THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

The impact of an Electrification of Road Transportation on the Electricity system in Scandinavia

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ABSTRACT

The transport sector needs to reduce CO_2 emissions by replacing fossil fuels with low-carbon options. An electrification of the road transport sector through electric vehicles (EVs) with static charging; electric road systems (ERS); and using electricity to produce a fuel, are all suggested as possible options. An electrification of the transport sector introduces a new demand to the electricity system, and hence, will create new load profiles depending on the time of consumption and the amount of electricity used in EVs. Depending on electrification strategy, this new demand may introduce a potential for EVs to provide demand-side management to the power grid. The overall aim of this work is to investigate how an electrification of the transport sector could impact the Scandinavian electricity system with respect to energy and power.

A vehicle energy consumption model was developed to estimate the variation of the energy and power demands with time and location for the transportation work on a highway under the assumption of different electrification options and drivetrains. Furthermore, demand for electric transportation have been included in electricity system models (a cost-minimizing investment model of the electricity system and one electricity system dispatch model) in order to investigate how EVs may impact the investment in new power capacity and integration of wind power in the Scandinavian and German electricity system by Year 2030.

Our results, using the Norwegian road E39 as an example, indicate that an electrification of road transport implies large variations in energy and power demand both over time and location, i.e. spatial and time distributions of demands, along the road. Installation of ERS on all the European (E) and national (N) roads in Sweden and Norway would cover more than 50% of the vehicle traffic. A 25% implementation of ERS out of the total E- and N-road sufficient in order to connect the larger cities in Norway and Sweden by ERS.

We have also shown that with a cap on CO_2 corresponding to 93% emission reduction by Year 2050, the demand from EV in Scandinavia and Germany are mainly met by an increase in generation from wind power and to some extent coal in combination with carbon capture and storage. A smart integration of passenger EVs (*vehicle-to-grid*; V*2G*) can to some extent be used to manage variability of renewable energy sources by, for instance, substantially reduce the need for peak power capacity in the system. If using an indirect strategy for electrification of transportation, via for instance hydrogen or electrofuels, the annual electricity demand would increase more than four times compared to static or dynamic charging, albeit with increased flexibility to distribute such demand both geographically and in time. Further studies is needed to compare *V2G* with other storage technologies and demand side management strategies.

Keywords: *electric car; energy system modelling; electric road systems; peak power; variation management; energy consumption*

SAMMANFATTNING

Transportsektorn måste minska utsläppen av koldioxid genom att ersätta fossila bränslen med koldioxidneutrala alternativ. En elektrifiering av vägtransportsektorn kan ske genom elbilar som laddas hemma, elvägar eller med hjälp av el producera ett fordonsbränsle. En elektrifiering av transportsektorn ökar det totala elbehovet och kan komma att också öka elsystemets toppbelastning eller skapa nya effekttoppar i elsystemet beroende på när och hur mycket el som används. Men elfordonens batterier kan också utnyttjas för lagring av el som sedan laddas tillbaka till nätet. Det övergripande syftet med detta arbete är att undersöka hur en elektrifiering av vägtransportsektorn kan komma att påverka det skandinaviska elsystemet med avseende på energi och effekt.

En fordons förbrukningsmodell har utvecklats för att uppskatta hur energi- och effektbehovet för transportarbetet på en motorväg varierar över tid och med plats beroende på olika elektrifieringsalternativ och drivlinor. Vidare har en kostnadsminimerande investeringsmodell och en kraftförsörjningsmodell av elsystemet använts för att studera hur elfordon påverkar investeringar i nya kapacitet och integreringen av mer vindkraft i det skandinaviska och tyska elsystemet år 2030.

Våra resultat visar att en väg så som E39an i Norge uppvisar stor variation i det tidsliga och geografiska energi- och effektbehovet. En utbyggnad av elväg på alla Europa och Nationella vägar (E- och N-vägar) i Sverige och Norge skulle täcka mer än 50% av fordonstrafiken. Resultaten visar också att en utbyggnad av elväg på 25% av de E- och N-vägar med mest trafik är tillräckligt för att binda samman de stora städerna i Norge och Sverige.

Vi har också visat att med en CO_2 minskning på 93% från elsystemet till år 2050 så kommer ett ökat elbehov från elfordon i Skandinavien och Tyskland huvudsakligen möts av en ökad investering i vindkraft och kol med koldioxidavskiljning och lagring. En smart integrering av elfordon kan hjälpa till att hantera mer variabelproduktion genom att avsevärt minska behovet av toppeffekt i systemet. Om man använder en indirekt strategi för elektrifiering av transportsektorn via exempelvis vätgas eller syntetiska bränslen så skulle det årliga elbehovet öka dramatiskt jämfört med statisk eller dynamisk laddning men med större möjlighet att distribuera efterfrågan på el både geografiskt och i tid. Ytterligare studier behövs för att jämföra smart laddning av elfordon med andra strategier för att hantera mer variabelproduktion i elsystemet.

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Göteborg, November 2017
Maria Taljegard

List of Publications included in the thesis

This thesis is based on the following three appended papers:

I. Taljegard, M., Göransson, L., Odenberger, M., & Johnsson, F. (2017) Spacial and dynamic energy demand of the E39 highway–Implications on electrification options. *Applied Energy*, 195, 681-692.

II. Taljegard, M., Thorson, L., Odenberger, M., & Johnsson, F. (2017) Large-scale implementation of electric road systems: associated costs and the impact on CO_2 emissions. Submitted to *Transportation research Part D: Transport and Environment.*

III. Taljegard, M., Göransson, L., Odenberger, M., & Johnsson, F. (2017) Impacts of electric vehicles on the electricity generation portfolio – a Scandinavian-German case study. To be submitted to *Applied Energy.*

Maria Taljegard is the principle author of Papers I-III and conducted all the modeling and calculations for these papers. Professor Filip Johnsson (who is the main academic supervisor) and Dr Mikael Odenberger contributed with discussions and editing of all three papers. Dr Lisa Göransson contributed with discussion and editing of Paper I and III, as well as, method development in Paper III. Ludwig Thorson contributed with geographic information system analysis and discussion of Paper III.

Other publications by the author not included in the thesis

Other publications by the author not included in the thesis:

A. Taljegard, M., Göransson, L., Odenberger, M., & Johnsson, F. (2016) Charging strategies – implications on the interaction between an electrified road infrastructure and the stationary electricity system. *EVS29 Symposium.* Montreal. *Published in World Electric Vehicle Journal.*

B. Taljegard, M., Thorson, L., Odenberger, M., & Johnsson, F. (2017) Electric road systems in Norway and Sweden – Impact on CO_2 emissions and infrastructure cost. *IEEE International Transportation Electrification Conference and Expo 2017*.

C. Johansson, V., Thorson, L., Goop, J., Göransson, L., Odenberger, M., Reichenberg, L., Taljegard, M., & Johnsson, F. (2017). Value of wind power – Implications from specific power. *Energy*, 126, 352-360.

D. Taljegard, M., Brynolf, S., Grahn, M., Andersson, K., & Johnson, H. (2014). Cost-effective choices of marine fuels in a carbon-constrained world: results from a global energy model. *Environmental science & technology*, 48(21), 12986-12993.

E. Adl-Zarrabi, B., Ebrahimi, B., Hoseini, M., Johnsson, J., Mirzanamadi, R., & Taljegard, M. (2016). Safe and Sustainable Coastal Highway Route E39. *Transportation Research Procedia*, 14, 3350-3359.

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CHAPTER 1

Introduction

1.1 Background

Carbon dioxide (CO_2) emissions from fossil fuel combustion is the largest contributor to the increased radiative forcing of the climate system [1]. The Paris Agreement signed in Year 2015 by 197 countries recognizes the primary goal of limiting global warming to well below 2°C above the preindustrial global annual average temperature [2]. The transport sector is to 93% dependent on oil, making the sector the least-diversified of all sectors in terms of primary energy supply. The global CO_2 emissions from transportation has increased with 28% since Year 2000 according to the International Energy Agency [3]. The climate goal for the transport sector in the European Union (EU) is a 65% CO_2 emission reduction by 2050 compared to emissions in 1990 [4]. Corresponding targets for Sweden is a 70% emission reduction by 2030 compared to emissions in 2010 [5]. There are also other strong drivers for reducing our dependence on fossil fuels in the transport sector besides CO_2, for example to reduce air pollution in cities and increase security of energy supply. Several strategies to reduce the use of fossil fuels are available: (i) to implement more energy efficient vehicles and eco-driving, (ii) to select modes of transportation that emit less CO_2 emissions per person or gods freighted, and (iii) to switch to low CO_2 emitting transport energy carriers (e.g., bioenergy based liquid and gaseous fuels, hydrogen and electricity). Figure 1 shows potential primary energy sources, energy conversion technologies, and energy carriers for different transport modes. The work in this thesis focuses on reduced fossil fuel use by electrifying the road transport sector. The number of electric vehicles (EVs) reached 2 million globally in 2016, following a year of strong growth in 2015 [3]. In Norway, EVs had a market share of 29% of sold passenger vehicles in Year 2016, which was the highest globally, but the total share of EVs in the world is still very low (<0.2% of the passenger vehicles) [3]. However, electrification of transportation sector is typically considered to play a significant role in order to reach Swedish and Norwegian climate targets [5, 6]. To enable a transition to EVs, governments have issued policies promoting such development, not only in Scandinavian countries but also elsewhere.

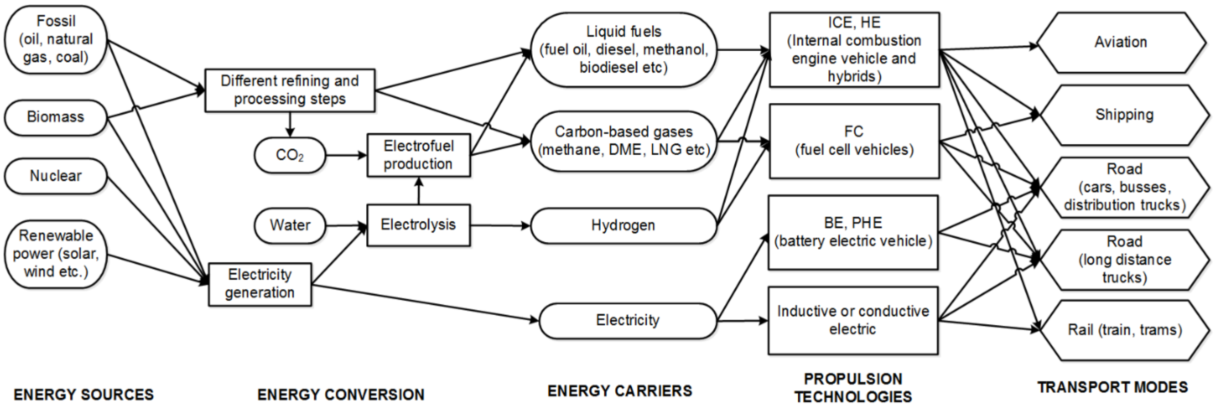

Figure 1. Simplified schematic of primary energy sources, energy conversion technologies, and energy carriers for different transport modes [7]. DME = dimethyl ether, LNG = liquefied natural gas, ICE = internal combustion engines, HE = hybrid electric propulsion, FC = fuel cells, BE = battery electric propulsion, PHE = plug-in hybrid electric propulsion

Table 1 shows the efficiency values from electricity sources to wheels, as well as, the main advantages and challenges for different transport options. One challenge for the road transport sector in replacing fossil fuels by electricity lies in the electric infrastructure needed for supplying the electricity to the EVs. For vehicles mainly supplied by on-board batteries electrification requires charging infrastructure at home or using fast charging in public places. Another option is Electric Road Systems (ERS), which uses dynamic on-road conductive or inductive power transfer while driving. This has recently been tested on public roads in Sweden and USA. Yet another option is to use electricity to produce a fuel (such as hydrogen or synthetic hydrocarbons) for on-board use in internal combustion engines or fuel cells. However, it is not obvious which option/options that are the best for the transport sector when moving away from fossil fuels, since each of alternatives has its own advantages and disadvantages, and these alternatives need to be investigated further [5]. Present EVs suffer from short driving range compared to conventional vehicles or fuel cell vehicles but they have high efficiency from grid to wheels and thereby low running costs. Fuel cell vehicles that use hydrogen or internal combustion engine vehicles that use synthetic fuels have today generally longer driving ranges than EVs and do not require long idle times for re-fuelling. However, there are currently few hydrogen vehicles on the market, mainly due to the lack of hydrogen infrastructure and difficulties associated with hydrogen storage. Additionally, both hydrogen and synthetic fuels face supply-chain efficiency issues with losses in several energy conversion steps before end-use. ERS, which builds on the technology used during decades for trolley buses, have gained a renewed interest during the past few years. This is mainly due to the fact that current battery technology are too heavy for long range vehicle categories such as buses and heavy trucks. ERS can potentially reduce the fuel costs per kilometre, but it is less clear what the vehicle cost will be since it depends on the extent of ERS and the possibility to reduce the on-board battery for trucks and buses, as well as cars. However, despite an increased interest during the past few years, ERS is still under early development and is currently only being tested on a couple of kilometre public road in Sweden and USA [5, 8-11]. Additionally, a large-scale implementation of ERS is associated with considerable up-front investment costs. Biofuel can be a cheaper energy carrier than electricity in the transport sector, since it can use the same infrastructure and vehicles as petroleum-based fuels. However, large-scale use of biofuels raises concerns with respect to potential availability of sustainable biomass, which compared to expected global transport demand [12-14] could be a limitation. Hence, this may lead to competition for land areas and water resources with food production.

Table 1. Efficiency values from electricity sources to wheels, main advantages and challenges for different transport options

Transport options	**Efficiency [15]**	**Main advantages**	**Main challenges**
Biofuels	20%	✶ Can use current infrastructure and vehicles ✶ All transport modes ✶ Fast refuelling time compare to charging a battery	× Low efficiency × Limited supply × Competing for resources with food production × Tailpipe emissions
EV (batteries)	73%	✶ Quiet and zero tailpipe emissions ✶ High efficiency	× Short driving range compare to combustion engine vehicles × Heavy batteries for trucks and buses
Electric road systems (ERS)	77%	✶ Quiet and zero tailpipe emissions ✶ Smaller on-board batteries than EVs with static charging ✶ High efficiency ✶All transport modes (depending on technology)	×New infrastructure with high upfront investment costs ×Technical challenges with the inductive power transfer technology
Electrofuels (P2G)	17%	✶ Fast refuelling time ✶ All transport modes ✶ Can use current infrastructure and vehicles	× Low efficiency × Tailpipe emissions × Store the CO_2 atoms instead of producing a fuel
Hydrogen	24%	✶ Fast refuelling time ✶ Quiet and zero tailpipe emissions	× Low efficiency × New infrastructure with high upfront investment costs × Difficulties associated with storage

One issue for the electricity generation system with using electricity for transport is that the charging of the EVs might correlate with the electricity system peak load and thereby increase the need for peak power capacity and an increase in CO_2 emissions from the electricity system, depending on the amount and time of electricity consumption for transport. Different strategies for electrification of transport will create different EV load profiles, and thus, will have different impacts on the electricity generation system. But EVs might also be able to provide demand response services to the power grid in the form of charge and discharge back to the grid according to what is most optimal from a system point of view. In the future electricity system, a higher penetration level of variable Renewable Electricity (vRE), such as solar and wind power, is expected which will put pressure on the electricity system to handle a more variable electricity production, i.e. from electricity generation which cannot be dispatched. The intermittency of renewable generation can be aided with different variation management strategies, for example, one that involves load management of EVs, different storage technologies, curtailment of vRE, pumped hydropower and expansion of the grid. Periods of excess of electricity generation may exist, leading to low or zero electricity prices, whereas periods of electricity generation deficit can cause high electricity prices. High price periods can incentivize consumers charging behaviour to avoid charging during hours with high net load. The electricity system needs ways of handling fluctuating electricity generation on different time scales, such as hours, days and weeks.

1.2 Aim and scope of this thesis

The overall aim of this thesis is to elucidate how an electrification of the transport sector affects the energy and power demand on hourly power balance level in the electricity system, mainly using the Scandinavian countries as example. Thus, the aim is to:

- Investigate how the energy demand from road transportation varies with time and location for a road (Paper I); and the impact of an electrified road on the power demand from the grid, assuming different electrification options and drivetrains (Papers I and III).
- Identify the potential benefits of large-scale implementation of ERS and its role in the transportation system by investigating which roads, the extent of the road network, and the vehicle types that could be environmental and economical beneficial to electrify (Paper II).
- Investigate how a large-scale deployment of EVs would, given different electrification strategies, affect investments in new generation capacity and the dispatch of the Scandinavian and German electricity system (Paper III).

European Highway Route 39 in Norway which traverses both urban and rural regions, is used as a case study in Paper I. In Paper II, an analysis of large-scale ERS is presented for Norway and Sweden. In Paper III, the geographical scope of the modelling study includes Norway, Denmark, Sweden and Germany. This work focuses on electrification of road transportation from an electricity systems perspective, i.e. requirements on technical aspects of the electricity supply at the roads such as strengthening local grids and the design of charging infrastructure are outside the scope of this thesis.

1.3 Contribution of this thesis

Paper I estimates the power demand, with an hourly time resolution as well as a spatial distribution, from electrifying the E39 road assuming different drivetrain technologies. Paper II investigates environmental and economic implications for light and heavy vehicles from ERS deployment at a national level, i.e. not only impacts from a single road and technical aspects, as has to a large extent been in focus in previous research on ERS. Thus, understanding the role of large scale employment of ERS infrastructure is vital to estimate the costs and benefits of making investment decisions in ERS compared to alternatives.

In Paper III, several methodologic advances have been made when it comes to modelling EVs interaction with the electricity supply system, both in terms of impact on investment decisions and from an operational dispatch point of view. Although the importance of controlled charging with large-scale introduction of passenger EVs in order to avoid an increase in demand during hours with high net load is shown in previous work (e.g. [16-22]), as well as, the possibility to handle more vRE in a system with more EVs, the present work (Paper III) adds the following to previous modelling studies: (i) analysing an electrification of the transport sector both with a cost-minimizing dispatch model and an investment model that have a geographical scope of several countries, taking into consideration trade of electricity between regions, (ii) modeling the road transport sector using optimization models that take into account individual driving data (i.e. several daily transport demand profiles) for passenger vehicles, (iii) also including electrification of trucks and buses, and (iv) taking into consideration ERS that can be used in combination with static charging.

1.4 Outline of this thesis

This thesis is based on three appended papers (Paper I-III) and this introductory essay. Chapter 2 gives an introduction to the different strategies for electrification of the transport sector and the connection to the electricity system. Chapter 3 describes the research methodology and development of the three models applied in this work. Chapter 4 summaries and discuss the main findings from Papers I-III. Chapter 5 gives the main conclusions, and further research questions/areas are proposed in Chapter 6.

CHAPTER 2

Electrification of transportation

The road transport sector could be electrified, as seen in Figure 1, through: (i) EVs with charging at home/work or fast/ultra-fast-charging in public places; (ii) electric road systems (ERS); and (iii) using electricity to produce a fuel (such as hydrogen or synthetic hydrocarbons). As mentioned in the introduction, there is no clear single solution for the road transport sector, either from a transport or electricity sector perspective. The main drawback with using electricity with static charging, compared to liquid and gaseous carbon-based fuels, is the low energy density of the present batteries and the comparative long refuel/charging times. At present, a vehicle battery has typically a range of 150-500 km and it takes between 30 min and 12 hours to fully recharge the battery depending on the charging power. A heavy truck would need a battery in the range 600-800 kWh in order to drive for four hours, which would mean a battery package of several tons. Ultra-fast charging (with charging power of more than 350 kW) can shorten the charging times for trucks and thereby the need for large batteries substantially. However, ultra-fast charging is not yet commercially available and the main challenge lies in the grid integration of several MW and associated costs. The development of battery technology is leading to increased battery energy and power density that will improve the driving range and charging time, as well as, reduce the battery cost compare to what is available today [23].

Thus, depending on charging options available and the size of the vehicle battery, different charging strategies can be applied. For static charging, the EVs can either be charged in an uncontrolled fashion whenever connected to a charging infrastructure or the charging could be controlled for instance to prevent correlation with peaks in the electricity system load. Controlled charging could either be by optimising the charging time or a charging strategy where the EVs also can be discharged back to the grid (i.e. vehicle-to-grid; V2G). V2G would open for advanced demand-response schemes given that forthcoming travelling plans can be fulfilled. An electrification of the transport sector may thereby, depending if a controlled charging strategy is implemented or not, inflict the need for more flexibility strategies from the electricity network than today, as well as, provide possibilities to supply flexibility services by being a storage option, providing hourly capacity and energy balancing services. Statistics from the USA and Sweden show that existing EVs are on average parked around 95% of the time and a car battery would therefore potentially be available in the electricity system during large parts of the day [24]. However, one important question is if the vehicles can be discharged to the grid at the hours most needed from an electricity system perspective. Possible economic incentives for using V2G are for example to reduce the need for investment in new peak power capacity, reduce curtailment of vRE, and reduce the need of stationary batteries.

There has been a number of studies published in recent years on the topic electrification of road transport with the aim to determine load profiles and impacts of EVs on the dispatch of generation technologies, curtailment on wind power and power peak demand (e.g. [16-19, 22, 25-32]). An approach commonly applied is formulating a V2G scenario as a mathematical optimization problem with the aim of finding the optimal charging strategy, given specific objectives and constraints. Yet, the optimisation objective has varied in previous literature, for example there are studies that optimise the cost for the vehicle owner, optimise the cost for the electricity system, and minimizing frequency disturbance in the electricity grid. Some studies, for example [25, 26, 30, 33, 34] solely used driving patterns to determine the load curve from EVs. Table 2 provides an overview of previous studies which used investments and/or dispatch models to investigate the impact on the electricity system from V2G. For example, Göransson et al [16], Hedegaard et al [17], Lund and Kempton [18], Sohnen et al [20] and Jochem et al [21] all used linear optimization investment models and/or dispatch models to analyse the benefit of a controlled charging strategy. However, they investigated a single country or regions as a closed system without inter-connections to surrounding electricity system. Studies using multi-regional energy models, for example those by Hadley and Tsvetkova [22] and Verzijlbergh et al [19] are limited to dispatch models, and thus, do not include the impact from EV employment in the long-term investment decisions in power generation capacity. The main results from previous studies show that a smart integration strategy of passenger EV can (i) reduce the need for peak power capacities, (ii) increase penetration of wind power, (iii) increase the utilization of hard coal/lignite plants in 2030, and (iv) reduce CO_2 emissions from the electricity system.

An Electric road system (ERS) is a potentially interesting future technology mainly as a drive range extender for longer trips by providing the electric vehicles with continuously electricity while moving, without using the on-board battery. This is of special relevance for heavy long-distance driving vehicles. ERS will also facilitate EVs to charge their battery while driving. An electrification of the transport sector including ERS will on the other hand, add a direct load to the current electricity load profile while reducing the need for large batteries in all road transport modes. Previous studies in the scientific literature have mainly investigated ERS with respect to technology improvements (e.g. [35-37]) and cost (e.g. [23, 38-40]). For example, Connolly [40] and Boer et al. [23] conclude that ERS has the potential to be more cost-competitive than both oil and purely battery EVs in the future. This is due to ERS having lower running costs than oil and that an ERS infrastructure is shared by many vehicles so the cost per vehicle is reduced and smaller batteries can be used. Some studies (e.g. [15, 25, 34] have modelled the electric power demand for roads and investigated the possibilities to meet the electricity demand for highway traffic flow on an average day with vRE [34]. But important research gaps pointed out by the previous studies mentioned are to investigate impacts on the power demand from trucks and buses together and to provide an environmental analysis of ERS. The environmental impact of ERS will to large extent depend on the technology mix used to generate the electricity required to power the ERS vehicles.

Table 2. Overview of previous works which apply different investments and dispatch models to study an electrification of the transport sector.

	Model	**Geographical scope**	**Time resolution**	**Aim**	**Charging options/ alternatives**	**Main conclusions**
Göransson et al [16]	linear programming investment optimisation model, objective: minimize investment cost (Balmorel)	Western Denmark	28 representative days	EV impact on: total power system costs and emissions, and the generation patterns	Modes: passenger PHEV Strategy: uncontrolled and controlled/V2G	PHEVs can reduce the CO_2 emissions if using controlled charging.
Hedegaard et al [17]	Investment and dispatch optimisation model (Balmorel), objective: minimise total system cost	Five northern European countries (no transmission)	Year 2010-2030, five year interval, representative days, perfect foresight	EV impact on: electricity system, e.g. investments and operation towards 2030	Modes: passenger BEV, PHEV. Strategy: controlled/V2G	V2G can reduce the need for investments in fossil power plants and increase penetration of wind power. Reduction of CO_2 emissions 2030 of 3-28%.
Lund & Kempton [18]	deterministic model that optimises the operation of a given energy system (Energy Plan)	Denmark	1 hour timestep, Year 2020	EV impact on: CO_2 emissions and the ability to integrate wind power	Modes: passenger PHEV Strategy: uncontrolled night-time charging and controlled/V2G	V2G allows integration of higher penetration levels of wind power without curtailment, and also greatly reduces national CO_2 emissions.
Jochem et al [21]	Cost optimizing energy system model (PERSEUS-NET-TS).	Germany	Year 2012-2030 (five year timesteps), 12 representative days	EV impact on: CO_2 emissions	Modes: passenger EV. Strategy: uncontrolled/ controlled charging (no discharge back to the grid)	A controlled charging strategy is needed for CO_2-free driving of EVs in Year 2030.
Schill & Gerbaulet [41]	Mixed integer linear optimization model, objective: minimise total system cost	Germany	1 hour timestep, year 2020 and 2030	EV impact on: dispatch of the electricity system and CO_2 emissions	Modes: passenger BEV, PHEV. Strategy: Uncontrolled and controlled/V2G	A controlled EV charging strategy can smoothen the load curve and strongly increase the utilization of hard coal/lignite plants in Year 2030.
Verzijlbergh et al [19]	a mixed-integer minimum-cost unit commitment dispatch model (EUPowerDispatch) objective: minimise total system cost	32 European country	1 hour timestep, an optimisation horizon of 1 week for Year 2010 and 2025	EV impact on: cross-border electricity transmission investment.	Modes: passenger EV. Strategy: uncontrolled and controlled charging, each vehicle is modelled separately	A controlled EV charging strategy and cross-border transmission capacity complement each other and reduce electricity dispatch costs and curtailment of vRE,
Hadley & Tsvetkova [22]	Dispatch model of the electricity system, objective: Minimize running costs (ORCED model)	USA (13 regions)	Year 2030	EV impact on: CO_2 emissions, electricity prices and the dispatch of the electricity system	Modes: passenger PHEV Strategy: uncontrolled charging	The demand, generation, electricity prices, and emissions from the utilities created by the introduction of PHEVs are expected to go up with uncontrolled charging of PHEV.
Fripp [42]	stochastic linear programming model, objective: minimise total system cost (SWITCH)	California (16 zones)	Year 2012-2027, 12 representative days with 1 hour timesteps	EV impact on: the cost reducing greenhouse gas emissions from the electricity system through large-scale use of wind and solar power	Modes: passenger EV Strategy: controlled/V2G	If EVs are charged at the optimal time of day, EVs can reduce system cost and emissions.
Schlachtberger et al [43]	linear programming model, objective: minimise total system cost (POWER)	United States	14 representative days	the cost benefits of a combinations of flexibility options e.g. PHEV	Modes: passenger PHEV Strategy: partly flexible PHEV demand	PHEV generated a larger total system cost but lower total system levelized cost.
Taljegard et al (this work, Paper III)	linear programming optimisation model, objective: minimize running costs and investment costs (ELIN & EPOD)	Denmark, Norway, Sweden and Germany	Investment model: Year 2010-2050, 20 representative days with hourly time steps, Dispatch model: Year 2030, hourly time steps	EV impact on: the electricity system, e.g. investments and operation of the system and CO_2 emissions	Modes: Passenger EV/PHEV, trucks and buses Strategy: controlled/V2G	V2G can substantially reduce the need for peak power, the main increase in demand from EV will be met by wind power and coal with CCS.

CHAPTER 3

Methods and Modelling

This chapter provides a summary of the three different models applied in this work to address the research questions listed in section 1.2, one developed specifically for this work and two further developed and adapted within this work. Table 3 provides a summary of the models developed and used in this thesis. The mathematical formulation can be found in Papers I-III and is therefore not included here. In Paper I, a *vehicle energy consumption model* is developed that estimate energy and power demands for the road transportation work required to propel the investigated vehicles along the road. This model include the ability to investigate different drivetrains. In addition, a *cost-minimising investment model (ELIN)* and an *electricity system dispatch model (EPOD)* have been used in Paper III. The ELIN and EPOD models were originally developed by other authors [44-46] but have been further developed in Paper III to also include electric vehicles via an electric vehicle module embedded in the ELIN/EPOD. The module is part of the optimisation in the ELIN-EPOD model package (see Figure 2) and included in Table 3. The vehicle energy consumption model and the ELIN-EPOD models are used separately in the appended papers. However, output from the work done in Paper I (e.g. traffic flow profile) has been used as an input for the model used in Paper III. Further, the calculation of the energy consumption per kilometre for vehicles driving on a highway from Paper I is used as an input for the calculations of CO_2 emissions in Paper II. Figure 2 shows the connection between the input data, models and output parameters used in this thesis.

Paper I uses a *vehicle energy consumption model* developed based on the same concept as similar mathematical models previously used in the literature (e.g., [47-52]) for estimating fuel consumption and fuel efficiency for vehicles. The model is designed to estimate the energy needed to overcome inertia, road inclination, tire friction, aerodynamic losses, and regeneration through braking. The model simulates the energy consumption and, if applicable, energy regeneration potential for different drivetrains, vehicle categories and transport options (static charging, hydrogen, electrofuels/power-to-fuel and ERS). The energy consumption per kilometre depends on a number of factors, such as the vehicle characteristics (i.e., vehicle mass, drivetrain efficiency, frontal area, etc.), vehicle speed, driving behaviour, pavement conditions, altitude, and weather conditions. The main limitations with the model is the difficulty to in a sensitivity analysis properly include, for example, driving behaviour, a slippery road, tire pressure, weather, and a detailed powertrain configuration, all of which also affect the energy demand.

Table 3. A description of the models developed and used in this thesis.

	Vehicle energy consumption model	**Investment model (ELIN)**	**Dispatch model (EPOD)**	**Electric vehicle module** *(part of the ELIN and EPOD model-package)*
Paper	I and II	III	III	III
Computer language	MATLAB	GAMS	GAMS	GAMS
Type of model	Simulation	Optimisation	Optimisation	Optimisation
Time resolution	Yearly and hourly	Investment period Year 2010 – 2050, with 20 representative days per year	Hourly (all hours for Year 2030)	Same as ELIN and EPOD
Vehicle categories	Passenger car, light truck, bus and heavy truck	Passenger car, light truck, bus and heavy truck	Passenger car, light truck, bus and heavy truck	Passenger car, light truck, bus and heavy truck
Geographical scope	1100 km highway in Norway	Scandinavia plus Germany	Scandinavia plus Germany	Scandinavia plus Germany
Data input	i) Road data *(slope, speed limit, IRI, MPD,)* ii) Vehicle data *(drivetrain efficiency, front area, mass, motor output, air & rolling resistance coefficient, etc.)* iii) Charging efficiency iv) Hourly traffic flows v) Average daily traffic	i) Energy demand ii) Information on current capacity installations (life time, efficiency, etc.) iii) Investment cost and properties by technology iv) EU CO_2 emissions targets and policies	i) Energy demand ii) Solar and wind profiles iii) Capacities by fuel and technology iv) Running costs and properties by technology	i) Number of vehicles per year (2010-2050) ii) Energy use per km iii) Number of kilometres per year iv) 200 days with individual driving profiles v) Charging profile for ERS
Output parameters	i) Energy consumption per km ii) Hourly and yearly energy demand for a highway iii) Regeneration potential iv) Traffic flow profile for a highway	i) Total system cost ii) Capacity investments iii) Fuel and CO_2 prices iv) Investments in transmission lines	i) Total system cost ii) Generation profile by fuel and technology iii) Marginal cost of electricity iv) CO_2 emissions	i) Charging and discharging profile ii) Battery storage level iii) Yearly number of battery cycles

As mentioned above, the energy consumption per kilometre from Paper I, is used as an input for calculations of the CO_2 mitigation potential in Paper II. In *Paper II,* data of the average daily traffic (ADT) from Norway and Sweden are used to estimate the CO_2 mitigation potential from the road and cost of a large-scale implementation of ERS.

The two electricity system models *ELIN* and *EPOD* were originally constructed by Odenberger and Unger [44, 45], and further developed by their co-authors [46]. These models have previously been used to study the transition of the European electricity system to meet European policy targets on CO_2 emissions and targets on investments in renewable energy sources (e.g. [45, 46, 53]. In both ELIN and EPOD, the goal is to minimize the total system cost. The ELIN-model is designed to analyze a transition of the electricity system by making investment decisions based on the age structure and competitiveness of different power generation technologies, while reaching a target on CO_2 emission. The EPOD-model takes the results (i.e. the description of the electricity system, fuel and CO_2 prices, and transmission lines) from the ELIN-model for a specific year (in Paper III the Year 2030) and then further carries out optimization in order to find the least-cost hourly dispatch of the system. The geographical scope of the modelling study in Paper III includes the Scandinavian countries (Sweden, Norway and Denmark) and Germany. Paper III applies the models to compare total system cost, electricity generation profiles, curtailment of wind power and capacity investments for different scenarios of EV deployment and integration strategies.

In Paper III, the ELIN-EPOD model package are expanded to also include electric transport in the form of passenger cars, trucks and buses. A new demand for electric transportation has been added both to the investment model and the dispatch model. The electricity demand for trucks and busses has to be met according to their demand profile, while the two models endogenously optimize the time of charging and discharging of the passenger EV back to the grid while at the same time fulfilling an exogenously given hourly passenger EV transportation demand. The number of EVs, the battery size and the hourly EV demand are predefined in the models and there is no optimisations of vehicle or battery investments in the models. The implementation of EVs includes the possibility to analyse prescribed strategies, such as a delay of the charging time of the passenger EVs and V2G strategy. Hence, the freedom of the electricity system to charge the passenger EVs is constrained to, for example the availability of charging strategies, battery storage capacity, and transportation demand patterns. The embedded modelling of EVs in Paper III, includes (i) EV impact on new investments in generation capacity, (ii) EV impact on optimal operation of the electricity system including cross-border trading of electricity, and (iii) comparing different EV charging alternatives, as well as ERS. In Paper III, passenger EV transportation demand is represented by a variety of assumed daily driving demand profiles corresponding to individual vehicles instead of one aggregated demand profile for the entire vehicle fleet. In this work, assumptions of passenger traveling patterns are based on data from GPS measurements of 429 randomly chosen gasoline and diesel vehicles conducting 107 910 trips between 2010 to 2012 in the region of the City of Gothenburg (see [24, 54] for more details). A clustering method called K-means [55] has been used to represent the hourly traveling demand of passengers with 200 1-day profiles out of 12 400 measured weekdays, where each day gets a weighting factor. The profile and driving distance of the 200 days together matches the profile and the distance of the aggregated fleet. These 200 hourly demand profiles make it possible to include the individual traveling patterns of the vehicles in a more representative way in the optimisations models. Thereby, compared to previous works in literature, this results in a more detailed way to investigate the impact of V2G on investment in new generation capacity, operation of the electricity system and the integration of vRE.

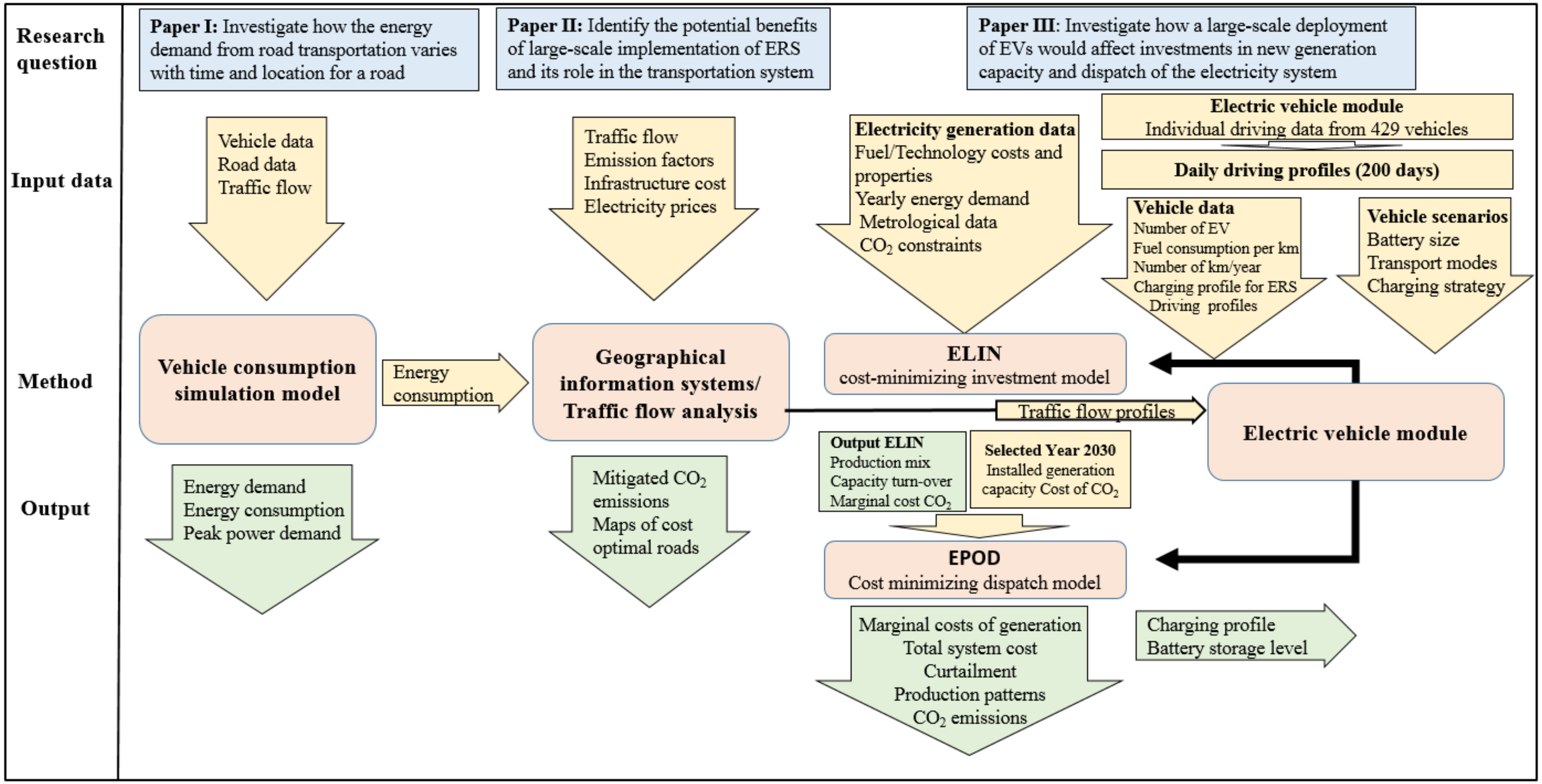

Figure 2. Connection between research questions, input and output data and models used in this thesis

CHAPTER 4

Main findings and Discussion

4.1 The role of electric road systems

In the current national infrastructure and transport plans for Norway and for Sweden, ERS is not emphasized as part of the transport system [6, 56]. However, ERS are getting an increased interest in, for example Sweden, Norway and USA, and an important question to investigate is to what extent ERS can play a role in a transport sector with emission restrictions. All three papers in this work tries, from different angels, to investigate the electricity system impact of ERS and highlight the benefits and drawbacks with a large-scale implementation. In Paper I, we show that a road with the characteristics of the Norwegian E39 exhibits large variation in the spatial and time distributions of its energy and power demands. ERS will add a direct load to the current load profile, which will add demand to hours with high net load. Paper I concludes that the power demand for the dimensioning hour (peak hour) of the regional electricity system could be increased by 1–2% if static charging or ERS is applied on E39 and with today's traffic volume. If all the main roads in Norway were equipped with ERS, the corresponding peak power increase is ~7%, assuming that all traffic on those roads make use of the ERS infrastructure for direct powering, i.e. not for recharging of any onboard batteries. Thus, if also recharging would take place the power increase can become significantly larger. For example, if 20–50% of the light vehicles on E39an are also charging when driving, that gives an increase of the peak power demand by 1 GW. In Paper III, we use the load profile for ERS from Paper I and modelled the Scandinavian and German electricity system with a large-scale implementation of ERS. All truck and buses were assumed to use ERS, and passenger cars were using ERS only for the distance that cannot be covered by the battery range. The results from the modelling of V2G and ERS in Paper III, show that the need for peak power will decrease, not increase, compared to a scenario without EVs, if V2G of passenger vehicles is allowed to increase system flexibility. As mentioned previously, if no V2G is applied, the ERS would then increase peak of the net load curve in Scandinavia with approximately 25 GW in Year 2030, which corresponds to an increase of the net load with 20%.

In Paper II, we found that installation of ERS on all the European (E) and National (N) roads in the two countries would potentially cover more than 60% and 50% of the traffic and CO_2 emissions from all heavy and light vehicles, respectively. Large-scale implementation of ERS on 25% of the E- and N-road lengths in Norway and Sweden (approximately 6,800 km) would require a total investment of 2.7–7.5 billion $€_{2016}$, assuming an investment cost of 0.4–1.1

M€$_{2016}$ per kilometre [23, 38, 39, 57]. The profitability of building an ERS depends of course on the cost of alternative drive trains and fuels, although the results of the present study reveal that for roads with high traffic volumes (ADT of >1,000 vehicles), the total driving cost per km does not seem to be an issue for roads with high ADT, as compared to the alternative solutions. Light vehicles appear to be important for bringing down the cost per vehicle kilometre. However, as concluded in Paper III, the passenger vehicles can cover most of the preferred distances with even a small battery, and thus the need of an ERS for passenger vehicles is limited to few trips assuming present traveling patterns. The role of large-scale implementation of ERS in a future transport sector depends to large extent also on many other factors such as: (i) development of battery technologies, (ii) development of technology for ultra-fast charging, (iii) future policy and investment climate for making decisions on costly infrastructure investments, and (iv) bioenergy potential and allocation. There could also be other technical obstacles to building ERS that has not been included in the three papers. For example a new infrastructure needs to be coordinated with other countries as many of the trucks are driving international routes that in the case of ERS would require common standards. It takes also time to build new infrastructure and it must be profitable to use the ERS network also for parts of the individual yearly driving distance.

4.2 Impact of electric transport on the electricity system

The model results from Paper III, shows that a new demand from an electrified transport sector in Scandinavia and Germany are mainly met by an increase in generation from wind power and traditional base load, the latter with high investment costs and low running costs, such as nuclear power, coal with CCS, biomass condense or biogas CCGT.

Figure 3 shows the distribution of investment in new capacity in Scandinavia and Germany from the investment model (ELIN) year 2020-2050 assuming without EV (S1) and different integration scenarios of EVs (S2-S12). The scenarios S2 to S12 represent different deployment level of EVs, battery sizes, CO_2 emission target by 2050 and electrification strategies. The different scenarios are described in detailed in Paper III. Electricity from wind power increases with 7-25% in the EV scenarios with V2G compare to the scenario without EV, which is slightly more than the increase in demand from EVs. The curtailment of wind power is reduced by 20-45% compared to a scenario without EVs. The EV batteries can substantially help to reduce the need for peak power capacity in the system (a reduction of more than 90%) by discharging back to the grid, as seen in Figure 3. The value of investing in solar power is reduced due the fact that in Northern Europe, with poor conditions for solar power, solar power is mainly used to meet daytime peak load. Under the conditions in Scandinavia and Germany, solar power competes with EVs to provide variation management and the modelling shows that it is less expensive to meet the peak power demand with charging and discharging the EVs than with solar power in Germany. However, there is no cost assigned to the electricity system for using the vehicle batteries for *V2G*.

The introduction of EVs helps smoothen the net load curve, which gives more room for base load as mentioned previously. None of the model runs allow new investments in nuclear power. As seen in Figure 3, assuming a CO_2 cap of 93% reduction by 2050 compare to 1990 in the EV scenarios S2-S9 and S11-S12, gives an increase investment from coal with CCS compared to without EVs (S1). The additional coal with CCS is run as a base load with close to 7500 full load hours in the dispatch model for Year 2030. In scenario S10, with a tighter CO_2 cap by 2050 (i.e. 99% emission reduction by 2050 compare to 1990) instead more biomass (both biomass condense and biogas CCGT) together with CCS lignite co-fired with biomass are used as base load to cover some of the increased demand from EVs, as seen in Figure 3.

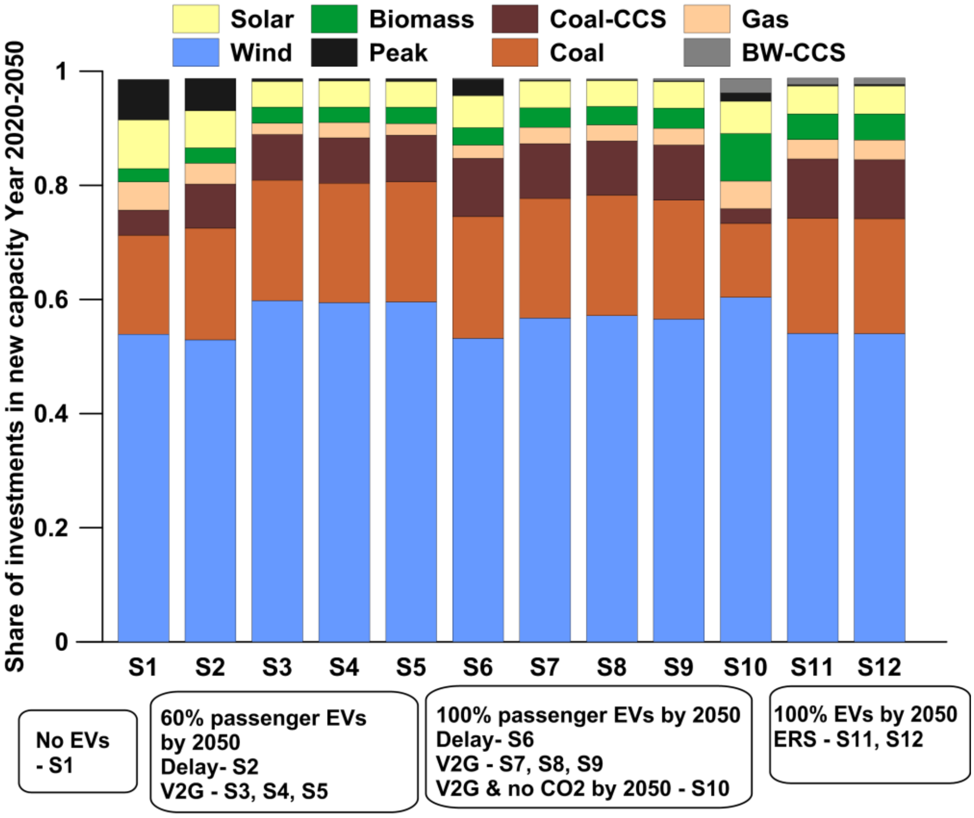

Figure 3. The share of investment in new capacity in Scandinavia and Germany Year 2020-2050 assuming without EV (S1) and different integration scenarios of EVs (S2-S12). EV= electric vehicles; CCS = carbon capture and storage.

The amount of electricity that is traded between regions increases with 1% to 44% depending on the EV scenario compared to without EVs. An increase in trading occurs in order to use the potential of the vehicle batteries providing flexibility for the system. Thereby, the results show that trading and *V2G* can complement one another in order to handle high volume of vRE in the electricity system.

There has been an ongoing debate during the last years about the climate impact of the production of batteries and the usage of EVs. It is obvious that electrification of the transportation sector assumes a cap on emissions from the electricity generation sector if to result in large emission reductions. This is confirmed by the model results of this work which show that with a cap on CO_2, the additional demand from an electrified transport sector are mainly met by an increase in the generation from wind power. The savings in CO_2 emission, when switching from fossil fuels to electricity in the transport sector, is close to 100% for all EV scenarios investigated. The CO_2 emissions in Year 2030 from the electricity used for all road transport in Scandinavia and Germany are less than 0.02 Mt CO_2 per year, which should be compared with the emissions from burning fossil fuels of more than 136 Mt CO_2. In order to do increase the share of renewable electricity generation, different policy instrument need to be used, such as the EU Emission Trading Scheme (EU-ETS), although this is likely to need a reformation in order to drive up the price of emission allowances to make cost to emit CO_2 sufficiently high. Figure 4 shows the price on CO_2 extracted from the ELIN-model for four different scenarios: without EVs; 60% passenger EVs by 2050; 100% passenger EVs by 2050; and 100% passenger EVs and 100% ERS for trucks and buses by 2050. As seen in Figure 4, to keep the CO_2 emissions below the given cap including a new load from EVs, a higher CO_2 price is induced, than in the scenario without EVs, leading to a less carbon intensive technology mix in the system.

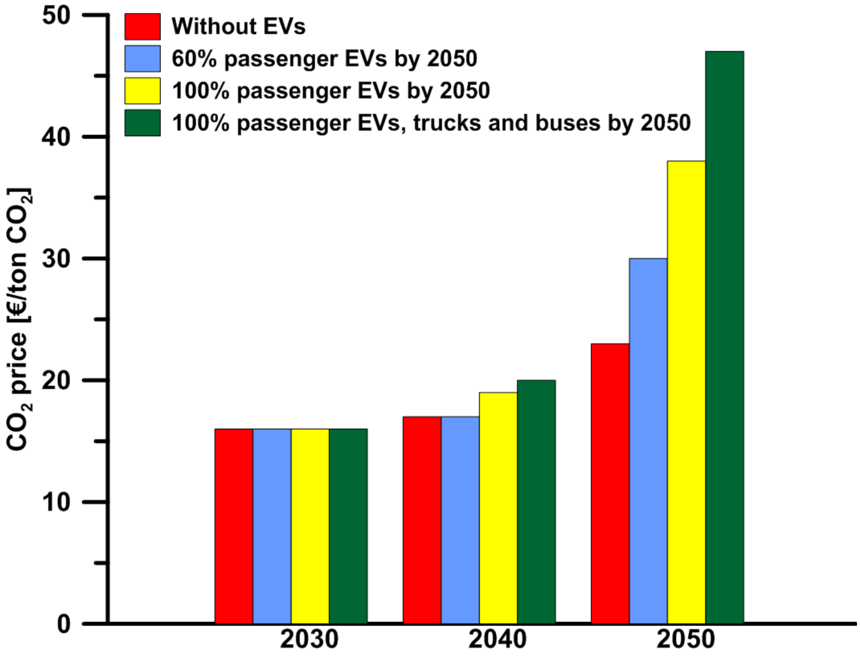

Figure 4. The price on CO_2 for four different scenarios: without EVs; 60% passenger EVs by 2050; 100% passenger EVs by 2050; and 100% passenger EVs + ERS for trucks and buses by 2050.

4.3 Electric vehicles for variation management

The different options for electrification of road transport vary greatly in terms electricity load profile and opportunities for variation management provision. The efficiency and the annual electricity demand resulting from the electrification options also differ greatly. This is highlighted in Paper I. EVs with static charging or ERS exhibit a high-level efficiency from grid to wheels of approximately 73-77%. If instead electricity was used to produce hydrogen or electrofuels (i.e. a synthetic hydrocarbons), the efficiency from grid to wheels for hydrogen and electrofuels will only be 24% and 17%, respectively, which is substantially less than using electricity directly. Figure 5 shows the electricity demand for road transport in Scandinavia for different electrification strategies assuming an EV deployment level of 60% by 2030, 80% by 2040 and 100% by 2050. A full electrification of road transport by 2050 in the Scandinavian countries using hydrogen would increase the electricity demand with more than 100%, while direct use of electricity would increase the demand with approximately 25%. However, it is not obvious that indirect electrification of transportation is less advantageous than direct electricity

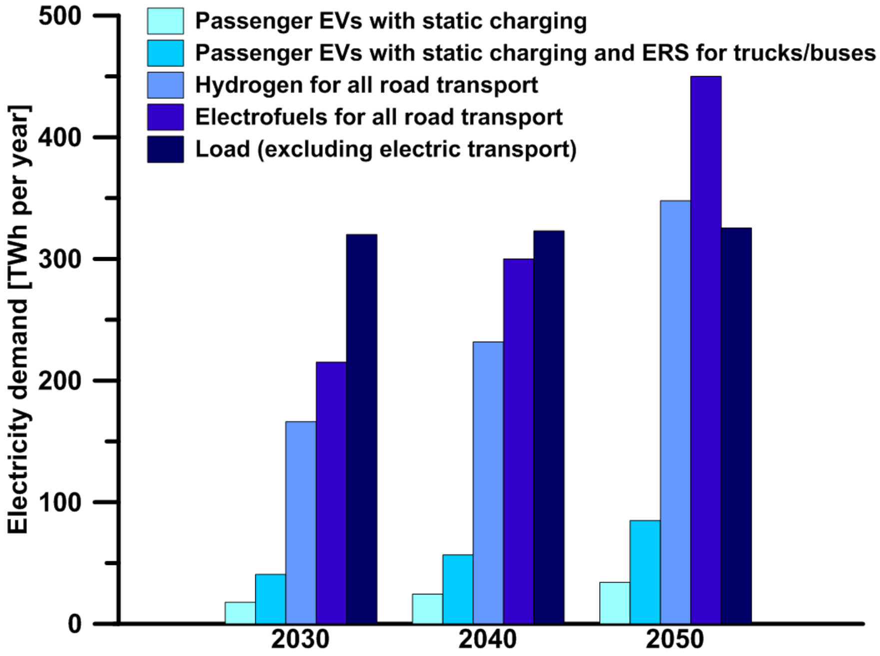

Figure 5. The electricity demand assuming an electrification of the road transport sector in Scandinavia using different electrification strategies.

use, since hydrogen and/or electrofuels offer possibilities of energy storage as well as these can be produced during periods of excess electricity generation. In Paper III, we investigate further how a massive deployment of EVs using V2G and ERS affects investments in new generation capacity and the potential role of EVs in integration of vRE in the Scandinavian and German electricity system. We also investigate different charging strategies (V2G and a Delay of the charging time), as well as, different battery sizes. Figure 6 shows the net load (i.e. load minus wind and solar generation), the net load including also the load from V2G and ERS, and the charging and discharging back to the electricity grid for one week in February in Scandinavia. As seen in Figure 6, the passenger EVs are discharged to the grid when the net load is high, which reduces investments need in peak power capacity. The amount of discharging ranges from 31 to 48 TWh in Year 2030 for the Scandinavian countries and Germany. This number is small compared to the total generation of approximately 900 TWh per year, although it gives a flexibility to the system which is important for reducing peak power demand and curtailment of wind power. For example, passenger EVs will smoothen the net load curve in the Scandinavian and German electricity system so that the hour with maximum net load is reduced with 9 GW (from 127 GW to 118 GW) if V2G is applied. With the Delay strategy (and no V2G), the peak net load will instead be reduced with 2 GW. ERS will on the other hand, as seen in Figure 6, enhance the current net load assuming the current traveling patterns. If no V2G is applied, the ERS would then increase peak in the net load curve with 25 GW in Scandinavia and Germany.

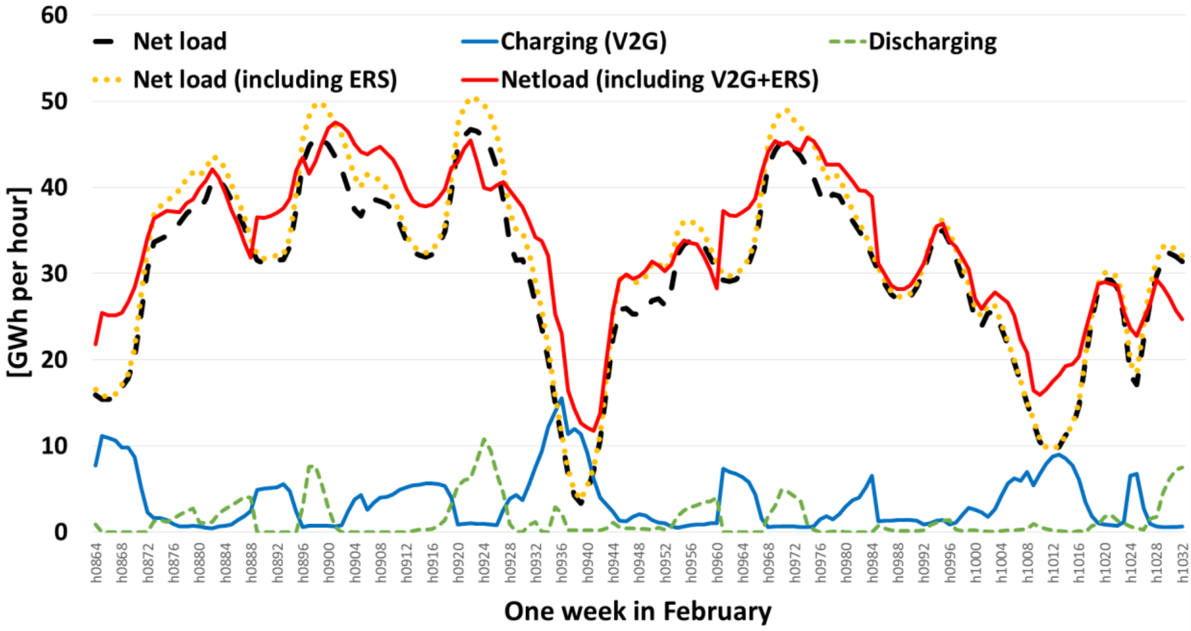

Figure 6. Net load (i.e., load minus wind generation), net load including electric road systems (ERS) for trucks and buses, and the load from extra charging used for discharging and discharging for one week in February in Scandinavia.

In the modelling in Paper III, we have shown that this enhancement of the net load could be handled by discharging EV batteries to avoid an increase in peak power investments. A major part of the static charging occurs during night time to avoid correlation with the net load. Further, the discharging occurs mainly during the peak demand hours in the morning and afternoon. The time of charging and discharging of passenger EVs are heavily influenced by the load curve from other sectors. However, the vehicle batteries can only provide diurnal storage in the model. In order to increase the penetration level of wind power further, diurnal storage from EV batteries is not enough, since there is variations in wind power on longer time scales calling for weekly harmonization measures. In the Scandinavian and German region, transmission capacity and hydro power is to a large extent handling those variations. Batteries has in other studies proven to be too expensive to invest in to handle weekly storage of wind power [58]. Yet, towards mid-century there may be potential role for spent EV batteries, which are too capacity degraded to be used in vehicles offering a second-life as stationary batteries. In the future, autonomous driving and modal systems might change part of the transporting of goods to night time, which will smoothen the load curve from trucks and buses. Other factors that might impact the way we transport goods and persons is urbanization, globalization, working hours, etc. which might have an impact on the charging profile and thereby also on the possibility to use V2G to reduce the need for peak power and handle more vRE in the electricity system.

In the ELIN and EPOD models, the option for handling variability in net load output is trade, charging and discharging EV batteries, curtailment of vRE, storage of hydro power and ramping of thermal power plants. Hydrogen and electrofuel production have the possibility to better distribute the electricity demand for transport both geographically and in time by storing the fuel. Producing a fuel that could be stored for several weeks and distributed with a constant flow could potentially provide other flexibility services than the vehicle batteries, and thereby help further with integrating more wind power. However, an analysis of this is outside the scope if this work.

It is not obvious that the results presented in Sections 4.2 and 4.3 are representative for other regions than those investigated in this work. For example, each region has its special energy mix, such as the relatively large share of reservoir hydropower in Scandinavia. Hydropower is a renewable energy source that can be used for storage over a large range of time scales up scales, including seasonal storage. Thereby, the flexibility of hydropower facilitates the integration of EVs in the system. Another region, with good solar conditions and no/small shares of hydropower, such as Spain, has different conditions for the integration of EVs.

This work shows the benefit of integrating an electrified transport sector using V2G charging. A so called “smart-grid” will most likely be needed when implementing V2G on a large scale since not only a power flow is needed between the vehicle and the grid, but also a flow of information. V2G is currently being tested in different pilot projects with the aim to improve the communication with the vehicle and the grid infrastructure that enables EVs to determine when to ultimately charging, and discharging the batteries. There are several benefits and challenges with V2G for different actors. Table 4 gives a summary of the advantages and drawbacks for the electricity system operator and the EV owner with uncontrolled charging (i.e. charging directly upon home coming), controlled charging through a Delay charging strategy, a V2G strategy, and ERS/dynamic charging. Two of the main challenges with V2G are the shortening of battery lifetime due to increased number of cycles and deeper cycling of the battery and the need for cyber-security as the information flow increases drastically when the vehicle is connected. Another issue is the practical implementation of the V2G since, for the private vehicle owners, the economic benefit is relatively small compared to the system benefit. Also, the private consumer needs in some way to be paid for the acceleration of the ageing of the battery or the connection to the network needs to be mandatory for all EV owners.

Table 4. Summary of the advantages and drawbacks with the different charging alternatives for the electricity system and the electric vehicle owner.

	Advantages	**Drawbacks**
Uncontrolled charging	***EV owner*** ✓ User friendly ✓ No extra cycling of the vehicle battery ***System operators*** ✓ Easy to implement ✓ Additional income from a new demand	***EV owner*** ✗ Higher electricity bill ***System operators*** ✗ Peak power increase ✗ Needs to reinforce the grid ✗ Increase CO_2 emissions and/or total system cost
Delay of the charging	***EV owner*** ✓ Lower electricity bill than uncontrolled charging ***System operators*** ✓ Additional income from a new demand ✓ Smoothening of the load profile ✓ Less investments in peak power than uncontrolled charging	***EV owner*** ✗ More complex implementation ✗ ICT technologies required ✗ Willingness to participate ***System operators*** ✗ Cyper-security
Vehicle-to-grid (V2G)	***EV owner*** ✓ Lower electricity bill than a *Delay* of the charging ***System operators*** ✓ Additional income from a new demand ✓ Better integration of wind energy at off-peak hours than *Delay* or ERS strategy ✓ Substantial peak power reduction ✓ Less investment in network/transmission ✓ Reduce the total system cost	***EV owner*** ✗ Very complex products ✗ ICT technologies required ✗ Willingness to participate ✗ Degradation of the battery ***System operators*** ✗ Cyper-security ✗ Energy losses in grid-battery-grid transmissions
Electric road system	***EV owner*** ✓ Smaller battery ✓ Less range anxiety ***System operators*** ✓ Additional income from a new demand	***EV owner*** ✗ Additional equipment on the vehicle ✗ Large network of ERS might be needed ***System operators*** ✗ Increase of the demand during peak hours ✗ Less battery capacity available for V2G

4.4 Reflections on the data and methods used

One obvious limitation with the types of optimization models used in Paper III is the perfect foresight with no uncertainty on, for example, future costs, traveling patterns and demand, new technology developments, bioenergy potential. However, the applied electricity system models are not developed to predict the future but rather designed to give important insights and a deeper understanding of the challenges and possibilities associated with transforming the electricity system by testing different assumptions. In this work we have chosen to minimize the total system cost of the electricity system. Other possible objectives would be to minimize the vehicle owner cost, maximize ancillary service provision, minimize emissions, etc., which might give other conclusion on the opportunities for integrating EVs in the electricity system.

In the modelling of the passenger EV fleet, real driving data has been used instead of data derived from national surveys on travel habits (as most previous studies use). Travel-habit surveys do not provide information down to the level of single trips. The EV driving patterns are represented in the models by 200 measured daily driving patterns. This is made in order to capture the spread in individual driving patterns to a better extent than just using an aggregated fleet. Approximately 200 days out of 12 400 weekdays were needed at least so that the 200 days together matched the profile and driving distance of the aggregated fleet. A clustering method called K-means [55] has been used to choose the hourly traveling demand of 200 days, where each day gets a weighting factor. However, running the model with 200 days is computational heavy. We have also tested to run the model with an aggregated fleet instead (i.e. no individual driving patterns included). The conclusions from the different approaches were shown to be approximately the same for Scandinavia and Germany. The main drawback by using the method with daily driving patterns for several days or an aggregated fleet is that it is not possible to store of electricity in the vehicle batteries between days. A better method would be to include the driving patterns for a large set of individual vehicles measured during a whole year, but that type of data is not presently available.

The vehicle energy consumption model developed and used in this work has several limitations, with the most important being that: (i) an average drivetrain efficiency is used; (ii) no speed reductions are assigned for sharp turns or traffic congestion; and (iii) an average vehicle type is assumed for each vehicle category. Other factors that also may impact the results from the vehicle energy consumption model, although they are not varied in a sensitivity analysis, are driving behavior, slippery road, tire pressure, weather, and the powertrain configuration. Cappiello et al. [52] has estimated those parameters to impact the results within 10%.

CHAPTER 5

Main conclusions

In this work, we have shown that the electricity demand from EVs are mainly met by an increase in generation from wind power and base load in the form of coal power with CCS. A V2G integration of passenger EVs will substantially reduce the need for peak power capacity in the system. Electrification of the transport sector including both V2G of passenger EVs and ERS of trucks and buses could be achieved without increasing the need for peak power or the electricity cost. If using an indirect strategy for electrification of transportation via for instance production of hydrogen or synthetic diesel, the annual electricity demand would increase more than four times compared to static charging or using an ERS, albeit with the increased possibility to distribute such demand both spatially and over time. Our results also show that a highway, like the E39 in Norway, show large variations in both spatial and time distributions of its energy and power demands. However, we have also shown that with some vehicle batteries, the electricity system can at an hourly time scale handle these variations. Installation of ERS on all the E- and N-roads in Sweden and Norway would potentially cover more than 60% of the energy demand from all heavy traffic and 50% of the light vehicle traffic. However, already an implementation of ERS of 25% of the total E- and N-road length could connect some of the larger cities in Norway and Sweden with ERS, covering a large part of traffic demand.

CHAPTER 6

Further research

No study has so far used an optimization model that includes a combination of the different ways of electrifying the transport sector (i.e. V2G of passenger vehicles, production of hydrogen and production of electrofuels for transport purposes). Such a study could thus explore an electricity system that includes all these methods of decarbonizing the transport sector and use an electricity system model to optimize according to what is most cost-efficient from an electricity system point of view. Other variation management strategies, such as stationary batteries or moving household load would also be interesting to include in the optimization models in order to investigate how they complement or compete with the flexibility advantages of passenger EVs.

V2G will potentially increase the degradation rate of batteries, due to more frequent and deeper cycling. Further research is needed in order to evaluate the cost of using EVs with V2G to reduce investments in peak generation compared to the avoided investment costs or the cost of deploying other peak shaving strategies. In this work, we conclude that even a small vehicle battery size, when aggregated, will generate a large battery capacity compared to what is needed to reduce the demand for peak power in Scandinavia and Germany. However, more studies are needed to evaluate the possibility to use mainly secondary-life batteries for storing purposes. Additionally, the results presented in Paper III are system specific, i.e. only valid for the region investigated, which, as pointed out above, has substantial amounts of reservoir hydro power, favourable conditions for wind power and less good conditions for solar power. Regions with different conditions for solar, wind and hydro will obviously also differ with respect to how EVs can be integrated in the electricity system. Thus, the modeling of this work also needs to be carried out for other regions.

This work applies driving pattern from 200 days taken from real-time daily driving patterns measured in one region in Västra Götaland. However, there are several parameters that are uncertain about using these type of data to investigate the integration of EVs in a future electricity system with more renewable energy. The development of autonomous vehicles might result in a substantial change in the way vehicles are used in the future. To what extent we will own our vehicles in the future might also heavily impact driving patterns and therefore also the results presented in Paper I-III. A study investigating also more disruptive technology developments that changes the traveling pattern/distance of the vehicles would complement the results presented in this work.

References

[1] Stocker T. Climate change 2013: the physical science basis: Working Group I contribution to the Fifth assessment report of the Intergovernmental Panel on Climate Change: Cambridge University Press; 2014.

[2] UNFCCC. Paris Agreement. United Nations; 2015.

[3] International Energy Agency. Global EV outlook - 2 million and counting. 2017.

[4] European Commission. WHITE PAPER Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system. Brussels 2011.

[5] Johansson T. Fossilfrihet på väg SOU 2013: 84. Stockholm, Statens offentliga utredningar (1000 s); 2013.

[6] Fridstrøm L, Alfsen KH. Vegen mot klimavennlig transport2014.

[7] Brynolf S, Taljegard M, Grahn M, Hansson J. Electrofuels for the transport sector: a review of production costs Renewable & Sustainable Energy Reviews. 2017.

[8] FABRIC. Feasibility analysis and development of on-road charging solutions for future electric vehicles. Available: http://www.fabric-project.eu/. [Accessed: 2016-03-19].

[9] Viktoria Swedish ICT. Slide-in Electric Road System. Conductive project report, phase 1. 2013.

[10] Global VG. Volvo global news - The road of tomorrow is electric. Available: www.news.volvogroup.com/2013/05/23/the-road-of-tomorrow-is-electric [Accessed 2016-03-19].

[11] Siemens. eHighway. Available: http://www.siemens.com/press/en/feature/2015/mobility/2015-06-ehighway.php [Accessed 2016-03-19].

[12] Souza GM, Victoria RL, Joly CA, Verdade L. Bioenergy & sustainability: bridging the gaps. SCOPE, Paris ISBN. 2015:978-2.

[13] Grahn M, Azar C, Williander M, Anderson JE, Mueller SA, Wallington TJ. Fuel and vehicle technology choices for passenger vehicles in achieving stringent CO2 targets: Connections between transportation and other energy sectors. *Environmental science & technology*. 2009;43:3365-71.

[14] Grahn M, Azar C, Lindgren K. The role of biofuels for transportation in CO 2 emission reduction scenarios with global versus regional carbon caps. *Biomass and bioenergy*. 2009;33:360-71.

[15] Taljegard M, Göransson L, Odenberger M, Johnsson F. Spacial and dynamic energy demand of the E39 highway–Implications on electrification options. *Applied Energy*. 2017;195:681-92.

[16] Göransson L, Karlsson S, Johnsson F. Integration of plug-in hybrid electric vehicles in a regional wind-thermal power system. *Energy Policy*. 2010;38:5482-92.

[17] Hedegaard K, Ravn H, Juul N, Meibom P. Effects of electric vehicles on power systems in Northern Europe. *Energy.* 2012;48:356-68.

[18] Lund H, Kempton W. Integration of renewable energy into the transport and electricity sectors through V2G. *Energy policy*. 2008;36:3578-87.

[19] Verzijlbergh R, Martínez-Anido CB, Lukszo Z, de Vries L. Does controlled electric vehicle charging substitute cross-border transmission capacity? *Applied Energy*. 2014;120:169-80.

[20] Sohnen J, Fan Y, Ogden J, Yang C. A network-based dispatch model for evaluating the spatial and temporal effects of plug-in electric vehicle charging on GHG emissions. *Transportation Research Part D: Transport and Environment*. 2015;38:80-93.

[21] Jochem P, Babrowski S, Fichtner W. Assessing CO 2 emissions of electric vehicles in Germany in 2030. *Transportation Research Part A: Policy and Practice*. 2015;78:68-83.

[22] Hadley SW, Tsvetkova AA. Potential impacts of plug-in hybrid electric vehicles on regional power generation. *The Electricity Journal.* 2009;22:56-68.

[23] Boer Ed, Aarnink S, Kleiner F, Pagenkopf J. Zero emissions trucks An overview of state-of-the-art technologies and their potential. Stuttgart, Germany: CE Delft; 2013.

[24] Karlsson S, Kullingsjö L-H. GPS measurement of Swedish car movements for assessment of possible electrification. *Electric Vehicle Symposium and Exhibition (EVS27), 2013 World: IEEE*; 2013. p. 1-14.

[25] Grahn P. Electric Vehicle Charging Impact on Load Profile. Litentiate Thesis. 2013.

[26] Weiller C. Plug-in hybrid electric vehicle impacts on hourly electricity demand in the United States. *Energy Policy*. 2011;39:3766-78.

[27] Hartmann N, Özdemir E. Impact of different utilization scenarios of electric vehicles on the German grid in 2030. *Journal of power sources.* 2011;196:2311-8.

[28] Mullan J, Harries D, Bräunl T, Whitely S. Modelling the impacts of electric vehicle recharging on the Western Australian electricity supply system. *Energy policy*. 2011;39:4349-59.

[29] Park W-J, Song K-B, Park J-W. Impact of electric vehicle penetration-based charging demand on load profile. *Journal of Electrical Engineering and Technology*. 2013;8:244-51.

[30] Vatne Å, Molinas M, Foosnas JA. Analysis of a scenario of large scale adoption of electrical vehicles in nord-trøndelag. *Energy Procedia.* 2012;20:291-300.

[31] Guille C, Gross G. A conceptual framework for the vehicle-to-grid (V2G) implementation. *Energy policy*. 2009;37:4379-90.

[32] Grahn P. Electric Vehicle Charging Modeling Doctoral Thesis, 2014. Stockholm, Sverige.

[33] Darabi Z, Ferdowsi M. Aggregated impact of plug-in hybrid electric vehicles on electricity demand profile. *IEEE Transactions on Sustainable Energy*. 2011;2:501-8.

[34] Stamati T-E, Bauer P. On-road charging of electric vehicles. *Transportation Electrification Conference and Expo (ITEC), 2013 IEEE*; 2013. p. 1-8.

[35] Wu HH, Gilchrist A, Sealy KD, Bronson D. A high efficiency 5 kW inductive charger for EVs using dual side control. *IEEE Transactions on Industrial Informatics.* 2012;8:585-95.

[36] Villa J, Llombart A, Sanz J, Sallan J. Practical development of a 5 kW ICPT system SS compensated with a large air gap. *IEEE International Symposium on Industrial Electronics: IEEE*; 2007. p. 1219-23.

[37] Covic GA, Boys JT, Kissin ML, Lu HG. A three-phase inductive power transfer system for roadway-powered vehicles. I*EEE Transactions on Industrial Electronics*. 2007;54:3370-8.

[38] Olsson O. Slide-in Electric Road System, Conductive project report. Gothenburg, Sweden: Viktoria Swedish ICT; 2013.

[39] Wilson M. Feasibility Study: Powering Electric Vehicles on England's Major Roads. London: Highways England; 2015.

[40] Connolly D. eRoads: A comparison between oil, battery electric vehicles, and electric roads for Danish road transport in terms of energy, emissions, and costs. 2016.

[41] Schill W-P, Gerbaulet C. Power system impacts of electric vehicles in Germany: Charging with coal or renewables? *Applied Energy*. 2015;156:185-96.

[42] Fripp M. Switch: a planning tool for power systems with large shares of intermittent renewable energy. *Environmental science & technology.* 2012;46:6371-8.

[43] Schlachtberger D, Becker S, Schramm S, Greiner M. Backup flexibility classes in emerging large-scale renewable electricity systems. *Energy Conversion and Management*. 2016;125:336-46.

[44] Unger T, Odenberger M. Dispatch modelling of the European electricity supply: the EPOD model. Methods and models used in the project pathways to sustainable european energy systems, Mölndal. 2011:97-101.

[45] Odenberger M, Unger T, Johnsson F. Pathways for the North European electricity supply. *Energy Policy.* 2009;37:1660-77.

[46] Göransson L, Goop J, Unger T, Odenberger M, Johnsson F. Linkages between demand-side management and congestion in the European electricity transmission system. *Energy*. 2014;69:860-72.

[47] Sandberg T. Heavy truck modeling for fuel consumption simulations and measurements: Division of Vehicular Systems, Department of Electrical Engineering, Linköping University; 2001.

[48] Hammarström U, Eriksson J, Karlsson R, Yahya MR. Rolling resistance model, fuel consumption model and the traffic energy saving potential from changed road surface conditions. 2012.

[49] Guzzella L, Sciarretta A. Vehicle propulsion systems: Springer; 2013.

[50] Björnsson L-H, Karlsson S. The potential for brake energy regeneration under Swedish conditions. Applied *Energy*. 2016;168:75-84.

[51] Ross M. Fuel efficiency and the physics of automobiles. *Contemporary Physics*. 1997;38:381-94.

[52] Cappiello A, Chabini I, Nam EK, Lue A, Abou Zeid M. A statistical model of vehicle emissions and fuel consumption. Intelligent Transportation Systems, 2002 *Proceedings The IEEE 5th International Conference on: IEEE; 2002*. p. 801-9.

[53] Nyholm E, Goop J, Odenberger M, Johnsson F. Solar photovoltaic-battery systems in Swedish households–Self-consumption and self-sufficiency. *Applied Energy*. 2016;183:148-59.

[54] Kullingsjö L-H, Karlsson S. The Swedish car movement data project. *Proceedings to EEVC* Brussels, Belgium, November 19-22, 20122012.

[55] MacQueen J. Some methods for classification and analysis of multivariate observations. *Proceedings of the fifth Berkeley symposium on mathematical statistics and probability*: Oakland, CA, USA.; 1967. p. 281-97.

[56] Johansson A, Carlén B, Mellin A, Pyddoke R. Förslag till Nationell plan för transportsystemet 2014–2025: kvalitetsgranskning av underlaget med fokus på samhällsekonomi: Statens väg-och transportforskningsinstitut; 2013.

[57] Olsson O. Slide-in Electric Road System, Inductive project report. Gothenburg, Sweden: Viktoria Swedish ICT; 2013.

[58] Johansson V, Thorson L, Göransson L. A quantitative method for evaluation of variation management strategies for integration of renewable electricity generation. *16th Wind Integration Workshop*. Berlin, Germany2017.