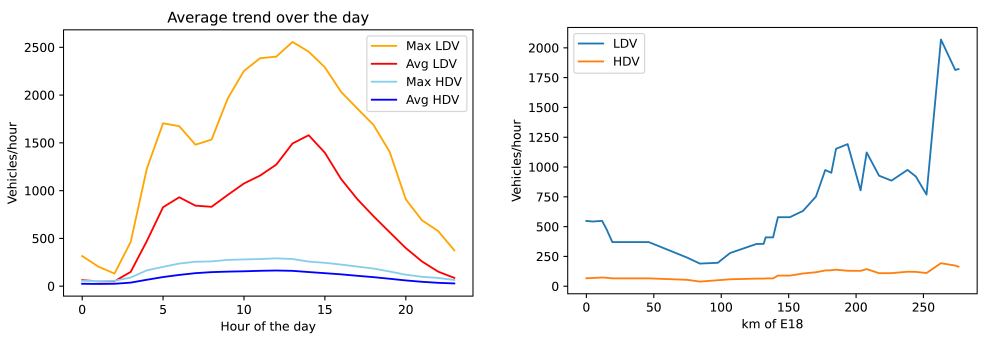

Figure 7. Traffic data.

Data Processing

The hourly traffic data measure the passing vehicles in the location where the measuring stations are located. This information can be used directly as input data for the Dynamic Energy Model, since it is not necessary to follow single vehicles in order to determine their charging needs: the energy demand is directly proportional to the amount of vehicles that are passing by. Instead, in order to develop the energy model for the static charging scenario, it was necessary to calculate the number of vehicles entering and exiting from road junctions, starting from the available data of passing vehicles. In order to do this, it was necessary to estimate the amount of vehicles going in and out, on average, for every point of access to the highway.

4.3. Results

4.3.1. Static

When locating charging stations, it was assumed that the same point of connection serves both driving directions: in reality, two separate charging stations are installed on the two sides of the road. For simplicity, we assume that they are located near to each other and the same feeder and distribution substation is supplying them. No queuing model is applied: all the vehicles that arrive to the stations are immediately charged. Because of this, the quality of the service offered is not evaluated. Nevertheless, if the cars have to be charged as they arrive to the station, an excessive amount of chargers should be installed. This inherently means that drivers must undergo queues, at least during the hours with most traffic. It is notable to mention that the average charging time calculated for HDVs results in being over 1.5 h, which can result in a decreased efficiency in the logistics of the transport sector. Finally, no power flow is included for the static scenario, since it is assumed that the feeder can sustain the voltage drop needed to supply the static energy demand.

Following the procedure elaborated in the static scenario methodology, it is decided that another charging station be added halfway between station 4 and 5 (see Figure 8). Figure 9 shows how the average load on charging station 5 reaches values up to 6 MW in one hour. Also, in the same Figure it is possible to recognize the impact of this adjustment on the loading of the charging station, which shows a reduction in the average values of the static charging demand to below 5 MW, which is finally considered acceptable.

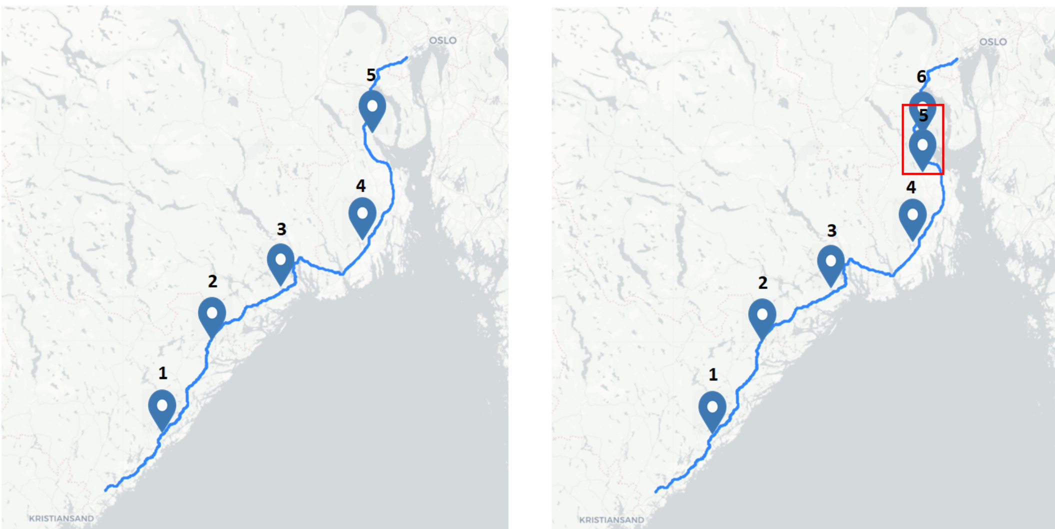

Figure 8. Static scenario.

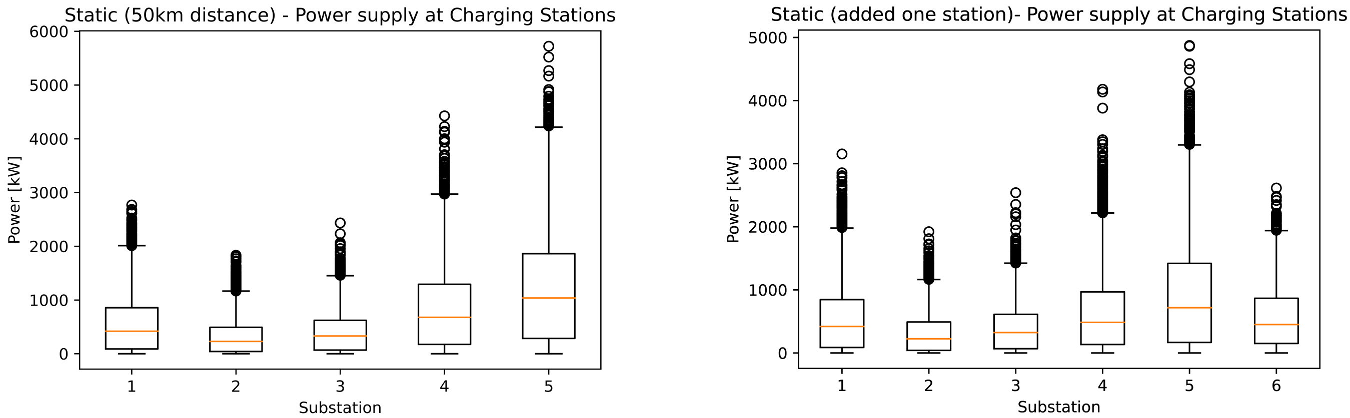

Figure 9. Static scenario charging power.

4.3.2. Inductive

The rate of electrification was chosen as 50% for both dynamic scenarios: the number of distribution substations assessed through the substation selection algorithm is 8, and the maximum energy demanded for the inductive scenario is almost 3 times the one for the static scenario (see Figure 10), Charging while driving substantially increases the total amount of energy demanded: this result is calculated based on the assumption that all electric cars driving on the highway will charge while driving.

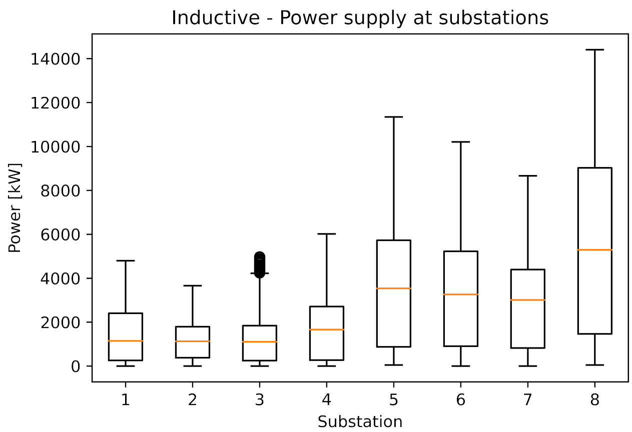

Figure 10. Inductive scenario charging power.

A power flow analysis was developed in order to assess whether the voltage drop along the MV line and the substations fall below the planning limit that is usually implemented by Norwegian grid companies (5%). For this scenario, it was assessed that the cable characterized by the FeAl nr. 50 (detailed characteristics of the cable can be accessed from [30]) effectively sustains the voltage drop.

4.3.3. Hybrid

In this case, the cable used is FeAl nr. 25 for the cable supplying only catenary traction substations and FeAl nr 50 [30] for the cable supplying both the CS and the catenary charging infrastructure. The hybrid scenario is the one that shows the smallest maximum load on distribution substations: the demand from LDVs is distributed along more charging stations than in the static scenario, decreasing the maximum power required. Moreover, the dynamic demand of the HDVs represents a small share of the total dynamic load, which can be assessed when comparing it to the inductive scenario (see Figure 11).

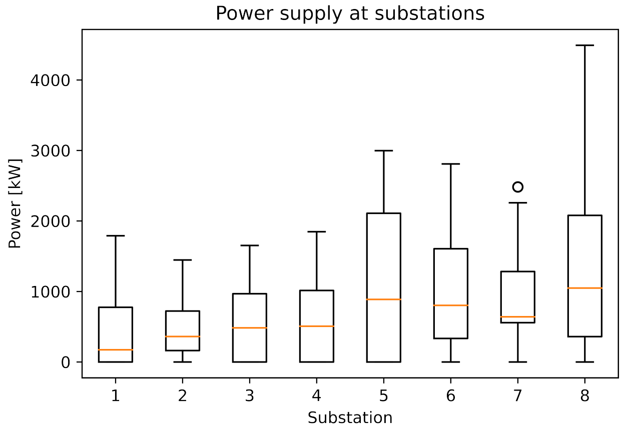

Figure 11. Hybrid scenario charging power.

4.4. Discussion

The results show that the static scenario gives the lowest average power load on the substations. On the other side, even if vehicles are assumed to charge as they arrive to the stations (since no queuing model is applied), the average charging time, especially for HDVs, is considerably longer compared to standard refueling time. This can hinder the implementation and investments in the uptake of electric trucks. The inductive scenario presents the highest average and maximum load. This, together with the fact that inductive charging is the least mature and the most costly [31] technology analyzed, makes this alternative the least suitable for the case study analyzed. A solution to decreased charging times would be to equip trucks with larger batteries (over 180 kWh) which is, on the other side, translated into higher total cost of the vehicles. Instead, the hybrid combination of the catenary charging infrastructure together with static CSs sensibly reduces the power requirements on the grid. From the final user perspective, the implementation of the hybrid scenario eliminates long charging times for HDVs (charged on the move), even if it requires the installation of pickup elements on trucks.

5. Conclusions

In this paper, a methodology to design the electric infrastructure to supply both heavy and light duty electric vehicles on a highway is described. For the scope of this paper, two types of energy models were used to estimate the electric charging potential, and three different charging technologies were implemented to supply the estimated load. The presented methodology suggests an approach to plan highway electrification through grid planning and expansion. The final output is the design of the charging infrastructure for three different scenarios: static, inductive, and hybrid, in which the latter makes use of both static and catenary dynamic charging. Medium-voltage substations are chosen through an algorithm in order to minimize the length of the cable used for each infrastructure scenario. The methodology is finally applied to a real case study, the E18 highway in Southern Norway, in which electric infrastructure geospatial information together with traffic and road infrastructure data is used to produce the electric supply design. Power flow calculations are performed in order to estimate the voltage drop and assess the suitable type of cable for the charging infrastructure. From the results, it is concluded that the hybrid scenario presents lower charging times compared to the static scenario. The hybrid scenario also substantially decreases the maximum load on the substations, which affects the sizing of cables and substations.

Further work should focus on the load assessment of substations: in fact, only geospatial position and mobility load were taken as decision variables. Grid expansion costs could therefore be evaluated more comprehensively, and a detailed cost-assessment can be the basis for a techno-economical comparison between scenarios. A queuing model or an admission mechanism (which redirect vehicles to nearby stations) should be applied in order to assess a realistic design of the static scenario. In fact, the assumption that vehicles charge as they arrive can substantially increase the maximum load on charging stations. Moreover, it could be relevant to add a user perspective and the EV users' possible impact on the overall waiting times. Finally, there is a need to further investigate the proposed architecture with different traffic conditions: even if the main contribution of the study relies on the formulated methodology, a sensitivity analysis of the traffic volume could be evaluated for a future scientific study.

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References

1. UNFCCC. *The Paris Declaration on Electro-Mobility and Climate Change and Call to Action*; UNFCCC: New York, NY, USA, 2015.
2. European Parliament. *Regulation of the European Parliament and of the Council setting CO_2 Emission Performance Standards for New Heavy-Duty Vehicles*; Technical Report; European Parliament: Brussels, Belgium, 2018.
3. Gnann, T.; Plötz, P.; Kühn, A.; Wietschel, M. *How to Decarbonise Heavy Road Transport?* ECEEE Summer Study; European Council for an Energy-Efficient Economy: Stockholm, Sweden, 2017.
4. Muncrief, R. *Shell Game? Debating Real-World Fuel Consumption Trends for Heavy-Duty Vehicles in Europe*; International Council on Clean Transportation: San Francisco, CA, USA, 2017.
5. Kenny, S.; Cornelis, S.; Sihvonen, J.; Ambel, C.C. *Roadmap to Climate-Friendly Land Freight and Buses in Europe*; Technical Report; Transport & Environment: Brussels, Belgium, 2017.
6. Bunsen, T.; Cazzola, P.; D'Amore, L.; Gorner, M.; Scheffer, S.; Schuitmaker, R.; Signollet, H.; Tattini, J.; Paoli, J.T.L. *Global EV Outlook 2019 to Electric Mobility*; OECD: Paris, France, 2019; p. 232.
7. Mareev, I.; Becker, J.; Sauer, D.U. Battery dimensioning and life cycle costs analysis for a heavy-duty truck considering the requirements of long-haul transportation. *Energies* **2018**, *11*, 55. [CrossRef]
8. Langhelle, O.; Bohne, R.; Nørbech, T.E. Electric Roads in Norway? Summary of a Concept Analysis; Technical Report; SINTEF: Trondheim, Norway, 2018.
9. Nicolaides, D.; McMahon, R.; Cebon, D.; Miles, J. A national power infrastructure for charge-on-the-move: An appraisal for Great Britain. *IEEE Syst. J.* **2019**, *13*, 720–728. [CrossRef]
10. Marquez-Fernandez, F.J.; Domingues-Olavarria, G.; Lindgren, L.; Alakula, M. Electric roads: The importance of sharing the infrastructure among different vehicle types. In Proceedings of the 2017 IEEE Transportation Electrification Conference and Expo, Asia-Pacific, Harbin, China, 7–10 August 2017. [CrossRef]
11. Taljegard, M.; Göransson, L.; Odenberger, M.; Johnsson, F. Spacial and dynamic energy demand of the E39 highway-Implications on electrification options. *Appl. Energy* **2017**. [CrossRef]
12. IEA. *Global EV Outlook 2020*; IEA: Paris, France, 2020. [CrossRef]
13. Arboleya, P.; Mayet, C.; Mohamed, B.; Aguado, J.A.; de La Torre, S. A Review of Railway Feeding Infrastructures: Mathematical Models for Planning and Operation. *eTransportation* **2020**, *5*, 100063. [CrossRef]
14. Suul, J.A.; Guidi, G. *Technology for Dynamic On-Road Power Transfer to Electric Vehicles—Overview and Electro-Technical Evaluation of the State-of-the-Art for Conductive and Inductive Power Transfer Technologies*; ELinGo: Freiburg, Germany, 2018.
15. Volkswagenag. *Towards a 'Zero Impact' eHighway*; Volkswagenag: Wolfsburg, Germany, 2018.
16. Plötz, P.; Gnann, T.; Jochem, P.; Ümitcan Yilmaz, H.; Kaschub, T. Impact of electric trucks powered by overhead lines on the European electricity system and CO_2 emissions. *Energy Policy* **2019**. [CrossRef]

17. Schulte, J.; Ny, H. Electric road systems: Strategic stepping stone on the way towards sustainable freight transport? *Sustainability* **2018**, *10*, 1148. [CrossRef]
18. Taljegard, M.; Thorson, L.; Odenberger, M.; Johnsson, F. Large-scale implementation of electric road systems: Associated costs and the impact on CO_2 emissions. *Int. J. Sustain. Transp.* **2019**, 1–14. [CrossRef]
19. Zhao, H.; Qian, W.; Fulton, L.; Jaller, M.; Burke, A. *A Comparison of Zero-Emission Highway Trucking Technologies*; University of California Institute of Transportation Studies: Berkeley, CA, USA, 2018; p. 58. [CrossRef]
20. Malik, F.H.; Lehtonen, M. Analysis of power network loading due to fast charging of Electric Vehicles on highways. In Proceedings of the 2016 Electric Power Quality and Supply Reliability (PQ), Tallinn, Estonia, 29–31 August 2016; pp. 101–106. [CrossRef]
21. Ivarsøy, E.; Torsæter, B.N.; Korpås, M. Stochastic Load Modeling of High-Power Electric Vehicle Charging—A Norwegian Case Study. In Proceedings of the 2020 International Conference on Smart Energy Systems and Technologies (SEST), Istanbul, Turkey, 7–9 September 2020; pp. 1–6. [CrossRef]
22. Ji, H.; Zhang, W.; Pan, X.; Hua, M.; Chung, Y.; Shu, C.; Zhang, L. State of health prediction model based on internal resistance. *Int. J. Energy Res.* **2020**, *44*, 6502–6510. [CrossRef]
23. Gkatzoflias, D.; Drossinos, Y.; Zubaryeva, A.; Zambelli, P.; Dilara, P.; Thiel, C.; Doi, E. *Optimal Allocation of Electric Vehicle Charging Infrastructure in Cities and Regions*; Technical Report; European Commission: Luxembourg, 2016. [CrossRef]
24. Rennemo, O.; Hjelkrem, O.A.; Terje, K.; Suul, J.; Brauhaus, P.; Aamodt, A. *Energy and Infrastructure-Demands and Requirements Work Package 3*; Technical Report; 2018. Available online: https://www.sintef.no/globalassets/project/elingo/18-0733-rapport-5-memo-work-package-3-til-nett.pdf (accessed on 20 May 2020).
25. Skoglund, J. *Her Blir Det Mulighet for påfyll og hvile: Det 36 mål Store Veiserviceanlegget åpner før Sommeren*; Veier24.No: Oslo, Norway, 2019.
26. Tesla. Tesla Superchargers | Tesla. Available online: https://chargeatlas.com/by_id/grenstolsupercharger.html (accessed on 20 May 2020).
27. Berg, K.; Hjelkrem, O.A.; Torsæter, B.N. A proposed methodology for modelling the combined load of electric roads and households for long-term grid planning. In Proceedings of the 2020 17th International Conference on the European Energy Market (EEM), Stockholm, Sweden, 16–18 September 2020. [CrossRef]
28. Trafficadata. Available online: https://www.vegvesen.no/ (accessed on 20 May 2020).
29. OPS. OpenStreetMap. Available online: https://www.openstreetmap.org/ (accessed on 27 January 2021).
30. Ivars, E. Optimal Planning of Fast Charging Stations for EVs—A Norwegian Case Study. Master's Thesis, NTNU, Trondheim, Norway, 2020.
31. Gustavsson, M.G.H.; Hacker, F. *Overview of ERS Concepts and Complementary Technologies*; Swedish-German Research Collaboration on Electric Road Systems, Ed.; Technical Report; CollERS Report; 2019. Available online: https://www.electricroads.org/report-overview-of-ers-concepts-and-complementary-technologies/ (accessed on 20 May 2020).