

THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Electrification of Road Transportation - Implications for the
Electricity System

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To my family

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ABSTRACT

It is incumbent upon the transport sector to reduce its CO₂ emissions by replacing fossil fuels with low-carbon alternatives. Suggested strategies include electrification of the road transport sector through the use of electric vehicles (EVs) with static charging, electric road systems (ERS), and the use of electricity to produce fuels. Electrification of the transport sector will create new electricity load profiles that depend on the time of consumption and the amount of electricity used in EVs. EVs can also contribute with flexibility to the electricity system – a feature that will be of increasing importance with a higher share of variable renewable electricity (VRE) in the electricity system.

The overall aim of this thesis is to investigate how electrification of the transport sector affects the electricity system with respect to the demands for energy and power on different geographical and temporal scales. In this work, a vehicle energy consumption model is developed to estimate the variations of the energy and power demands according to time and location for the transportation work on a highway (the E39 in Norway). Furthermore, charging of passenger EVs and ERS is included in several electricity system models, to investigate how EVs influence investments in electricity generation capacity and VRE integration.

Our results, using the Norwegian E39 highway as a case study, indicate that electrification of the road transport entails large variations in the spatial and time distributions of the energy and power demands along the road. Installation of ERS on all the European (E) and National (N) roads in Sweden and Norway would encompass more than 50% of the national vehicle traffic. Implementation of ERS on 25% of the total E- and N-roads (~6,800 km) would be sufficient to cover 70% of the traffic on these roads and would connect most of the larger cities in Norway and Sweden through ERS.

We conclude that with a cap on CO₂ emissions from the European electricity system, which corresponds to 99% reduction by 2050, the demand from EV is mainly met by an increase in generation from VRE, e.g., solar power in regions with adequate solar conditions and wind power in regions with good wind conditions. Re-charging of EVs directly subsequent to driving or ERS will require increased investments in peak power (by up to ~15%), as well as, in thermal power plants compared to optimised EV charging. The model results show that an optimised charging strategy with vehicle-to-grid (i.e., discharging electricity back to the grid) that minimises the cost of the electricity system can: (i) avoid investments in other storage technologies; (ii) reduce the need for peak power capacity in the system; and (iii), for some regions, stimulate increased shares of VRE (mainly solar power), as compared to direct charging.

This thesis also shows that it is important to represent the heterogeneity of individual driving patterns in electricity system optimisation models when the charging infrastructure is limited to the home location and a battery capacity of 30 kWh or less per vehicle.

Keywords: *highway E39; electric vehicle; energy system modelling; electric road systems; CO₂ emissions; variable renewable electricity*

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Göteborg, September 2019
Maria Taljegård

List of Publications

This thesis is based on the following publications, which are referred to in the text by their Roman numerals:

- 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. (2019) Large-scale implementation of electric road systems: Associated costs and the impact on CO₂ emissions. *International Journal of Sustainable Transportation*, pp.1-14.
- III. Taljegard, M., Göransson, L., Odenberger, M., & Johnsson, F. (2019) Impacts of electric vehicles on the electricity generation portfolio - A Scandinavian-German case study. *Applied Energy*, 235, 1637-1650.
- IV. Taljegard, M., Göransson, L., Odenberger, M., & Johnsson, F. (2019) Electric vehicles as flexibility management strategy for the electricity system - A comparison between different regions of Europe. *Energies*, 12(13), 2597.
- V. Taljegard, M., Walter, V., Göransson, L., Odenberger, M., & Johnsson, F. Impact of electric vehicles on the cost-competitiveness of generation and storage technologies in the electricity system. *Submitted for publication*.
- VI. Taljegard, M., Göransson, L., Odenberger, M., & Johnsson, F. Electric vehicles in electricity systems modeling- aggregated vehicle representation vs. individual driving profiles. *Submitted for publication*.

Maria Taljegard is the principal author of **Papers I–VI** and conducted all the modelling and calculations for these papers. Professor Filip Johnsson (who is the main academic supervisor) and Doctor Mikael Odenberger contributed with discussions and editing of all five papers. Doctor Lisa Göransson contributed with discussions and editing of **Papers I, III, IV-VI** as well as method developments in **Paper III** and **VI**. Ludwig Thorson contributed with the geographical information system analysis in **Paper II**. Viktor Walter contributed with analysis, discussions and editing of **Paper V**.

List of other publications by the author not included in the thesis

The following publications have been produced by the author but are not included in the thesis:

- i. Jelica, D., Taljegard, M., Thorson, L., & Johnsson, F. (2018) Hourly electricity demand from an electric road system – A Swedish case study. *Applied Energy*, 228, 141-148.
- ii. 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.
- iii. 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. *World Electric Vehicle Journal*, 8 (4), 1008-1019.
- iv. Taljegard, M., Thorson, L., Odenberger, M., & Johnsson, F. (2017) Electric road systems in Norway and Sweden – Impact on CO₂ emissions and infrastructure cost. *IEEE International Transportation Electrification Conference and Expo 2017*. Harbin. China.
- v. Grahn, M., Taljegard, M., & Brynolf, S. (2018) Electricity as an energy carrier in transport – Cost and efficiency comparison of different pathways. *Electric Vehicle Symposium 31*. Kobe. Japan.
- vi. Taljegard, M., von Bonin, M., Ernst, B., Gerhardt, N., & Johnsson, F. (2018) Impact of implementation of ERS on the German and Swedish electricity system. *2nd E-Mobility Power System Integration Symposium*. Stockholm. Sweden.
- vii. 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.
- viii. Brynolf, S., Taljegard, M., Grahn, M., & Hansson, J. (2018) Electrofuels for the transport sector: A review of production costs. *Renewable and Sustainable Energy Reviews*, 81, 1887-1905.
- ix. Hansson, J., Hackl, R., Taljegard, M., Brynolf, S., & Grahn, M. (2017) The potential for electrofuels production in Sweden utilizing fossil and biogenic CO₂ point sources. *Frontiers in Energy Research*, Vol. 5, Issue 4.
- x. 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.

ACRONYMS & DEFINITIONS

ADT	Average daily traffic, i.e., the average number of vehicles passing per day
AGG	Aggregated vehicle profile
BEV	Battery-powered electric vehicle
BW	Fossil fuels co-fired with biomass
CCGT	Closed-cycle gas turbine
CCS	Carbon capture and storage
CHP	Combined heat and power
CO ₂	Carbon dioxide
DDP	Representative daily driving profiles
Direct charging strategy	Re-charging of the EVs directly subsequent to driving
DSM	Demand-side management
E39	European highway 39 in Norway
E- and N-roads	European and National roads
Electrofuels	Carbon-based fuels produced from water and CO ₂ using electricity
Electrification strategies	<i>Direct electrification</i> (i.e., static charging of EVs or ERS) and <i>indirect electrification</i> (i.e., use electricity to produce hydrogen or electrofuels)
ELIN	European electricity system investment model
ENODE	Regional electricity system investment and dispatch model
EPOD	European electricity system dispatch model
ERS	Electric road systems
EV	Electric vehicle (includes BEV and PHEV)
FC	Fuel cell
GPS	Global Positioning System
Greenfield	An empty system as a starting point without generation capacity in place
GT	Gas turbine
H ₂	Hydrogen
Heavy vehicles	All vehicle types weighing >3.5 tonnes or with a length of >5.6 meter
ICE	Internal combustion engine
Light vehicles	All vehicle types weighing <3.5 tonnes or with a length of <5.6 meter
Net-load	The load minus variable renewable electricity generation
NPRA	Norwegian Public Road Administration
O&M	Operation and maintenance
Optimised charging strategy	The charging time of the EV batteries is optimised in order to minimise the electricity system cost of meeting the electricity demand
Optimised with V2G charging strategy	The charging time of the EV batteries is optimised and there is the possibility to discharge the EV batteries to the grid, so as to minimise the electricity system cost of meeting the electricity demand
PHEV	Plug-in hybrid electric vehicle
V2G	Vehicle-to-grid
VMS	Variation management strategy
VRE	Variable renewable electricity
YDP	Yearly driving profiles

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CHAPTER 1

Introduction

Carbon dioxide (CO₂) emissions from fossil fuel combustion represent the largest contributor to the increased radiative forcing of the climate system [1]. The Paris Agreement, which was signed in 2015 by 197 countries, recognizes the primary goal of limiting global warming to well below 2°C above the pre-industrial global annual average temperature [2]. The *2030 Agenda for Sustainable Development*, adopted by all Member States of the United Nations in 2015, calls for a substantial increase in the share of renewable energy in the global energy mix by 2030 [3]. The 17 Sustainable Development Goals constitute an urgent call for action by all countries to, for example, tackle climate change and preserve our oceans and forests.

The transport sector is up to 96% dependent upon fossil fuels, making the sector the least-diversified of all the sectors in terms of global primary energy supply [4]. Since 1990, the CO₂ emissions from transportation have increased globally and within the European Union (EU) by 60% and 20%, respectively [5]. Figure 1.1 shows the trends for CO₂ emissions for different sectors in EU since 1990. The transport sector is the only sector that has increased its levels of emissions between 1990 and 2017. All the other sectors in EU have managed to decrease their CO₂ emissions by at least 20% [5].

The climate goal for the transport sector in the EU is a 65% reduction of CO₂ emissions by year 2050 compared to the level of emissions in 1990 [6]. The corresponding goals for Sweden and Norway are 70% and 40% reductions in emissions by year 2030, as compared to the levels of emissions in 2010 and 1990, respectively [7, 8]. Besides CO₂, there are other strong drivers for reducing our dependence on fossil fuels in the transport sector, for example, reducing air pollution in cities and boosting the security of energy supply.

Strategies to reduce the use of fossil fuels include: (i) implementation of more-energy-efficient vehicles; (ii) selection of modes of transport that have lower CO₂ emissions per person or goods freighted; and (iii) switching to low-CO₂-emitting transport energy carriers (e.g., bioenergy-based liquid and gaseous fuels, hydrogen, and electricity) [9, 10]. The work of this thesis focuses on reducing fossil fuel use by electrifying the road transport sector.

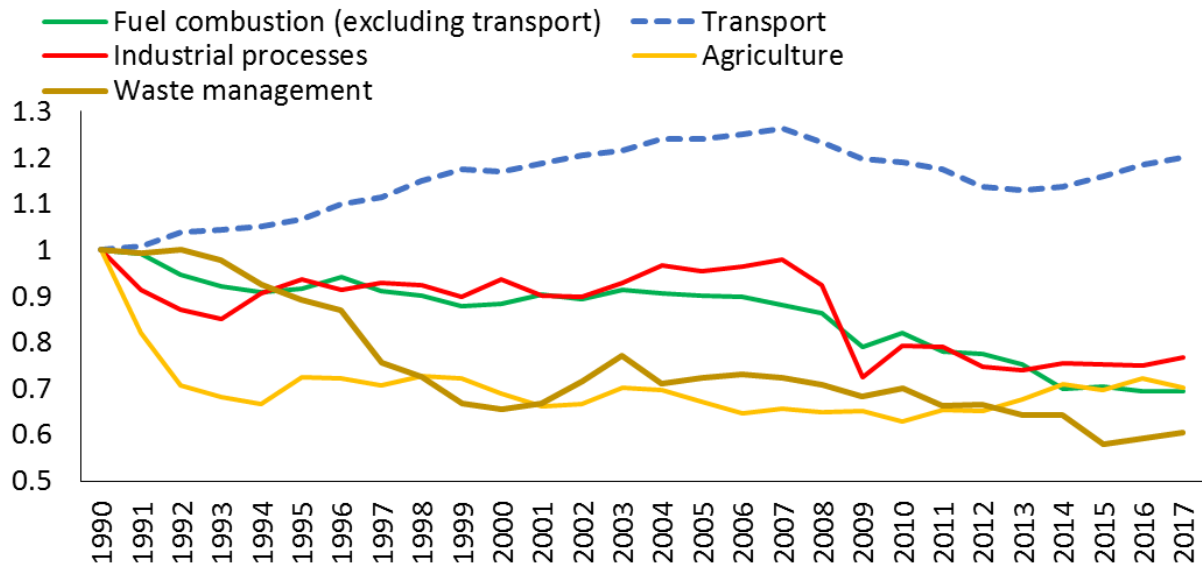


Figure 1.1: Trends for emissions of CO₂ in the European Union in the time period 1990–2017 relative year 1990. Based on data from European Environment Agency published in Eurostat [5].

Figure 1.2 shows the potential primary energy sources, energy conversion technologies, and energy carriers for different transport modes. The global number of electric vehicles (EVs) reached more than 5 million in 2018, following several years of strong growth [11]. In Norway, EVs had a market share of 46% of sold passenger vehicles in year 2018, which was the highest share globally. In all other countries (e.g., Germany, Canada, US, UK, and Sweden), the EV market share of sold passenger cars was less than 10%. Therefore, the total share of EVs in the world is still very low (<0.2% of all passenger vehicles) [11].

Electrification of the transportation sector is typically considered to have a significant role to play in reaching the European [12], as well as the Swedish [9] and Norwegian climate targets [13]. The International Energy Agency (IEA) projects that the number of EVs will increase to 130–250 million globally by 2030 depending on the scenario [11]. In line with this, the electricity demand is predicted by the IEA to increase by 640–1,100 TWh by 2030. This can be compared with approximately 950 million passenger cars in use globally 2015 [14] and the global electricity generation of 25,700 TWh in year 2017 [11]. To enable a transition to EVs, governments have issued policies that are promoting such a development [11].

A major challenge facing the road transport sector in terms of replacing fossil fuels with electricity is the integration of the resulting electricity demand into the electricity system. Together with the foreseen electrification of different industries, this will exert pressure on the grid infrastructure needed to supply the electricity to the EVs. Table 1.1 shows the efficiency values from electricity sources to wheels, as well as the main technical related advantages and challenges associated with the different transport options that apply electricity as the energy conversion technology.

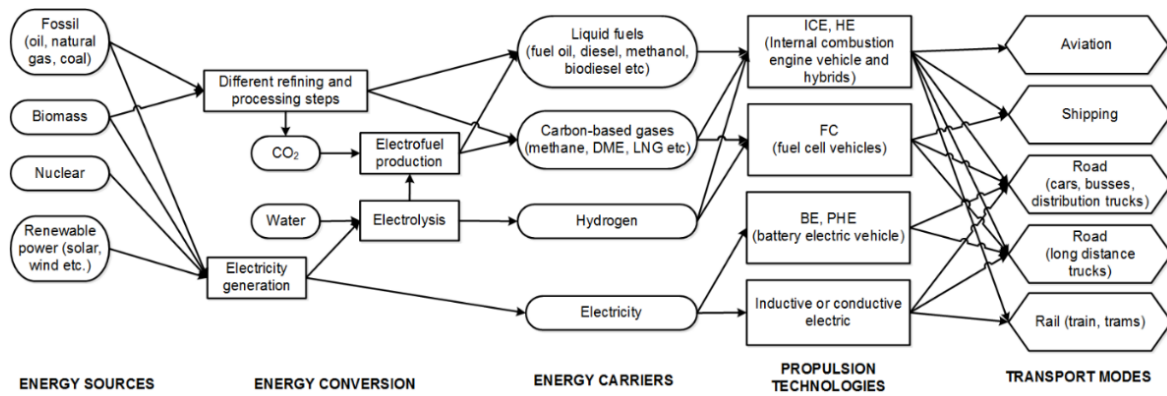


Figure 1.2: Simplified schematic of the primary energy sources, energy conversion technologies, and energy carriers for the different transport modes [15]. ICE, Internal combustion engines; HE, hybrid electric propulsion; FC, fuel cells; BE, battery-powered electric propulsion; PHE, plug-in hybrid electric propulsion.

For vehicles that are mainly powered by on-board batteries, electrification requires a charging infrastructure at home, work and/or in public places. Another option is electric road systems (ERS), which employ dynamic on-road conductive or inductive power transfer while the vehicle is being driven. Yet another option is to use electricity to produce a fuel (such as hydrogen or an electrofuel) that is then used on-board in internal combustion engines or fuel cells. However, it is not obvious which of these choices is optimal for the transport sector when there is a move away from fossil fuels, since each of the alternatives has its own technical related advantages and disadvantages (Table 1.1).

Presently used battery-powered vehicles (BEV) suffer from having a short driving range compared to conventional or fuel cell vehicles, although they have high efficiencies from grid to wheels and, therefore, low running costs. Today's fuel cell vehicles that use hydrogen and internal combustion engine vehicles that use electrofuels generally have longer driving ranges than BEVs and do not require long idle times for re-fuelling. However, there are currently few hydrogen vehicles on the market (less than 12,000 in 2018) [16], mainly due to the lack of a hydrogen fuelling infrastructure. In addition, both hydrogen and electrofuels face supply-chain efficiency issues, with losses in several energy conversion steps before end-use.

ERS have attracted a renewed interest in some countries during the past few years. This is mainly due to the fact that current battery systems are too heavy for long-range vehicle categories. While ERS can reduce the fuel cost per kilometre, it is less clear what the effect is on total vehicle cost, as this depends on both the penetration level of ERS and the possibility to reduce the size of the on-board battery. ERS are in the early development phase and are being tested on a couple of kilometres of public road in Sweden, Germany and the US [9, 17-20].

Biofuels can benefit from the existing energy (fuel) infrastructure and vehicles, which means that in the near term they are a cheaper energy carrier than electricity for the transport sector. However, large-scale use of biofuels raises concerns with respect to the availability of sustainable biomass, which given the expected global transport demand may be a serious limitation [21-23]. The increased demand for biomass could lead to competition for land and water resources with the food production industry. In a future that has an increased demand for biomass, the biomass may need to be directed to sectors where the substitution of fossil (carbon-based) fuels or feedstocks is difficult, i.e., where it is challenging to electrify (such as aviation, shipping, materials production).

Table 1.1: Efficiency values from electricity sources to wheels, as well as the main technical related advantages and challenges for different energy carriers and propulsion technologies.

	Efficiency (Paper I)	Main advantages	Main challenges
Biofuels with internal combustion engines	20%	<ul style="list-style-type: none"> ★ Can use the current infrastructure and vehicles ★ All transport modes ★ Faster refuelling time then charging a battery 	<ul style="list-style-type: none"> ✘ Low efficiency ✘ Limited supply of biomass ✘ Competing for resources with food production ✘ Tail-pipe emissions
Battery-powered vehicles (BEV)	73%	<ul style="list-style-type: none"> ★ No tail-pipe emissions ★ High efficiency ★ low-noise vehicles 	<ul style="list-style-type: none"> ✘ Shorter driving range than combustion engine vehicles ✘ Heavy batteries for trucks and buses ✘ Scarcity of materials for batteries
Electric road systems (ERS)	77%	<ul style="list-style-type: none"> ★ No tail-pipe emissions ★ Smaller on-board batteries than BEVs with static charging ★ High efficiency ★ All transport modes (depending on technology) 	<ul style="list-style-type: none"> ✘ Requires new infrastructure with high up-front investment costs ✘ Technical challenges with the inductive power transfer technology (as opposed to the conductive technology)
Electrofuels (synthetic fuels; e-diesel)	17%	<ul style="list-style-type: none"> ★ Fast refuelling time ★ All transport modes ★ Can use the current infrastructure and vehicles 	<ul style="list-style-type: none"> ✘ Low efficiency ✘ Tail-pipe emissions ✘ Possibility to use the captured CO₂ for other purposes than electrofuels
Hydrogen with fuel cell	24%	<ul style="list-style-type: none"> ★ Fast refuelling time ★ low-noise vehicles ★ No tail-pipe emissions 	<ul style="list-style-type: none"> ✘ Low efficiency ✘ New infrastructure with high up-front investment costs ✘ Storage costs

One issue for the electricity generation system providing electricity for transport is that the use of electricity for transport might correlate with the current electricity system peak load, thereby increasing the need for peak power capacity and/or increasing the CO₂ emissions from the electricity system. This depends on the amount and time of electricity consumption for the road transport sector. Different strategies for electrification of transport will create different load profiles, and thus, will have different impacts on the electricity generation system. However, EVs can provide flexibility to the power grid in the form of strategic charging with or without vehicle-to-grid (V2G), i.e., charging and discharging back to the grid according to what is the most optimal strategy from the system point of view.

In the future electricity system, it is expected that there will be a higher penetration level of variable renewable electricity (VRE), e.g., solar and wind power, which will exert pressure on the electricity system to handle the output from electricity generation that cannot be dispatched.

The consequences of the variability of solar and wind power can be mitigated with different variation management strategies (VMS), such as load management of EVs, different storage technologies, curtailment of VRE, pumped hydropower and expansion of the grid. Periods of excess electricity generation may thus exist, resulting in hours with very low prices for electricity, whereas periods when there is a deficit of electricity generation may result in high electricity prices. High-price periods can incentivise EV owners to avoid charging during those hours and, if allowed, to discharge electricity back to the grid.

1.1 Aims and research topics

The overall aim of this thesis is to analyse how electrification of the transport sector affects the electricity system when achieving zero emissions of CO₂ from both the transport and power sectors. The work of this thesis spans investigations at different levels, from dedicated analyses of how to electrify a specific road (Norwegian highway E39) to the impacts of road transport electrification at the national and multi-national levels. Thus, the specific aims are to:

- Investigate how the energy demand from road transportation varies with time and the location of a road, assuming different electrification options and drive-trains technologies (**Paper I**).
- Identify the potential benefits of large-scale implementation of ERS in the transportation system by investigating the extent of the national road network, and for which vehicle types electrification with ERS could be environmentally and economically beneficial (**Paper II**).
- Investigate how large-scale deployment of EVs and ERS would affect investments in new electricity generation capacities and storage technologies, and the dispatch of the electricity system (**Papers III–V**).
- Compare an aggregated passenger vehicle profile with two methodologies of integrate individual driving profiles in an electricity system optimisation model (**Paper VI**). The consequences for the integration of variable renewable electricity, are evaluated.

In this thesis, the research topics posed are addressed by studies that focus on one specific case or region. The generalisability of the outcomes is addressed in the Chapter *Results and Discussion*.

The E39 highway 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 the European and National road network in Norway and Sweden. In **Paper III**, the geographical scope of the modelling includes Norway, Denmark, Sweden and Germany, while in **Paper IV** the scope is extended to include Spain, Portugal, France, Ireland and the United Kingdom. In **Papers V** and **VI**, the electricity system modelling is carried out for four regions in Europe (central Sweden, central Spain, Ireland, and Hungary) that have different conditions for renewable energy sources. Figure 1.3 gives an overview of the different geographical scopes, the levels of system complexity, and the relationships between the papers included in this thesis.

As this work focuses on large-scale electrification of road transportation from a techno-economic perspective, requirements related to the technical aspects of the electricity supply at the roads, such as strengthening local grids and the design of the charging infrastructure, lie outside the scope of this thesis. This thesis investigates the economic potential of using passenger EVs as a variation management strategy (VMS) from an electricity system perspective, but without considering the practical implementation of V2G. A consideration of the costs related to battery degradation and the willingness to participate in an optimised EV charging strategy and V2G are also outside the scope of this thesis.

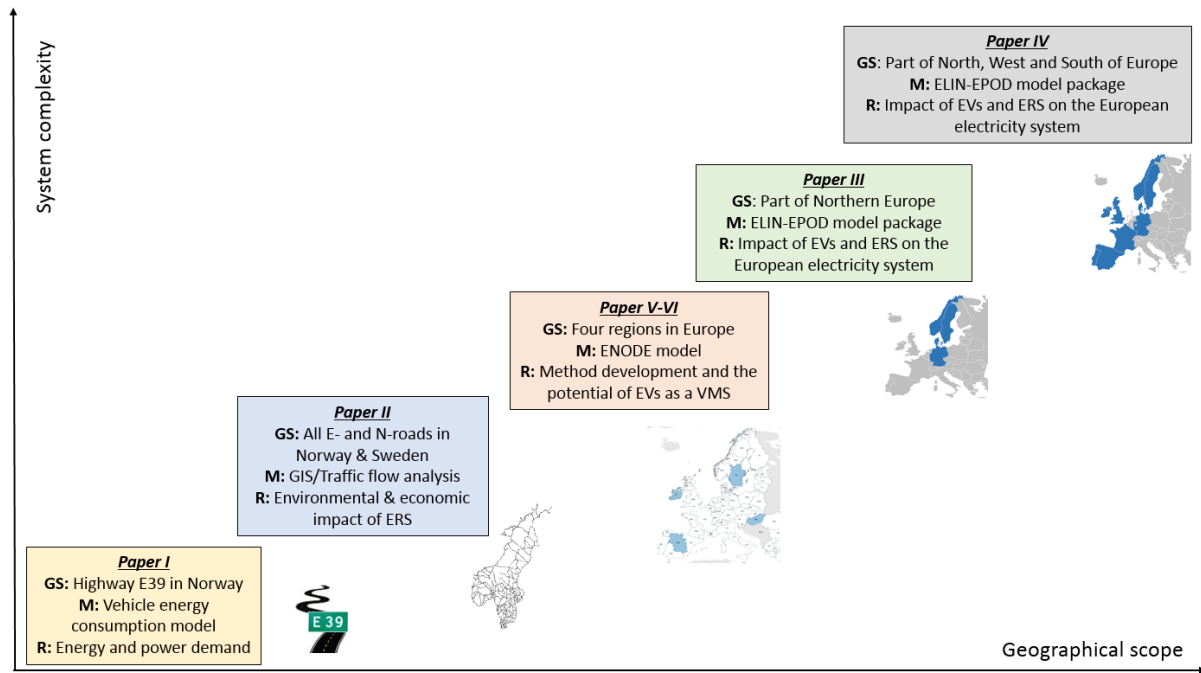


Figure 1.3: Overview of the different geographical scopes, levels of system complexity (such as more regions being inter-connected), and the relationships between the papers included in this thesis. GS, Geographical scope; M, method; R, research topic; EV, electric vehicle; ERS, electric road system; VMS, variation management strategy; GIS, geographic information system; E, European; N, national.

1.2 Contributions of this thesis

Paper I estimates the power demand when electrifying the E39, with an hourly time resolution as well as a spatial distribution, based on the use of different drive-train technologies. Stamatí & Bauer [24] have modelled the electric power demand for an average day for a highway in the Netherlands, although their study was limited to one vehicle type (passenger cars). Most of the studies conducted to date have not included trucks and buses in the load curve for modelling electrification of the road transport sector.

Paper II investigates the environmental and economic implications for light and heavy vehicles from ERS deployment at a national level. Hitherto, the impacts from technical aspects or road maintenance have to a large extent been in focus in previous research on ERS (e.g., [24–28]). Understanding the role of large-scale employment of ERS infrastructure is vital in terms of estimating the costs and benefits of making investment decisions in ERS, as opposed to alternative pathways to reduce CO₂ emissions, for road transport.

In **Papers III–VI**, several methodological advancements have been made in relation to modelling the interactions of EVs with the electricity supply system. The two new methods for integrating individual EV driving profiles into electricity system models have impacts on both the electricity system investment models and dispatch models.

Paper VI compares the implementation of EVs using three different methodologies, all of which are based on an earlier study of individual driving profiles [29]. The first methodology is characterised by a comprehensive aggregation of the EV fleet that is represented as “one huge battery”. The other two methodologies apply different ways of defining categories using individual driving profiles, 426 and 200 vehicle profiles, respectively (see Section 3.3).

The electricity system model used in **Paper VI** (ENODE) was designed so that all the methodologies could be tested in the same model within a reasonable time-frame. However, more comprehensive energy system models that also include, for example, trade between regions or several sectors, are not suitable for calculations that include individual driving profiles, due to the excessive computing time and other size problems. Thus, **Paper VI** contributes with knowledge as to when an aggregated vehicle profile is a good proxy in energy system models that are used to estimate the potential of passenger EVs to act as a variation management strategy (VMS).

Papers III–V investigate the impacts of different strategies for charging EVs and EV battery capacities on investments in new electricity generation capacity and storage technologies, and the dispatch of the electricity system. Previous studies have been limited to showing the importance of controlled EV charging with large-scale introduction of passenger EVs, so as to avoid an increase in electricity demand during hours with a high net-load, and the potential for electricity system flexibility provided by V2G to integrate a higher share of VRE (e.g., [30-37]). **Papers III–V** refine and improve upon previous modelling studies by:

- analysing electrification of the transport sector with a cost-minimising dispatch model and an investment model with the geographical scope of several countries, taking into consideration the trading of electricity between regions (**Papers III and IV**)
- modelling of the road transport sector using optimisation models that take into account individual driving data for passenger vehicles (**Papers III–VI**)
- including electrification of trucks and buses (**Papers III and IV**)
- taking into consideration of ERS that can be used in combination with static charging (**Papers III and IV**)
- considering EV batteries as a VMS together with other VMS (**Papers V and VI**).

1.3 Structure of this thesis

This thesis is based on the six appended papers (**Papers I–VI**) and this introductory essay. Chapter 2 gives the background to the different strategies for electrification of the transport sector and the connections to the electricity system. Chapter 3 describes the four models applied in this work. In Chapter 4, input data and scenarios are presented. Chapter 5 summarises and discusses the results from **Papers I–VI**. Chapter 6 presents the conclusions, and future research activities are proposed in Chapter 7.

CHAPTER 2

Background

This chapter gives a background to the different strategies for electrification of the transport sector and the connections to the electricity system. The main concepts that are important for understanding the results derived in this work are explained.

2.1 Electric vehicles and their charging possibilities

For vehicles that are mainly supplied with power by on-board batteries, electrification requires a charging infrastructure at home, work and/or in public places. The main drawback associated with using electricity with static charging, as compared to using liquid and gaseous carbon-based fuels, is the low energy density of present batteries and the comparatively long re-fuelling/re-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 re-charge fully the battery, depending on the charging power. In order to drive for 4 hours, a heavy truck would need a battery with capacity in the range of 600-800 kWh, which would necessitate a battery package weighing several tonnes.

Ultra-fast charging (with charging power >350 kW) can significantly shorten the charging times for trucks, and thereby the need for large batteries. However, ultra-fast charging is not yet commercially available, and the main challenge lies in the grid integration of loads of several megawatts and the associated costs. The development of vehicle battery technologies is directed towards increased battery energy and power densities that will improve the driving range and charging time, as well as reducing the battery cost [38].

Therefore, depending on the charging options available and the capacity of the EV 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 can be controlled (optimised), for instance, to prevent correlation with peaks in the electricity system net-load or to take advantage of low-net-load events with low electricity prices. Controlled charging could be combined with strategic discharging of the vehicles back to the grid (so called vehicle-to-grid; V2G).

EVs may, depending on whether or not a controlled charging strategy is implemented, impose a need for more flexibility strategies from the electricity network than is currently the case, as well as provide possibilities to supply flexibility services (see Section 2.6). V2G is still in an early phase, anticipating an increase in the number of EVs and the need for electricity system balancing services with more solar and wind power in the system. To realise the V2G concept, an aggregator is needed that provide the interface between the system operator and the EV owners [39].

2.2 Electrofuels

Electrofuels is a rather new concept. In this thesis, it is defined as carbon-based fuels that are produced from CO₂ and water, with electricity as the primary source of energy. Hydrogen is discussed separately in this thesis. Electrofuels are also known as power-to-gas/liquids/fuels, e-fuels, and synthetic fuels.

Electrofuels are produced by mixing hydrogen and CO₂ in a reactor to form carbon-based energy carriers. A range of liquid and gaseous fuels, including gasoline and diesel, can be produced. In addition to representing a possible future option for transport fuels, electrofuels allow for increased biofuel production by using the associated excess CO₂ [40] and could contribute to balancing variable renewable electricity generation on weekly to seasonal time-scales owing to the low cost for storing fuels. However, the energy efficiency for the production of electrofuels is relatively low (30%–70% LHV efficiency, depending on the technology) [15].

Several demonstration-scale facilities of electrofuels have been developed in Europe in the last decade [41]. For example, Carbon Recycling International in Iceland produces methanol using geothermal energy and CO₂ from the same source. Another example is Audi AG's ETOGAS, which has invested in a 6-MW electrofuel plant in Germany [15].

Electrofuels (and hydrogen) could be produced at large-scale and thereafter transported to re-fuelling stations. The fuels could equally well be produced in small-scale at the re-fuelling station, with the benefit of transporting electricity rather than a fuel.

2.3 Electric road systems

ERS represent a potentially interesting technology, mainly as an extender of the driving range for vehicles undertaking longer trips, in that they provide the EVs with a continuous supply of electricity while moving, without using the on-board battery. Thus, ERS reduce the size and weight of the on-board vehicle battery without compromising the driving range. This is of special relevance for heavy long-distance-driving vehicles.

The size of the batteries could be adjusted to ensure a maximum off-grid driving range of, for example, 50 km. The battery cost is the major reason for a BEV being more expensive than an internal combustion engine (ICE) vehicle [42]. However, reducing the size of the battery would require large-scale implementation of ERS, in the same way as the use of hydrogen requires a new infrastructure, and this will be associated with high up-front investment costs. The dynamic transfer of electricity can be made through overhead transmission lines or lines built into the road [18, 26, 43]. Electricity transfer systems that use overhead transmission lines are conductive, with the vehicle connecting to the transmission lines through a type of

pantograph, whereas the road-based technologies can be either conductive or inductive (see Figure 2.1). For a conductive system, the supply of electricity is through a physical pick-up which connects to an electrified rail in the road, whereas in an inductive system the electricity is supplied via wireless, magnetic field-based power transfer from a coil in the road to a pick-up point in the vehicle [18, 26, 43]. The overhead lines can – at least in current design concepts - only be used by heavy vehicles (i.e., buses and heavy trucks), while the electrified rail in the road and the inductive supply systems can be used by all types of vehicles (cars, buses, and trucks). The ERS infrastructure can be divided into three main parts: the vehicle fleet, the electric road infrastructure, and the electricity supply system (Figure 2.1).

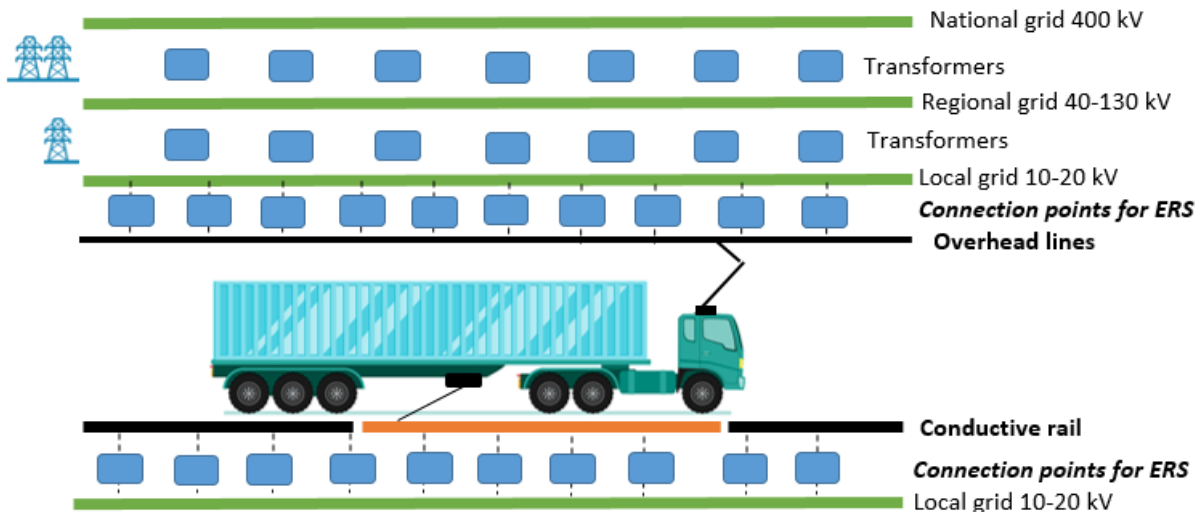


Figure 2.1: Schematic illustration of the main component levels in an electric road system (ERS). Electricity supply via both a rail in the road and overhead lines are included in the illustration.

Previous studies in the scientific literature have mainly investigated ERS with respect to technology improvements (e.g., [24-28]), costs or CO₂ (e.g., [18, 43-49]) and business models [50, 51]. For example, Connolly [47], Gnann et al. [49] and Boer et al. [46] have concluded that ERS have the potential to be more cost-competitive than either oil- or BEVs in the future. This is because ERS entail lower running costs than oil and the ERS infrastructure is shared by many vehicles, so that smaller batteries can be used and the cost per vehicle is reduced.

Stamati et al. [24] have modelled the electric power demand for roads, with the possibilities to meet the electricity demand for traffic flow on an average day with VRE. Plötz et al. [44] have shown that ERS can reduce the CO₂ emissions from heavy road transport. However, important research gaps exist, in relation to investigating the impacts on the power demand from cars, trucks and buses combined, and carrying out an environmental analysis of ERS. The environmental impact of ERS will, as presented by Nordelöf et al. [52], depend to a large extent on the technology mix used to generate the electricity required to power an ERS.

There remain several challenges with ERS, such as finding viable economical business models, agreeing on technology standards, and accommodating radical increases in the technical, business, and systems complexities. In addition, electrification of the transport sector (including ERS) will increase the load at hours with a currently high load. Electrification of the road transport sector with ERS could, therefore, also impose local or regional constraints on the electricity grid, depending on how, when, and to what extent the vehicles are charged.

2.4 Variable renewable electricity generation

Most of the scenarios for the development of electricity supply systems that meet the required cuts in CO₂ emissions to 2050 employ, of course, large amounts of electricity generation from renewable energy sources (RES), and in particular from variable renewable electricity VRE [53]. VRE involves non-dispatchable electricity generation technologies that provide electricity with varying outputs, such as wind and solar power. The variability of VRE generation can be managed, with different VMS providing flexibility to the system [54, 55].

Figure 2.2 exemplifies the output from solar and wind power, as well as a load profile covering a period of 3 weeks in Spain (2.2a) and Germany (2.2b). As seen in Figure 2.2, solar and wind power require different forms of flexibility from the electricity system. Electricity systems that rely on large amounts of solar power benefit from storage between day and night, day and the next morning (Figure 2.2), as well as support during cloudy days (especially in less-sunny regions, such as Germany; Figure 2.2b) and seasonal variations.

In contrast, wind power exhibits fluctuations in electricity production that have spans from several hours to several days (Figure 2.2), as well as between seasons, with typically higher levels of generation in winter-time in the Northern Hemisphere [56]. Such variations require the shifting of large amounts of energy for at least a couple of days. The load profile has a higher demand during the day-time, with peaks in the morning and afternoon/evening (Figure 2.2). As shown in Figure 2.2, solar power correlates, only to some extent, with the demand for electricity on a diurnal basis, whereas there is no correlation between wind power and the demand for electricity in the hour-to-week time-span.

The net-load, i.e., the load minus VRE generation, needs to be met with electricity generation other than VRE. For the electricity system, there is a benefit from having a stable and low net-load, since, for example, investments in peak power capacities are dimensioned by the hour with the highest demand in terms of net-load.

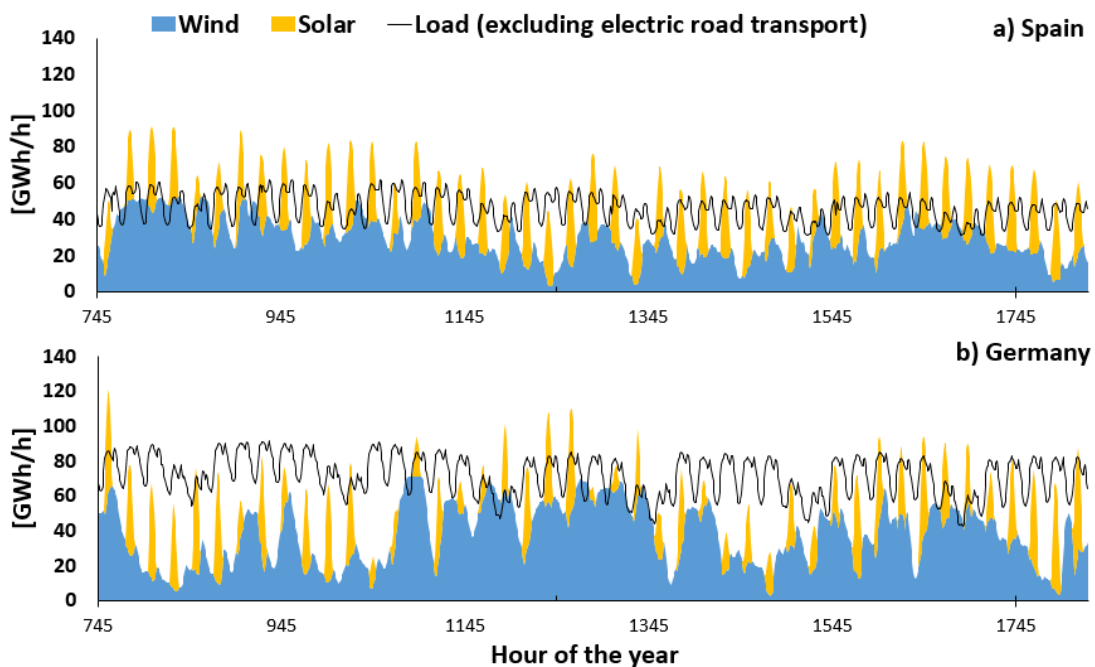


Figure 2.2: Electricity generation patterns from solar and wind power, as well as the load profile for 2050: Spain (a); and Germany (b). Close-to-zero CO₂ emissions from the electricity system are assumed.

The fluctuations in output from solar and wind power create a need, or rather a potential market, for VMS, which can improve the ability of VRE to meet the electricity demand. The electricity system benefits from such strategies to handle fluctuating electricity generation on different time-scales, such as hours, days, and weeks, in order to smoothen the net-load curve. There will also be grid-related challenges with VRE on shorter time-scales, e.g., inertia of the power system (milliseconds to seconds), frequency and voltage stability (milliseconds to minutes) [57].

Figure 2.3 shows those cases in which the EV battery can be used for managing the challenges in the electricity system on different time-scales. Depending on the travelling distance and driving patterns, EV batteries can move energy on time-scales that range from hours up to several days. This thesis is focussed on analysing electricity systems in which shifting energy on time-scales ranging from hours up to seasons is required (green box in Figure 2.3), albeit not necessarily through the exclusive use of EV batteries.

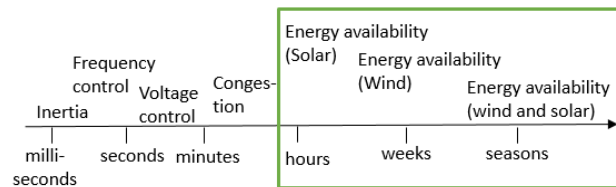


Figure 2.3: Grid integration challenges for different time-scales, where the EV battery can be used for managing the issues. The green box indicates the aspects in focus in this work.

2.5 Variation management strategies

Different VMS can be used to handle fluctuations in the electricity supply and demand. The electricity system benefits from VMS, as mentioned in Section 2.4, which can handle fluctuating electricity generation on different time-scales of hours, days, and weeks, so as to smoothen the net-load curve. An increased VRE share decreases the system value of VRE. This could be mitigated with VMS. The VMS needs to be able to: store or shift large amounts of electricity over both the short and long terms; provide a high capacity during certain hours; and have high levels of flexibility, availability, and predictability. No single VMS can meet all of these conditions in a cost-efficient manner. Therefore, the system benefits from combining several types of VMS to handle a large share of VRE [58].

There are regional differences in the access to renewable energy (e.g., hydropower, offshore wind power, and bioenergy), as well as differences in the output profiles from wind and solar power. The import/export capacities to neighbouring regions (and the characteristics of the electricity systems in the neighbouring regions) also create regional differences in the benefits that can be derived from VMS. The benefits that can be obtained from VMS in a particular region depend mainly on cost, the nature of the net-load curve for the region, and the possibilities for electricity trading with neighbouring regions.

Göransson and Johnsson [54] have divided VMS into groups that: (i) store and move electricity locally in time (shifting strategies); (ii) consume electricity during low-net-load events or remove electricity generation from such events (absorbing strategies); and (iii) add to the VRE generation when such generation is insufficient to meet the demand or remove demand from such occasions (complementing strategies). Table 2.1 gives examples and short descriptions of the different VMS that are included or not included in this work.

Table 2.1: Examples of variation management strategies.

<i>VMS</i>	<i>Paper</i>	<i>Time-scale</i>	<i>Type of strategy</i> <i>[54,59]</i>	<i>Short description</i>
Vehicle-to-grid	Papers III–VI	Seconds to several days	Shifting (small EV batteries) Complementing (large batteries)	Charging at hours with a low net-load and discharging back to the grid at hours with a high net-load.
Optimised electric vehicle (EV) charging	Papers III–VI	Minutes to several hours	Shifting (small EV batteries) Absorbing (large EV batteries)	Charging vehicles when it is most beneficial for the electricity system (i.e., at hours with a low net-load).
Stationary batteries	Papers V and VI	Seconds to a day	Shifting	Charging at hours with a low net-load and discharging back to the grid at hours with a high net-load.
Hydropower	Papers III–VI	Hour to season	Complementing	Storing water in reservoirs to be used at hours with a high net-load.
Pumped hydropower	Not included	Hour to season	Shifting	Pumping water to a reservoir at hours with a low net-load and using the stored energy during hours with a high net-load.
Curtailement	Papers III–VI	-	Absorbing	Loss of electricity at hours that have higher production than consumption.
Hydrogen and electrofuels	Papers V and VI (only hydrogen)	Minutes to season	Absorbing and/or Complementing	Producing hydrogen/electrofuels at hours with a low net-load, either for use in another sector or for conversion back to electricity during hours with a high net-load.
Thermal power	Papers III–VI	Minutes to hours	Complementing or absorbing	Starting/stopping or changing the output level from a power plant.
Trade	Papers III and IV	Minutes to several hours	Different depending on the regions	Import and export of electricity between neighbouring regions.

In **Papers V** and **VI**, we model EV batteries, together with most of the VMS mentioned in Table 2.1 (with the exceptions of trade and pumped hydropower). Thereafter, two types of stationary batteries, lithium-ion batteries and flow batteries, are modelled. The flow batteries are modelled with lower investment costs and longer life-times, as well as a lower power-to-storage capacity ratio. The C-factor (i.e., the rate at which the battery is charged or discharged) is in **Papers V** and **VI** assumed to be more limited for the flow batteries (0.25) than for the lithium-ion batteries (0.5). The lower round-trip efficiency value also differs between the batteries (0.7 for flow batteries and 0.9 for lithium-ion batteries).

Two types of hydrogen storage (tanks and caverns) are also included in **Papers V** and **VI**. Caverns are cheaper than tanks and are used as a more long-term storage. The tanks are used more frequently than the caverns but store lower levels of energy.

As shown in Table 2.1, a few strategies are described in **Papers V** and **VI** to handle the seasonal variations: mainly hydropower and the production of hydrogen. The hydrogen can either be used in another sector (such as transport or industry) or be subsequently converted back to electricity, albeit with a low round-trip efficiency. The cost-benefit ratios of such VMS depend mainly on the investment cost of the electrolysers. Strategic charging of EVs is assumed in **Papers III–VI** for passenger EVs and no shifting of the household load or industrial load is considered.

2.6 Electric vehicles as a variation management strategy

EVs may serve as a VMS by moving electricity from hours with a low net-load to periods with a high net-load (shifting strategy). In the case of large EV batteries in relation to the daily driving demand (i.e., with the possibility to store electricity over several days), EVs may also serve as an absorbing strategy to optimise the charging of the EV battery to only hours with high output from VRE (see Table 2.1). The capacity and time-scale to move electricity by the EVs depends on the individual driving profile and the battery capacity, as well as on the relationship between the driving demand per day and battery capacity.

In general, three aspects of EVs make them suitable for use as VMS. First, EV batteries have a very rapid response time, in that they can transition from zero to maximum power in milliseconds. Second, an individual owner of an EV can only store about 15–85 kWh in their battery, whereas on an aggregated scale, EV batteries can provide substantial amounts of battery capacity and energy storage capacity for the electricity system. This makes the EV fleet suitable as a storage option also on longer time-scales (hours to several days).

Third, statistics from passenger vehicle driving patterns in Sweden show that existing vehicles are parked for around 95% of the time on average [29], so a car battery could potentially be connected to the electricity system for large parts of the day. However, one important issue is whether the vehicles can be discharged to the grid during the hours when power is most needed from the electricity system perspective.

When it comes to stationary batteries, in other studies, they have been proven to be too expensive for weekly storage of wind power [58]. Instead, investments in stationary batteries are mainly relevant for sunny regions with a high share of solar power in the electricity system. EV batteries can nowadays attain energy storage capacities in excess of 40 kWh in most of the passenger cars on the market, while stationary batteries to handle solar PV is today a few kWh per battery installation in a household with PV systems. Over-dimensioning of EV batteries with respect to the daily driving demand, a large share of idle time (being parked), and the deployment of a more comprehensive charging infrastructure could create opportunities for the electricity system to use EV batteries also for handling wind power (weekly storage). However, for the EV owner, controlled charging means constraining the freedom to have the EV battery fully charged at all times.

For trucks and buses, the possibilities to provide variation management from the charging of batteries should be more limited than is the case for passenger vehicles, since the heavy vehicles are driven many hours per day and that possibilities to control charging are limited. The batteries are likely to need to be charged for transportation purposes when being parked due to the costs associated with large batteries for trucks and buses.

Table 2.2 lists the possible benefits of an optimised EV charging and V2G strategy for the electricity system. For the direct charging strategy, the outcome can instead be the direct opposite of the benefits listed in Table 2.2, in particular the enhancement of afternoon peaks in electricity demand.

Table 2.2: Possible benefits for an electricity system of using optimised charging and vehicle-to-grid (V2G) as a variation management strategy. VRE, variable renewable electricity.

Electricity system benefit	Description
Frequency control and voltage stability	V2G can be used when the frequency deviation is greater than the threshold value, and the amount of power charged or discharged by EVs would be controlled in proportion to the frequency deviation.
Integrate more VRE	Optimised charging with V2G can contribute with flexibility, by storing electricity from hours with low net-loads to hours with high net-loads. Low-cost flexibility is important for the system, in allowing for VRE to compete with thermal power.
Peak power shaving	Discharge the EV battery back to the grid during hours of higher demand for electricity than can be met by production, in order to avoid additional investments and the use of peak power units (e.g., gas turbines).
Reduce curtailment	Charging the EV batteries during hours when the level of electricity generation is higher than the load, to avoid curtailment.
Reduce investments in storage technologies	V2G can replace investments in other storage technologies than EV batteries, by using the EV batteries as a storage.
Reduce total system cost	Reduce the total electricity system cost, by having less investments in peak power units, less cycling of thermal power plants, and fuel costs for thermal power plants.
Power reserve	Participate as a back-up reserve capacity to reduce over-investment in power units.

EVs could be part of the back-up power or power reserve system on the regulating market. The back-up power is normally used for just a few hours per year, providing capacity during the most crucial hours. EVs can contribute in two ways to the power reserve: by avoiding charging during those hours and by discharging the EV battery when the power reserve is needed.

Some studies have used exclusively driving patterns to determine the load curve from EVs, without optimising the charged amounts and duration of charging [24, 60-68]. An approach that has been commonly applied in the studies listed in Table 2.3 involve the formulation of a V2G scenario as a mathematical optimisation problem, with the aim of finding the optimal charging strategy, given specific objectives and constraints. However, the optimisation objectives and imposed limitations have varied between the studies.

Table 2.3 provides an overview of some of the previous studies that used investment and/or dispatch models to investigate the impact on the electricity system of V2G. As shown in Table 2.3, several studies have been published in recent years on the topic of electrification of road transport, with the aim of determining the impacts of EVs on the electricity system (e.g, [30-37, 69-75]).

Göransson et al. [30], Hedegaard et al. [31], Lund and Kempton [32], Sohnen et al. [34], and Jochem et al. [35] have all used linear optimisation investment models in the form of dispatch models to analyse the benefits of a controlled charging strategy. However, they all have limited their investigations to a single country or regions without inter-connections to the surrounding electricity system. Studies using multi-regional energy models, for example those of Hadley and Tsvetkova [36] and Verzijlbergh et al. [33], are limited to dispatch models, and thus do not include the impact of EV employment on the long-term investment decisions related to power generation capacity.

Further, previous studies on modelling the system impact of VMS have been limited mainly to investigating one VMS at a time. However, there are studies that have compared the impacts of a broader range of VMS and their applications on the electricity system composition (e.g., [58, 69, 70]). The main results from the abovementioned previous studies show that uncontrolled charging of EVs may increase the need for more flexibility in the system in terms of larger investments in peak electricity generation, which will increase the electricity system cost and could also increase the CO₂ emissions from the system. However, when the integration of EVs includes a controlled charging strategy, previous studies mentioned have shown that passenger EVs can be beneficial for the electricity system in terms of, for example integrate more VRE (Table 2.3).

For example, in a case study of California until year 2027 conducted by Fripp [37], the Switch-model shows that wind and solar power could be used to reduce emissions by 90%, as compared to the year 1990 levels, without losing flexibility in the system or increasing the total electricity system cost. A high penetration level of solar and wind power in the electricity system is possible by using controlled charging of EVs [37]. Mileva et al. [71] show that high levels of solar generation in the electricity system can be cost-effectively integrated using a portfolio of technological options. Schuller et al. [70] conclude is that EV smart charging can provide balancing on shorter time-scale (intra-day) and to handle long-term flexibility, EV batteries need a complement, such as power-to-gas.

Many of the previous studies involving modelling of the electricity system with the inclusion of charging of EVs have based their driving demands on data from travelling surveys, standardised driving cycles, and 1-day measured driving distances (e.g., [30-37, 72, 73]). Thus, the EV fleets are aggregated to one overall EV fleet in these models, since travelling surveys lack detailed data on the actual individual driving patterns. For example, Šare et al. [73] have used the traffic load measured for the Dubrovnik region for one specific day, and Juul et al. [72] have examined transport patterns with average values based on statistical data from a Danish travel study.

There is a gap in the literature regarding studies that have used real-time driving patterns of passenger cars in an electricity system model designed to analyse the potential of EVs to integrate both more solar and wind power, as well as, replace other VMS. The analysis of passenger vehicle driving patterns performed by Karlsson and Kullingsjö [29] has shown that even with relatively small EV battery capacities (i.e., around 15 kWh), a large proportion of the passenger EV fleet does not require battery re-charging every day in order to manage the daily driving demand [29]. In addition, the aggregated EV battery capacity for a region will be large relative to the number of stationary batteries in which an investment is made to handle diurnal fluctuations [54].

Table 2.3: Overview of some previous studies that have applied different investments and dispatch models to study electrification of the transport sector.

	Model	Geographic scope	Time resolution	Aim	Charging options/ alternatives	Main conclusions
Göransson et al. [30]	Linear programming investment optimisation model; Objective: minimise investment cost (Balmorel)	Western Denmark	28 representative days	EV impacts on total power system costs and emissions, and the generation patterns	Mode: passenger PHEV; Strategy: uncontrolled and controlled/V2G	PHEVs can reduce CO ₂ emissions if using controlled charging.
Hedegaard et al. [31]	Investment and dispatch optimisation model (Balmorel); Objective: minimise total system cost	Five northern European countries (no transmission)	Period of 2010–2030, 5-year interval, representative days, perfect foresight	EV impacts on electricity system, e.g., investments in and operation of the system towards year 2030	Modes: passenger BEV, PHEV; Strategy: controlled/V2G	V2G can reduce the need for investments in fossil fuel-fired power plants and increase penetration of wind power. Reduction of CO ₂ emissions by 3%–28% in year 2030.
Lund & Kempton [32]	Deterministic model that optimises the operation of a given energy system (Energy Plan)	Denmark	1-hour time-step, year 2020	EV impacts on CO ₂ emissions and the ability to integrate wind power	Mode: passenger PHEV; Strategy: uncontrolled night-time charging and controlled/V2G	V2G allows the integration of higher penetration levels of wind power without curtailment, and also greatly reduces national CO ₂ emissions.
Jochem et al. [35]	Cost-optimising energy system model (PERSEUS-NET-TS).	Germany	Period of 2012–2030 (5-year time-steps), 12 representative days	EV impact on CO ₂ emissions	Mode: 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. [74]	A mixed integer linear optimisation model; Objective: minimise total system cost	Germany	1-hour time-steps, year 2020 and year 2030	EV impacts 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 utilisation of hard coal/lignite plants in year 2030.
Verzijlbergh et al. [33]	A mixed-integer minimum-cost unit commitment dispatch model (EUPowerDispatch); Objective: minimise total system cost	32 European countries	1-hour time-steps, an optimisation horizon of 1 week for year 2010 and year 2025	EV impact on cross-border electricity transmission investment.	Mode: passenger EV; Strategy: uncontrolled and controlled charging, with each vehicle modelled separately	A controlled EV charging strategy and cross-border transmission capacity complement each other and reduce the electricity dispatch costs and curtailment of VRE.
Hadley & Tsvetkova [36]	Dispatch model of the electricity system; Objective: minimise running costs (ORCED model)	USA (13 regions)	year 2030	EV impacts on CO ₂ emissions, electricity prices, and the dispatch of the electricity system	Mode: 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 PHEVs.
Fripp [37]	Stochastic linear programming model; Objective: minimise total system cost (SWITCH)	California (16 zones)	Period of 2012–2027, 12 representative days with 1-hour time-steps	EV impacts on the cost reducing greenhouse gas emissions from the electricity system through large-scale use of wind and solar power	Mode: passenger EV; Strategy: controlled/V2G	If EVs are charged at the optimal time of day they can reduce the system cost and emissions.
Schlachtberger et al. [75]	Linear programming model; Objective: minimise total system cost (POWER)	USA	14 representative days	The cost benefits of a combinations of flexibility options, e.g., PHEVs	Mode: passenger PHEV; Strategy: partly flexible PHEV demand	PHEV generates a higher total system cost but a lower total system levelised cost.
Taljegard et al. (this work, Paper III and IV)	Linear programming optimisation model; Objective: minimise running costs and investment costs (ELIN & EPOD)	Denmark, France, Spain, Norway, Ireland, Sweden, Germany	Investment model: period of 2010–2050, 20 representative days with hourly time-steps, Dispatch model: year 2030, hourly time-steps	EV impacts on the electricity system, e.g., investments in 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, with the main increase in demand from EV being met by wind power and solar power.

CHAPTER 3

Models

This chapter provides an overview of the four different models applied in this work to address the research topics listed in Section 1.1 (see Figure 3.1): a vehicle energy consumption model, a cost-minimising investment model (ELIN), an electricity system dispatch model (EPOD), and a combined cost-minimising investment and dispatch model (ENODE). The vehicle energy consumption model has been developed specifically for this work. The three electricity system models have been further developed and adapted within this work.

The development of the optimisation models comprises inclusion of the possibility to model electrification of road transportation into the models (i.e., an EV add-on). The models are described in Sections 3.1 to 3.3. A comparison of the three electricity system models is provided in Section 3.4. The full mathematical model formulation of the EV add-on can be found in **Papers I** and **III–V**, and is therefore not included in this chapter. The traffic flow analysis performed and explained in **Paper II** will not be further described in this Chapter.

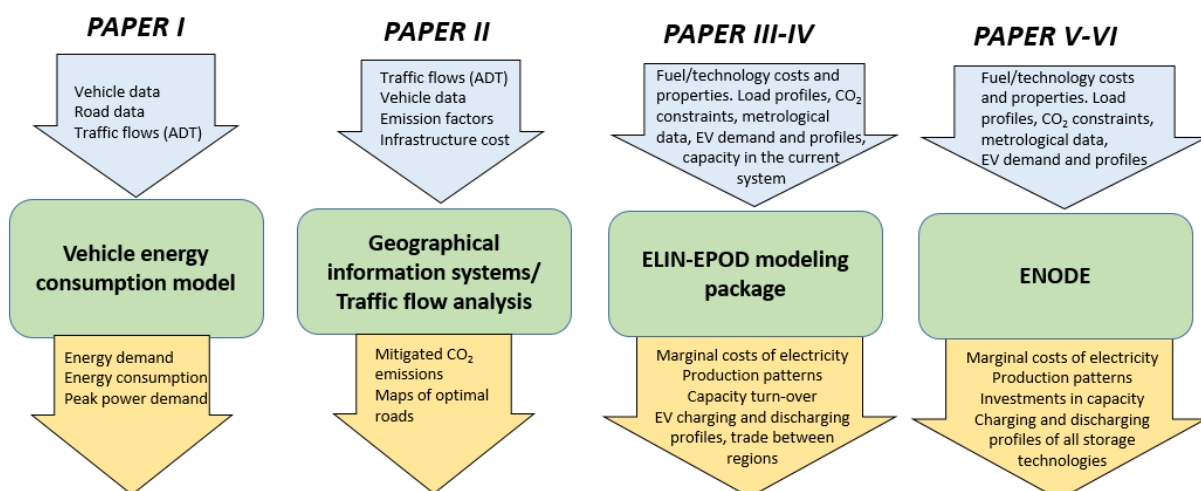


Figure 3.1: Overview of the models and methods used in this thesis, including input and output parameters.

3.1 Vehicle energy consumption model

Paper I uses a *vehicle energy consumption model* that was developed from the same concepts used previously in similar mathematical models for estimating the fuel consumption and fuel efficiency of vehicles (e.g., [76-81]). The vehicle energy consumption model simulates the energy consumption and, if applicable, energy regeneration potential of different drive-trains, vehicle categories, and transport options (static charging, ERS, hydrogen and electrofuels). Figure 3.2 shows the forces that act on the vehicle included in the vehicle energy consumption model. The model is designed to estimate the energy needed to overcome the following forces acting on the vehicle:

- road inclination (F_g)
- rolling resistance (F_r)
- aerodynamic force (F_a)
- tractive force (F_t)

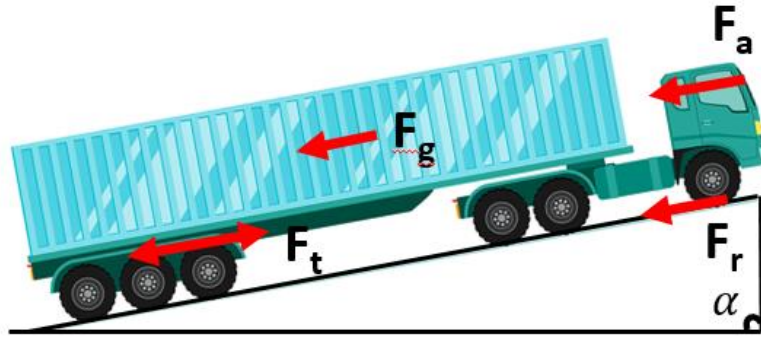


Figure 3.2: Illustration of the forces included in the vehicle energy consumption model that affect the motion of the vehicles. F_a is the aerodynamic force, F_r is the rolling resistance force, and F_g is the gravitational force acting on the vehicle due to the slope of the road, F_t is the tractive force generated by the prime mover, which can act in both directions depending on whether the vehicle is braking or accelerating.

The power demands of a vehicle that is being driven a certain distance depend on a number of factors, such as the vehicle characteristics (i.e., vehicle mass, drive-train efficiency, frontal area, etc.), vehicle speed, driving behaviour, pavement conditions, altitude, and weather conditions. The power to the wheels, P_{wheel} , in the model is given by Eq. 3.1:

$$P_{wheel} = v (m \cdot g \cdot \sin(\alpha) + m \cdot g \cdot C_r + \rho \cdot v^2 / 2 \cdot A \cdot C_D + m \cdot a) \quad (3.1)$$

where m [kg] is the vehicle mass, g [$m \cdot s^{-2}$] is the gravitational constant, α [radians] is the longitudinal slope, C_r is the rolling resistance coefficient, v [$km \cdot h^{-1}$] is the vehicle speed, ρ [$kg \cdot m^{-3}$] is the air density, A [m^2] is the frontal area of the vehicle, C_D is the aerodynamic drag coefficient, and a [$m \cdot s^{-2}$] is the average vehicle acceleration level (dv/dt).

The main limitations associated with this model are the difficulties linked to modelling different driving behaviours, road conditions, tire pressures, weather conditions, and power-train configurations, all of which affect the energy demand. Furthermore, the model uses data from road speed limits in the calculations.

The outputs from the vehicle energy consumption model in **Paper I** (e.g., traffic flow profiles and energy demand per kilometre) have been used as inputs for the calculations of CO₂ emissions in **Paper II** and the modelling of EV and ERS electricity demand in **Papers III–VI**.

3.2 Electricity system optimisation models

This thesis uses linear optimisation models. Modelling of the electricity system using linear programming techniques started already during the 1950's within academia and among electricity utilities [82]. At that time, the modelling was fairly simple, with mostly new thermal power generation units meeting the increase in electricity demand.

Since then, electricity system modelling has developed and today encompasses a wide range of detailed techno-economic tools to analyse changes in the electricity system in the form of, for example, planning of the dispatch of units, investments in new generation, and the trading of electricity between regions [83]. The modelling has been, and still is, used to analyse policy decisions and business development plans to provide valuable guidance to governments and industry on the best economic and environmental approaches to meet electricity demand under a given set of constraints [84].

Many different types of optimisation models can be used to analyse the electricity system, e.g., dispatch models, investment models, and unit commitment models [83-85]. Today, much of the work conducted within the electricity system modelling community is focused on investigating a close-to-100% renewable electricity system. Thus, in an electricity system that is dependent upon a large share of VRE, it has been important to improve the time resolutions in the models [85]. The technical constraints and cost of integration of additional wind and solar power have been the topics of a number of scientific papers during the last decade, using different optimisation models of the electricity system (e.g., TIMES, MARKAL, BALMOREL, SWITCH, etc.) [83, 85]. The electrification of several sectors, such as the transport and industry sectors, is also the focus of today's electricity system modelling community.

In optimisation models, there is an objective function that either maximises or minimises something that is quantifiable. In the models used in this study (ELIN, EPOD and ENODE), the objective is to minimise the total system costs. Equation 3.2 gives the general formulation of the objective function of an investment and dispatch model. An optimisation model of the electricity system also consists of a number of constraints and equations that reflect the known technical and physical limitations and relationships, as well as policy and targets. For example, within a dispatch model, there is an equation that dictates that the level of generation should match the demand for electricity at each time-step (see Eq. 3.3).

$$\min C^{tot} = \sum_{p \in P} C_p^{inv} i_p + \sum_{p \in P} \sum_{t \in T} (C_{p,t}^{run} g_{p,t} + c_{p,t}^{cycl}) \quad (3.2)$$

$$\sum_{p \in P} g_{p,t} + \sum_{p \in PSTR} b_{p,t}^{disch} + \sum_{dp \in DP} E_{dp,t}^{Dgrid} \geq D_t + \sum_{dp \in DP} E_{dp,t}^{CPEV} + \sum_{p \in PSTR} b_{p,t}^{ch} \quad \forall t \in T \quad (3.3)$$

where C^{tot} is the total system cost, C_p^{inv} is the investment cost of technology p , i_p is the investments in technology p , $C_{p,t}^{run}$ is the running cost of technology p in time-step t , $g_{p,t}$ is the electricity generation from technology p in time-step t , $c_{p,t}^{cycl}$ is the cycling cost (sum of the start-up cost and part-load costs) of technology p in time-step t , $b_{p,t}^{disch}$ is the electricity discharged to the grid with storage type $pSTR$ at time-step t , $E_{dp,t}^{Dgrid}$ is the passenger EV discharging to the grid for driving profile dp at time-step t , D_t is the demand of electricity at time-step t , $E_{dp,t}^{CPEV}$ is the passenger EV charging for driving profile dp at time-step t , and $b_{p,t}^{ch}$ is the amount of electricity with which the storage type $pSTR$ is charged at time-step t .

3.2.1 ELIN-EPOD model package

The two electricity system models ELIN (investment model) and EPOD (dispatch model) were originally constructed by Odenberger and Unger [86, 87], and further developed by colleagues [88]. These models have previously been used to study the transition of the European electricity system to meet European policy targets for CO₂ emissions and targets for investments in renewable energy sources (e.g., [86, 88-90]). In both ELIN and EPOD, the goal is to minimise the total system cost to meet the demand for electricity under certain constraints, such as a cap on CO₂ emissions.

The ELIN model is designed to analyse a transition of the electricity system by making investment decisions based on the current age structure and the competitiveness of different power generation technologies, while reaching a target for CO₂ emissions. ELIN has a temporal scope of 20 representative days with 1-hour time-steps (i.e., in total, 480 time-steps per investment period) and an investment period every 10 years between 2020 and 2050.

The EPOD model takes the results (i.e., the descriptions of the electricity system, fuel and CO₂ prices, and transmission lines) from the ELIN model for a specific year (in **Papers III** and **IV**, the year is 2030), and thereafter performs optimisation, in order to identify the least-cost hourly dispatch of the system. Figure 3.3 shows the connections between the ELIN and EPOD models.

Papers III and **IV** apply the ELIN and EPOD models to compare the total system cost, electricity generation profiles, curtailment of VRE, and electricity generation capacity investments for different scenarios of EV deployment and charging strategies.

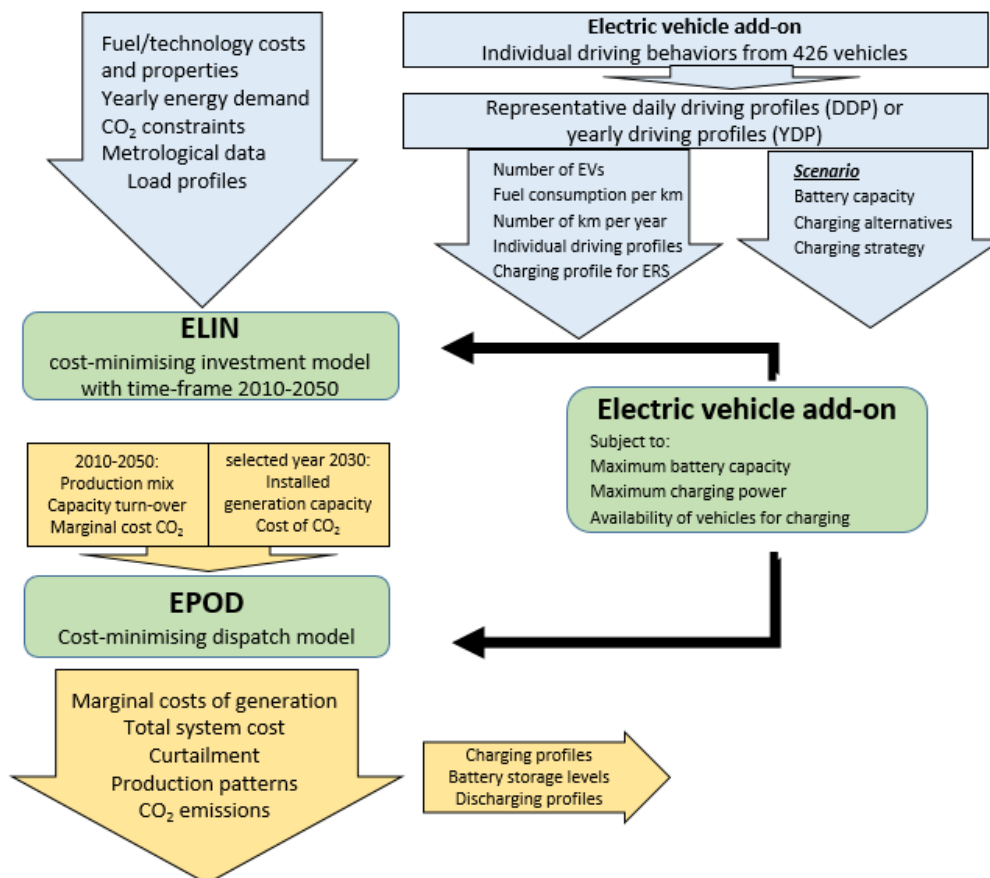


Figure 3.3: Connections between the ELIN and EPOD models. The electric vehicle (EV) add-on has been developed in the models used in this thesis.

In **Papers III** and **IV**, the ELIN-EPOD model package is expanded to include electric road transport in the form of passenger cars, trucks, and buses (see the description of the EV add-on in Figure 3.3). A new demand for electric road transportation has been added, both to the investment model and the dispatch model. A new demand for electricity is introduced based on the demands for driving and vehicle technology options, e.g., EV with static charging and/or ERS. The two models endogenously optimise the time of charging and discharging back to the grid of the passenger EV, while at the same time fulfilling an exogenously given hourly EV driving demand.

The EV add-on includes the possibility to analyse different EV charging strategies and ERS. Thus, the freedom of the electricity system to charge the EVs is only constrained by, for example, the availability of a charging infrastructure, the battery storage capacity, and the driving demand patterns. The number of EVs, the EV battery capacities, and the hourly EV driving demands are pre-defined in the models, and the present work does not include optimisations of vehicle or battery investments in the models (see Figure 3.3).

One reason for including EVs in the models was to take into account individual driving profiles rather than only a single aggregated demand profile for the entire passenger vehicle fleet. In the present work, assumptions regarding passenger travelling patterns are based on the data from GPS measurements of 426 randomly chosen gasoline- and diesel-powered vehicles in a Swedish region (for details, see Section 4.2). Two methods have been used to account for individual driving patterns. In **Paper III**, passenger EV transportation demand is represented by a variety of representative daily driving profiles, while in **Papers IV** and **V** this is represented by yearly driving profiles (for a detailed description, see Section 3.3).

3.2.2 ENODE model

The electricity system model used in **Papers V** and **VI**, called ENODE, is similar to the ELIN-EPOD modelling package, in that it is an optimisation model that is designed to analyse the electricity system under the constraints of climate targets and minimising system cost. ENODE is both an investment and a dispatch model with an hourly time resolution that covers both electricity and district heating demand.

The connections between hours across days, weeks, and seasons in ENODE make it possible to include investments in all types of storage technologies, such as stationary batteries and hydrogen storage. Thus, in ENODE, the EV batteries can store electricity between days, depending on the assumed capacity of the EV battery and the individual driving profile. The version of ELIN-EPOD used in this thesis does not include any investment in storage technologies. The use of representative days, i.e., days that are statistically representative of a full year using weighting factors, does not give any information on how these days are linked in time, and thus, the value of storage technologies that span periods longer than those within a single day cannot be visualised in ELIN.

The ENODE model is a Greenfield model, while the ELIN-EPOD starts from the existing capacity [91] analysing the pathway of the system to 2050. To enable calculations and limit the model size, inter-connections between regions in Europe are not included in ENODE.

Generation and storage technologies in which the model can invest include: wind, solar and hydropower, nuclear power, heat pumps, and different types of thermal power plants, stationary batteries, hydrogen storage tanks, and caverns.

The model applied is based on the version formulated by Göransson et al. [92], with the following modifications: (i) Garðarsdóttir et al. [93] added an improved representation of thermal power plant flexibility; (ii) Göransson and Johnsson [54] added different flexibility measures; and (iii) Johansson et al. [94] added new biomass and gasification generation technologies. In this thesis, the ENODE model has been further developed by adding an EV add-on, so as to include the charging and discharging of passenger EVs. This has been done in the same way as for the ELIN-EPOD model package, as described in Section 3.2.1 and depicted in the upper-right part of Figure 3.3.

Hydropower in ENODE is modelled for southern Sweden, including both local hydropower and hydropower imported from northern Sweden, with historical limits on ramp-rates [58, 95, 96]. The capacity of the imported hydropower is constrained by the transmission capacity between northern and southern Sweden (7 GW). The Swedish hydropower is coupled to reservoirs, and the ability to store energy is represented by an energy balance constraint over the reservoir. The hydropower in-flow follows a weekly profile, with a total annual in-flow [96]. The flexibility of the hydro power plants is limited by historical limits on production increase and decrease [95], as proposed by Göransson and Johnsson [54].

Table 3.1 lists the most important differences between the ELIN-EPOD model package and the ENODE model.

Table 3.1: Most important differences between the ELIN-EPOD model package and the ENODE model.

	ELIN-EPOD model package	ENODE model
Geographical regions	Sweden, Norway, Denmark, Germany Spain, UK and neighbouring countries.	Central Sweden (SE3), central Spain (ES3), Ireland, and Hungary.
Transmission	yes	no
Existing capacity	yes	no
Time resolution	ELIN has 480 time-steps (20 representative days) per year for the investment period 2020–2050, where each decade is represented by one year in the model; EPOD has 8,784 time-steps for 2030.	One year with 8,784 time-steps.
Storage technologies	EV batteries with intra-day storage in the investment (and dispatch) model, hydropower.	EV batteries with unlimited storage time, hydrogen, stationary batteries, hydropower.

3.3 Methods to account for electric vehicles and ERS

Previous work looking at the impact of EVs on the electricity system have typically based their driving demands on data derived from travelling surveys, standardised driving cycles or 1-day measured driving distances (e.g., [30-37, 70, 72-74, 97, 98]). Two main reasons why electricity system models often aggregate EVs to a single fleet without evaluating the consequences of this simplification are that: (i) GPS measurement data-sets for passenger vehicles that is representative for the whole fleet and available for scientific purposes, are scarce; and (ii) there is a large increase in the number of decision variables inherent to a model that includes individual driving patterns (see Table 3.2 for an example of the required computational times and numbers of variables).

In the present work, passenger EVs have been integrated into ELIN, EPOD and ENODE using three different methodologies:

- aggregated vehicle profile (AGG)
- representative daily driving profiles (DDP)
- yearly driving profiles (YDP)

DDP and YDP include individual driving patterns, while AGG uses only the values averaged from the measured individual vehicles. In this work, assumptions as to passenger travelling patterns are based on the data from GPS measurements of 426 vehicles measured during 30-73 days (for details on the GPS vehicle data-set, see Section 4.2).

The AGG methodology entails only an aggregated vehicle profile (i.e., one vehicle category), where it is assumed that a share of the fleet is parked and a share is out being driven. YDP and DDP divide the measured vehicles into several categories of individual driving profiles (200 to 426 categories). On the one hand, DDP applies a K-means clustering method [99] to determine which of the daily driving profiles (in this work, approximately 200) are representative of the total number of daily profiles (27,879 measured days in the GPS vehicle data-set) and how these should be weighted to represent the total aggregate. YDP, on the other hand, uses the measured driving period (between 30 to 73 days) per vehicle and extrapolates the data from the original measurement campaign period to 12 months.

Table 3.2 gives a description, as well as the main drawbacks and benefits of the three different integration methodologies of EVs in electricity system models. A more detailed description of how the GPS vehicle driving data have been used in the three methodologies is presented in **Paper VI**.

In summary, AGG can be used in most optimisation models, regardless of the size of the model. If including individual driving demands, as in DDP and YDP, there may be other aspects in the model that need to be less-detailed, e.g., excluding trade between regions, as in the ENODE model in **Papers V** and **VI**. With the AGG methodology, there is the risk that a vehicle that is standing still can be charging so as to supply an EV that is out driving, leading to an over-estimation of the potential of using the EV batteries for optimised charging and V2G.

In **Paper VI**, we analyse when the AGG methodology is sufficiently good to estimate the value of V2G using electricity system models (i.e., without over-estimating the V2G potential). The results of the analysis in **Paper VI** are discussed in Section 5.4. The drawback with DDP, as mentioned in Table 3.2, is that it uses representative days out of a full year of driving using

weighting factors, which will not give any information as to how these days are linked in time, and thus, there is no possibility to store electricity in the EV batteries between days.

Trucks and buses are assumed to be electrified using ERS. The load profiles for buses and trucks are taken from the analysis of traffic flow data (ADT) (see Section 4.1). The demand from ERS is then the yearly load profile, i.e., the hourly share of the yearly demand, multiplied by the total amount of yearly driving for the fleet (see **Papers I and III**).

Table 3.2: Overview of the three methods to integrate electric vehicles (EVs) into electricity system models.

	Aggregated vehicle profile (AGG)	Representative daily driving profiles (DDP)	Yearly driving profiles (YDP)
Number of vehicle profiles	One (or possible two)	200	200–426
Number of variables	2,828,445	9,046,053	9,046,053–17,022,065
CPU time per ENODE region [seconds]	~ 241	~ 1,485	~ 1,485–3,589
Description	One large vehicle battery, share of the fleet out driving and being parked, storage between days is possible	Chosen 200 representative daily driving profiles out of the ~28,000 measured days with a weighting factor attached to each profile	The measured driving demands and profiles of 426 vehicles extrapolated to a full year of driving
Benefits	Not computationally demanding and can therefore be used in most optimisation models, regardless of the size of the model	200 DDP gives a good approximation of the driving profile/demand of the passenger car fleet	Good approximation of the driving profile, storage between days can be included in the model, possibility to analyse research topics related to individual EVs
Drawbacks	Risk of over-estimating the V2G potential, no possibility to analyse research topics related to individual EVs	Computationally demanding, no connections between days in the model, no possibility to analyse research topics related to individual EVs	Extrapolation of the relatively short measured period to a full year, computationally demanding
Applied in paper	Paper VI	Papers III and VI	Papers IV–VI

3.4 Modelling comparisons

In **Papers III–VI**, the impacts of EVs on the electricity system are analysed, together with determining the system value of V2G using different models and EV integration methodologies. Why is it desirable to use different EV integration methodologies and different optimisation models when estimating the system benefits of V2G?

An optimal model to use would, of course, be a model that can include many more features, like trade between regions, pathway from existing system to a system with zero emissions, individual EV driving profiles and seasonal storage. However, such an optimisation model would be too computationally demanding to be useful.

By running both the ELIN-EPOD model package and the ENODE model, we can conclude that: (i) the ELIN-EPOD model package under-estimates the potential of V2G by not including storage between days in ELIN (and, therefore, also in EPOD, which obtains investments from ELIN); and (ii) the ENODE model may over-estimate the potential of V2G, since trade, which is not included, has a smoothing effect of the net-load curve in a system. The geographical smoothing effect of wind power has been shown by Reichenberg [100].

The “true value” of V2G can be expected to lie somewhere between the results obtained from the ELIN-EPOD model package and the ENODE model. Figure 3.4 shows the value of V2G in a qualitative way assuming different models and EV integration methodologies.

The time resolutions in ELIN, EPOD and ENODE are hourly, which means that other system benefits of V2G, such as frequency regulation and voltage stability (described in Section 2.5) are not included in the cost optimisation. In that sense, both ELIN-EPOD and ENODE may under-estimate the value of V2G. Other limitations of the models, which might lead to an over-estimation of the system value of V2G, are that there is no price elasticity in the models and the models have perfect foresight and perfect information sharing. It assumes that all EV owners participating in V2G are always acting according to what is optimal from the system perspective and, thereby, over-estimating the potential of V2G. Furthermore, the models include only the electricity sector and parts of the heating sector, while the industry sector and the parts of the transport sector that are not yet electrified do not lie within the system boundaries of the models.

Figure 3.4 also shows the value of V2G for the three different EV integration methodologies (described in Section 3.3). DDP potentially under-estimate the value of V2G due to the limitation of only intra-day storage (using representative days), as shown in **Paper VI**. In contrast, AGG, as seen in **Paper VI**, is usually as good as YDP for estimating the system benefit of V2G. However, AGG over-estimates the potential of V2G when the infrastructure is limited to the home location for a region without access to large volumes of hydropower (see Section 5.4). YDP represent the best of the three EV integration methodologies to represent the “true” value of V2G, as YDP include individual driving patterns over several months. However, a limitation of YDP is the lack of similar data-sets for the purposes of comparison, which makes it difficult to decide if the driving patterns of the chosen 426 vehicles are representative of the whole Swedish vehicle fleet.

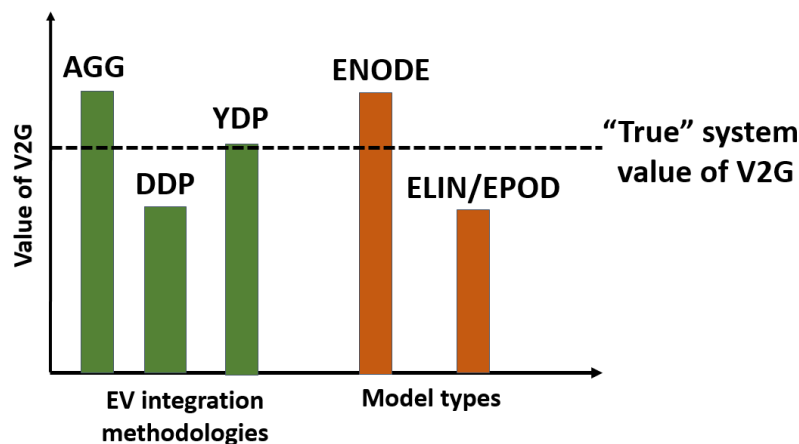


Figure 3.4: The qualitative system value of vehicle-to-grid (V2G) assuming three EV integration methodologies (AGG, DDP and YDP) and three electricity system optimisation models (ENODE, ELIN-EPOD model package). AGG; aggregated vehicle profile; DDP, representative daily driving profiles; YDP, yearly driving profiles.

Table 3.3 lists the main features of the models developed and used in this thesis. In Table 3.3, the main input and output parameters are described and information is listed on the geographical scope, time resolution, syntax, and type of model.

Table 3.3: A description of the models developed and used in this thesis.

	Vehicle energy consumption model	Investment model (ELIN)	Dispatch model (EPOD)	Investment and dispatch model (ENODE)
Paper(s)	I	III and IV	III and IV	V and VI
Syntax	MATLAB	GAMS	GAMS	GAMS
Type of model	Simulation	Optimisation	Optimisation	Optimisation
Time resolution	Yearly and hourly	Investment period 2010–2050, where each decade is represented by 1 year, 20 representative days per year	Hourly (all hours for one selected year, i.e. 2030)	All hours for 1 year
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
Geographical scope modelled	1,100 km of highway in Norway (highway E39)	Scandinavia, Germany, Spain, Portugal, France, UK, Ireland	Scandinavia, Germany, Spain, Portugal, France, UK, Ireland	Hungary, central Spain, central Sweden, Ireland
Main data inputs	i) Road data (slope, speed limit, IRI, MPD) ii) Vehicle data (drive-train efficiency, front area, mass, motor output, air and rolling resistance coefficient) iii) Charging efficiency iv) Hourly traffic flows v) Average daily traffic	i) Energy demand ii) Information on current capacity installations (lifetime, efficiency) iii) Investment cost and properties by technology iv) CO ₂ targets v) Numbers of vehicles and driving patterns ii) Energy use per vehicle kilometre	i) Energy demand ii) Solar and wind profiles iii) Capacities by fuel and technology iv) Running costs and properties by technology v) Number of vehicles and driving patterns ii) Energy use per vehicle kilometre	Same as in ELIN and EPOD combined except that it does not include present installed capacity for installations of power technologies and cables Cost and properties for different storage technologies (hydrogen, stationary batteries)
Main output parameters	i) Energy consumption per kilometre ii) Hourly and yearly energy demands for a highway iii) Regeneration potential iv) Traffic flow profile for a highway	i) Total system cost ii) Investments in power capacities iii) Fuel and CO ₂ prices iv) Investments in transmission lines v) EV charging and discharging profiles vi) trade between regions	i) Total system cost ii) Generation profile by fuel and technology iii) Marginal cost of electricity iv) CO ₂ emissions v) EV charging and discharging profiles vi) trade between regions	i) Total system cost ii) Investments in power and storage capacities iii) Generation profile by fuel and technology iv) Stationary batteries and hydrogen storage charging/discharging profiles v) EV charging and discharging profiles

CHAPTER 4

Scenarios and Input Data

This chapter provides a description of the two data-sets used in this thesis for vehicle driving demand and patterns. The two data-sets are: the Traffic data-set that consist of measurements of the average daily traffic on road segments (section 4.1); and the GPS vehicle data-set consisting of GPS measurements of individual vehicles over several months (section 4.2). Section 4.3 presents the scenarios and parameters investigated in **Papers I-VI**.

4.1 The Traffic data-set

Average daily traffic (ADT) data (i.e., average number of vehicles per day) were used for the analyses in **Papers I** and **II**. ADT data were provided by Norwegian National Public Road Administration (NPRA) [101] and the Swedish Transport Administration (STA) [102]. ADT is measured by NPRA and STA for two vehicle categories, light and heavy vehicles, where all vehicle types of length >5.6 meter or of weight >3.5 tonnes are classified as heavy vehicles. In the present study, mainly road traffic statistics from 2015 and 2016 were used, and no projections of future traffic flows were considered in **Papers I** and **II**.

In **Paper I**, the energy and power demands of a single road (E39 in Norway) are analysed, and in **Paper II**, the CO₂ emissions and cost for ERS are estimated for the network of European (E) and National (N) roads. For these two research topics, ADT data have several advantages, for example in terms of being accurate and being measured frequently. The ADT is measured at 770 check-points along the E39, while the hourly traffic for all the hours of the year is measured at 70 check-points.

However, the disadvantage with ADT data is that the driving patterns of individual vehicles are not measured. For example, there is no information on where the vehicles were driving before entering or after passing the measured check-point. Therefore, in **Papers III-VI**, we use individual driving data for passenger vehicles to understand the movements of individual vehicles (see section 4.2). Figure 4.1 shows the ADT for the European, National, County and Municipality roads in Norway.

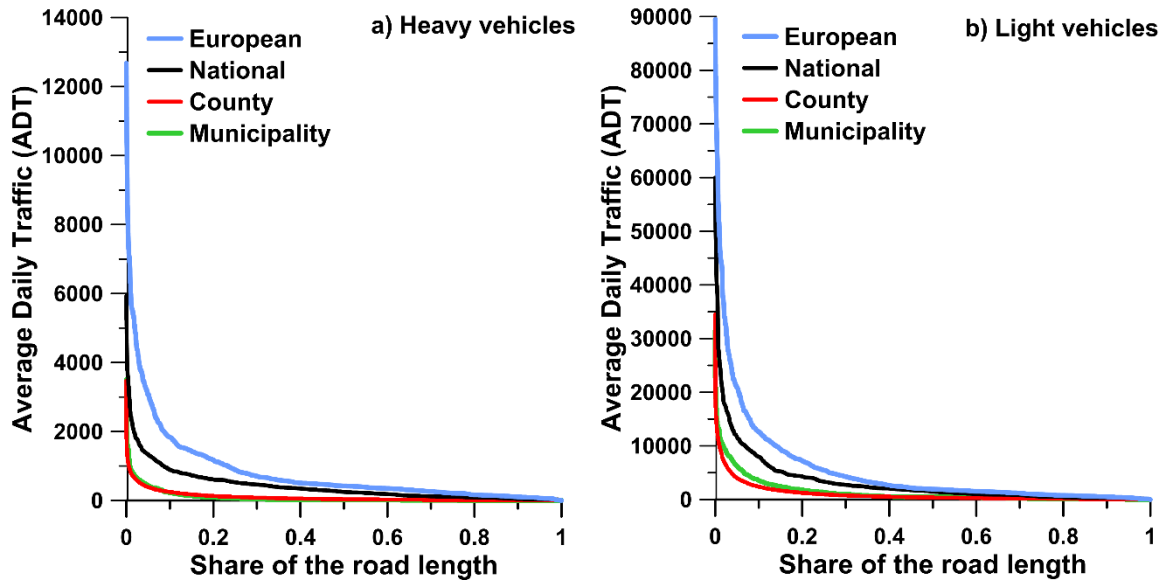


Figure 4.1: Average daily traffic (ADT; average number of vehicles per day) values along the lengths of the European (6,800 km), National (4,100 km), County (46,000 km) and Municipality (4,000 km) roads in Norway for: heavy vehicles (a); and light vehicles (b). Data from NPRA for year 2015 and 2016 [101].

As shown in Figure 4.1, there are large variations in the ADT, both within and between the road categories. Compared to all other types of roads, the E- and N-roads have a higher share of road length with ADT >10,000 light vehicles (Figure 4.1b). In terms of kilometres of road length, all the other types of roads have more kilometres with ADT in the range of 1,000–5,000 than the E- and N-roads. E-roads have more kilometres with a very high ADT, as expected.

In Figure 4.2, the ADT for three E-roads are shown: the E39 (between Kristiansand and Trondheim); the E6 (between Malmö and Gothenburg); and the E18/E20 (between Gothenburg and Stockholm).

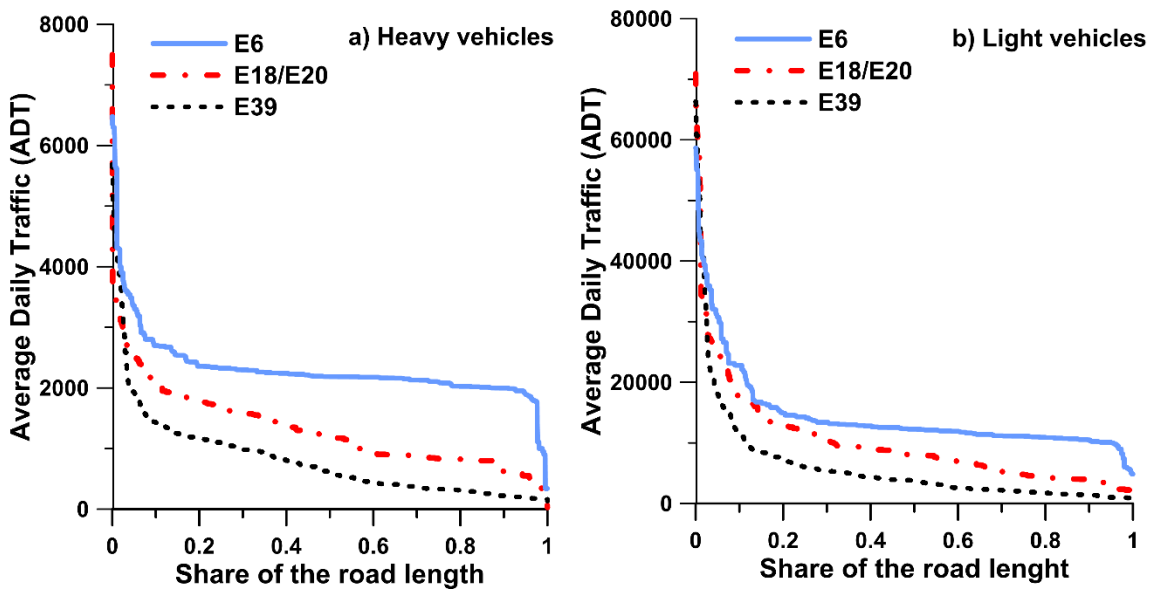


Figure 4.2: Average daily traffic (ADT; average number of vehicles per day) values along the lengths of the E39, E6, and E18/E20 roads in Norway and Sweden for: heavy vehicles (a); and light vehicles (b). Data from NPRA [101] and STA [102] for year 2016.

There are large geographical variations in the intensities of the traffic flows along all the roads in Figure 4.2. The steep curve in Figure 4.2 for an ADT of <10,000 light vehicles is due to the fact that these parts of the roads are primarily used for commuting to and from work. On an average day, the traffic on the E39 varies from less than 1,000 vehicles/day in the rural areas to about 70,000 vehicles in one of the urban areas (Stavanger). The ADT values for the E39 highway in Norway (both heavy and light vehicles) are lower than the traffic levels on the E18/E20 and E6 in Sweden (Figure 4.2).

4.2 The GPS vehicle data-set

In the modelling of the passenger EV fleet in **Papers III–VI**, real-world, individual driving data have been used instead of data derived from national surveys on travel habits (as have been used in most of the previous studies [30–37, 72–74, 97, 98]). Travel-habit surveys do not provide information down to the level of single trips, including travel patterns for several days in a row.

The travelling patterns used in this thesis are from a campaign that was conducted in the region of Västra Götaland (western part of Sweden), in which approximately 770 randomly chosen gasoline- and diesel-powered vehicles were monitored with GPS. In total, about 107,910 trips were logged between 2010 and 2012 [29, 103].

The vehicles, which were randomly selected from the Swedish vehicle database, are assumed to be reasonably representative for western Sweden in terms of fleet composition, car ownership, household size, owner income level, and the distributions of cars across larger and smaller towns and rural areas. Of the around 770 households that had GPS equipment sent to them, 529 were logged for more than 30 days, and 426 of these provided high-quality data (i.e., excluding those vehicles for which too much data were missing).

Each vehicle was measured for a period of 30–73 days, although the 1–3-month periods occurred during different times of the year for the vehicles involved. In total, 27,879 days during weekends and holidays were included. Two different methodologies to include individual driving patterns in the models (ELIN, EPOD and ENODE) were developed in **Papers III–VI** (for a detailed description, see Section 3.3).

An analysis of the GPS vehicle data-set revealed two important aspects: (i) at any hour of the year, at least 70% of the vehicle fleet are parked somewhere and 40% of the vehicle fleet are parked at the assumed home location; and (ii) already at an assumed battery capacity of 15 kWh per vehicle, such a battery can, on average, cover 70% of all the distance travelled by the vehicle. This means that a large proportion of the fleet can be connected to the charging infrastructure during all hours of the year, and that few trips are for distances longer than the battery range. Figure 4.3 shows the share of the fleet that is parked on an average day (4.3a) and the share of the driving distance that cannot be covered by the battery range (4.3b). In Figure 4.3b, an electricity demand of 0.17 kWh/km is assumed.

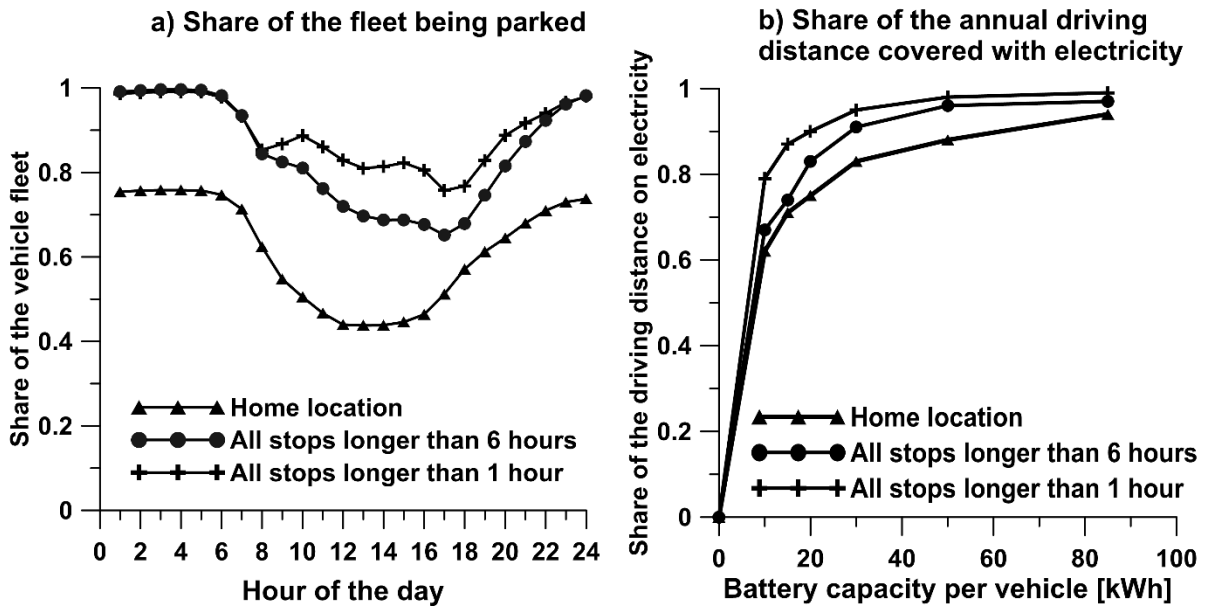


Figure 4.3: Share of the vehicle fleet that is parked at the home location, and parked at all stops longer than 6 hours, and longer than 1 hour during an average day (a); and the share of the driving distance that can be covered by electricity and that charging is possible according to the stop strategy presented by the lines (b). Hour 1 corresponds to 1 am. Based on data from the GPS vehicle data-set [29, 103].

The GPS data applied in this work to determine individual driving patterns for several days in a row, are unique and so far only available for one region in Sweden and only for passenger cars (i.e., not for buses and trucks). Since no such data were available for the other regions investigated, we have assumed the same driving profiles for all the regions investigated in Europe. However, there may be regional differences in, e.g., working hours and leisure time activities, as well as in geographical factors, in that Sweden is a low-population-density country. We also assume that the current driving demand and profile, as seen in the data-set, remains the same in the future. Nevertheless, autonomous driving and car sharing may significantly change the future use of passenger vehicles.

4.3 Scenarios

Table 4.1 shows the parameters that were varied in **Papers I–VI** when assuming different scenarios. As shown in Table 4.1, the electrification rate is assumed to be 60% or 100% EVs by year 2050. The geographical scope of the modelling study varies from a single road in **Paper I** to a national road network in **Paper II** to several regions and countries in **Papers III–VI**.

The scenarios include three different charging strategies for passenger EVs: (i) recharging of the passenger EVs directly subsequent to driving (*Direct*); (ii) optimisation of the charging time to minimise the cost of meeting the electricity demand (*Optimised; Opt*); and (iii) optimised charging and a passenger vehicle-to-grid strategy that includes the possibility to discharge the passenger EVs to the grid (*Optimised with V2G; Opt+V2G*).

Investments in nuclear power are allowed in the modelling of the electricity system in **Papers V** and **VI**, but not allowed in **Papers III** and **IV**. The area limitation for solar power is, in ELIN and EPOD, assumed to be 134 kW/km² in **Paper III**. This is a rather conservative estimate, since for example in a recent publication by Wirth et al. [104], it turns out that the area limitations are less strict. In **Papers IV–VI**, the area limitation for solar power is removed.

Table 4.1: Overview of the parameters varied in the studies described in **Papers I–VI**. V2G, vehicle-to-grid; EV, electric vehicle; ERS, electric road systems; H₂, hydrogen.

Parameter	Paper I	II	III	IV	V	VI
Electrification strategies	EV static charging, ERS, H ₂ , electrofuels	ERS	EV static charging, ERS	EV static charging, ERS	EV static charging	EV static charging
CO ₂ reduction target for the electricity system (%)	100	100	93	99	100	100
Electrification rate(s) of the transport sector by year 2050 (%)	100	100	60, 100	60	60	60
Maximum available EV battery capacity (kWh/car)	30	-	15, 30, 85	15, 30, 85	15, 30, 85	15, 30, 85
Charging strategies	-	-	Opt, Opt+V2G	Direct, Opt, Opt+V2G	Direct, Opt, Opt+V2G	Opt, Opt+V2G
Charging infrastructure connection	-	-	All stops longer than 1 hour	All stops longer than 1 hour	Home, All stops longer than 1 hour	Home, All stops longer than 6 hours, 1 hour
Percentage of EVs participating in Optimised charging or V2G (%)	100	-	100	100	0, 20, 40, 60, 80, 100	0, 20, 40, 60, 80, 100
Cost for V2G (EUR/MWh)	-	-	0	0	0, 10, 20, 30, 40, 50, 75, 100	0
Road transport modes (passenger cars, trucks, buses)	All	All	All	All	Passenger cars	Passenger cars

Figure 4.4a shows the number of EVs until 2050 in a scenario, ending at 60% EVs, for different countries in Europe, as well as for all countries in Europe. In Figure 4.4a, a yearly increase of the total passenger vehicle fleet is assumed to be 1%, in accordance with Johansson et al [9]. As seen in Figure 4.4a, a rapid increase in the number of EVs is needed to reach such a target, which will require the production of a large number of batteries. Figure 4.4b shows the battery capacity level that needs to be provided each year between 2019 and 2050 to reach the number of passenger EVs presented in Figure 4.4a. The calculations made in Figure 4.4b assume an average battery capacity of 30 kWh, the number of EVs presented in Figure 4.4a (ending in 2050 at 60% of the prognosed passenger vehicle fleet), and a vehicle battery lifetime of 10 years.

In the EU, approximately 4,000 GWh of battery capacity needs to be produced per year by 2050 if electrifying 60% of the European vehicle fleet with EVs. This can be compared with the total global annual production of 200 GWh in 2018 [105]. This means that until 2050, at least 100 battery factories corresponding in size to the Tesla Giga Factory (~40 GWh per factory) must be created to cover the European EV battery demand estimated in Figure 4.4b.

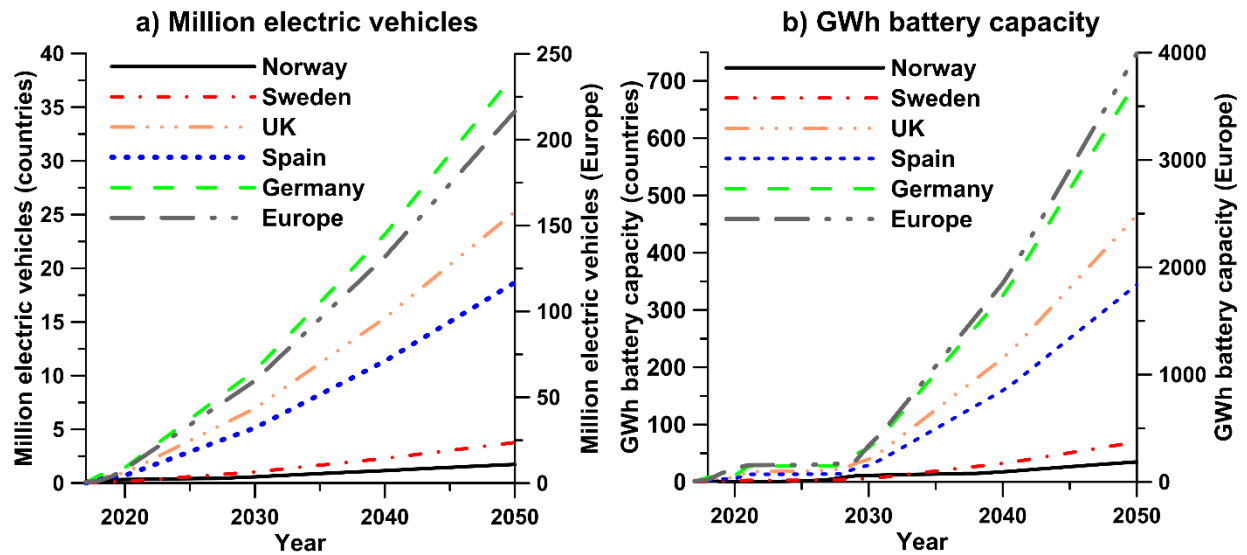


Figure 4.4: Numbers of passenger electric vehicles assumed in the modelling scenario with 60% EV by year 2050 for selected countries (left y-axis) and for Europe (right y-axis) (a) and the battery capacity produced per year to reach 60% EV in the fleet by 2050 for selected countries (left y-axis) and for Europe (right y-axis) (b). An average battery capacity of 30 kWh and a battery life-time of 10 years is assumed.

CHAPTER 5

Results and Discussion

This chapter provides the results for the four aims of this thesis, where Sections 5.1 to 5.4 correspond to Aims i to iv in Section 1.1, respectively. In addition, this chapter provides a reflection on the models and data used in this thesis (Section 5.5) and some implications for policy (Section 5.6).

5.1 Electrification of transport – when, where and how much?

Electrification of the transport sector will obviously increase the total electricity demand, assuming that other sectors will not decrease their usage of electricity. The impacts from electrification of the transport sector on the electricity system depend on the amount of electricity (how much), whether it correlates with peaks in electricity use (when), and how the new load is allocated geographically (where). The different options for electrification of road transport, as introduced in Chapter 2, differ significantly in terms of the load profile, amount of electricity, and opportunities for shifting the demand both spatially and temporally. Described in this section (5.1) is an analysis of the electricity demand on two different geographical scales: a single road; and roads at the national level. Furthermore, Section 5.1.3 describes the patterns of EV charging and discharging to the grid obtained from the modelling in this thesis.

5.1.1 A single road - highway E39

In **Paper I**, we have used the vehicle energy consumption model to analyse how the electricity demand varies with time and how this occurs along the stretch of a single highway (in this case, the E39). **Paper I** shows that a road with the characteristics of the E39 exhibits large variations in both the geographical and time distributions of its energy and power demands.

The yearly electricity demand of the traffic on the E39, assuming direct electrification of the current traffic flow, is comparable to that of a larger industry (i.e., consuming approximately 1 TWh per year). The energy demand of heavy vehicles (trucks and buses) is approximately 57% of the total energy demand, even though heavy vehicles account for only 12% of the vehicle kilometres.

Figure 5.1 shows the distribution of the electricity demand between sectors, when electrifying 100% of the current traffic flows on the E39 using a direct electrification strategy. Figure 5.1 shows that electrification of the E39 will increase the yearly municipal electricity consumption by 1%–100%. If electrification of the E39 is performed using an indirect, instead of direct, electrification strategy *via*, for instance, hydrogen or electrofuels, the annual electricity demand from traffic on the E39 would increase substantially (4–5-fold) (**Paper I**).

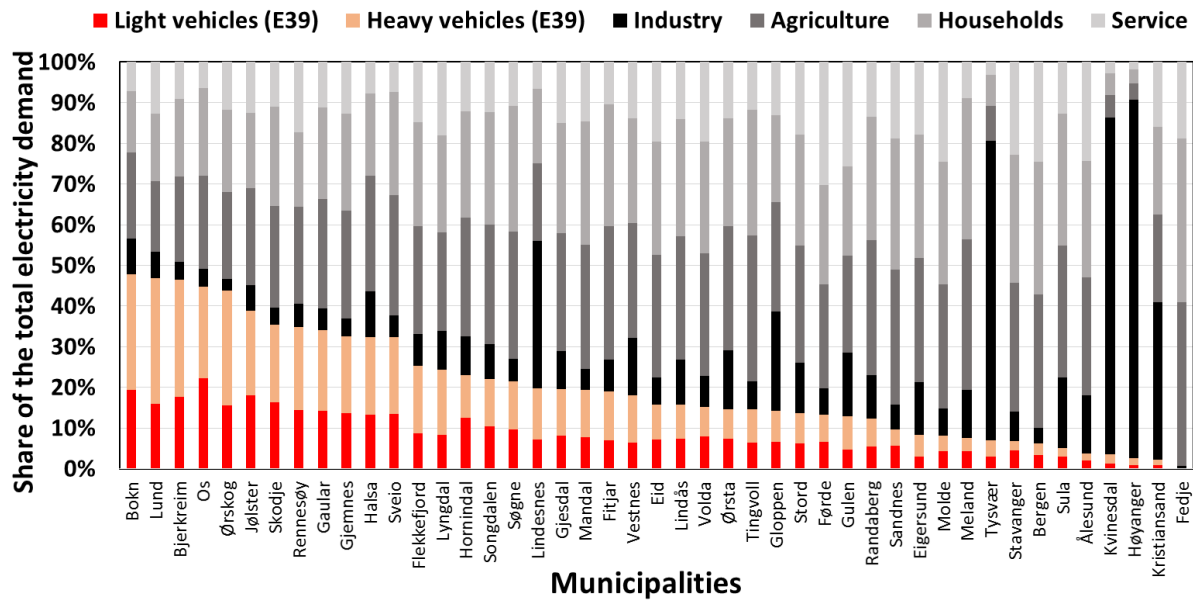


Figure 5.1: Distributions of the electricity demand between sectors when electrifying the E39 highway applying a direct electrification strategy. It is assumed that 100% of the current traffic flow on the E39 is electrified [101]. The statistical data for the present electricity demand from all sectors (except transport) are taken from Statistics Norway [106].

The geographical distribution of the electricity demand for a single road depends to a large extent on the traffic flow along the road, with a higher demand seen in the vicinity of urban areas, as concluded in **Paper I**. The geographical peaks around the densely populated areas, mainly caused by light vehicles that are used for shorter commutes and for distribution purposes, could instead of day-time charging with ERS or fast chargers, be met by larger vehicle batteries that are charged during night-time or during a period of high power output from VRE.

There are also considerable differences for both light and heavy vehicles in the time distribution of the energy demand for a road between:

- night-time and day-time
- weekends and weekdays
- working weeks and holiday weeks

The energy demand peaks during day-time, with the absolute highest peak occurring between 3 pm and 4 pm on a weekday when most people are leaving the work-place (as in the Norwegian E39 case in **Paper I**). The peak power demand for the dimensioning hour of the present regional electricity system when electrifying the E39 would increase by 1%–2% if a direct electrification strategy is applied, assuming the present traffic volume (**Paper I**). However, static charging of EVs could, to some extent, be moved in time and geographical allocation.

The geographical and time distribution of the demands for power with an indirect electrification strategy depend on where and when the hydrogen and electrofuels are produced, as well as the storage capacity of the fuel. With the storage of hydrogen or electrofuels, the fuel can be produced at any time and place, which means that, in contrast to direct electrification, using the fuel would make it possible to avoid increasing the peak power demand in the regional electricity system during peak periods.

The flexibility gained from using indirect electrification via electrofuels, in terms of when and where such fuels are produced, depends on the infrastructural choices made for such fuels. Thus, the availabilities and costs of storage solutions, the options and costs for the fuel transportation infrastructure, and the direct cost of fuel manufacture are important issues to consider in the light of potential flexibility and system gains.

Hydrogen is much more challenging to transport and store locally compared to electrofuels, due to its low energy density in volumetric terms. In addition, large hydrogen storage units at low compression are much more efficient than smaller storage units at high compression. Thus, it appears that hydrogen offers less geographical flexibility than electrofuels. However, the scope of this thesis encompasses direct electrification of transport. Therefore, investigations of the value for the regional electricity system of ensuring more flexible use of electricity in the transport sector through an indirect electrification strategy (with the drawback of lower efficiency from electricity source to the wheels) is left for future work.

5.1.2 Regional and national levels – examples from some OECD countries

To reach the climate target of zero emissions in the energy system, the electrification of a single road will, of course, not be sufficient. In Norway, the total lengths of the European (E)- and National (N)-roads are 6,830 km and 4,130 km, respectively [107]. The yearly electricity demand from full electrification of current road transportation on these roads is calculated to be about 3.5 TWh when using direct electrification, or 44 TWh when using indirect electrification (in this case, electrofuels).

Figure 5.2 shows the current total hourly electricity demand in Norway from all sectors, as well as the demand from road transport that would arise when using direct electrification of the current traffic volumes on all E- and N-roads in Norway.

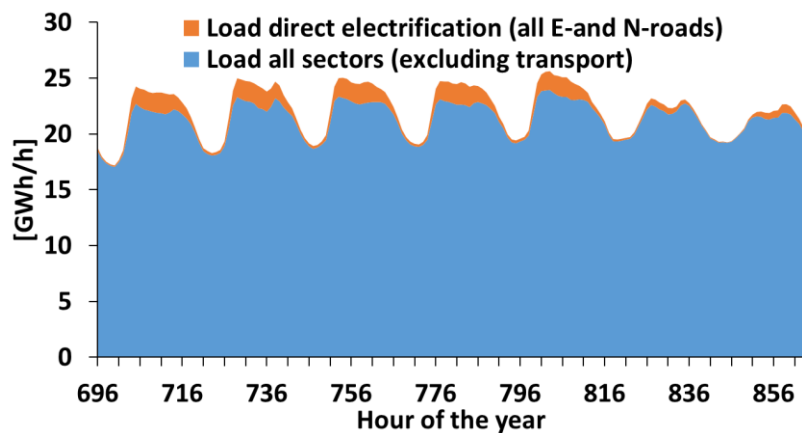


Figure 5.2: The hourly electricity load in Norway during the first week of February, and the load if electrifying all Norwegian European (E) and National (N) roads using a direct electrification strategy. The starting Hour 696 is 12 AM on a Sunday night. Data for the load from all sectors are from year 2018 [108]. The load from direct electrification assumes 100% electrification of current traffic volumes [101].

Direct electrification will add a new load to hours that currently already experience a high load (Figure 5.2). If all the E- and N-roads in Norway were to be equipped with ERS, the peak power increase would be ~7%, assuming that all the traffic on those roads would make use of static charging and/or the ERS infrastructure.

A full electrification of all passenger cars, and not just a single road or road network as shown previously, would incur a 6%–24% increase in electricity demand *via* direct electrification strategies depending on the country (Table 5.1). However, an indirect electrification strategy using hydrogen, with an assumed grid-to-wheel efficiency of 24%, would imply substantially more electricity, i.e., an increase in demand in the range of 19%–84% depending on the country (Table 5.1).

This percentage increase differs between countries in relation to the structure of the current electricity demand, in that it reflects which part and how much of the entire energy system is dependent upon electricity as the energy carrier. Given that there are numerous ways to electrify the transportation sector, e.g., EVs, hydrogen with fuel cells, electrofuels with internal combustion engines and/or ERS, it is not clear if the main challenge is related to energy or capacity within the electricity system. It will depend on the composition of the current electricity system and the conditions for renewable energy (see Section 5.3).

Table 5.1 includes some of the countries investigated in this thesis, as well as some other selected countries for comparison. As shown in Table 5.1, the countries analysed in this thesis include those in which the electricity demand for passenger cars will have a strong impact (e.g., Germany and UK) and those in which it will have a weak impact (e.g., Norway and Sweden) on the total national yearly electricity demand. The difference between, for example, Norway (6%–26%) and Germany (21%–96%) reflects the fact that the current electricity demand per capita (excluding EVs) is higher in Norway than in Germany. The high electricity demand per capita in Norway can be explained by the presence of electricity-intensive industry and electricity use for heating in the form of heat pumps.

Table 5.1: Electricity demand in year 2017 [4], number of passenger cars in year 2017 [105], and the increase in electricity demand if electrifying 100% of the present passenger vehicles, using both direct (EV and ERS) or indirect electrification strategies (hydrogen and electrofuels).

Country	Electricity generation year 2017 [4] (TWh/yr)	Number of passenger cars year 2017 [105] (thousands)	Increase in electricity demand due to EV/ERS [%]*	Increase in electricity demand due to hydrogen vehicles [%]*	Increase in electricity demand due to electrofuels [%]*
China	5899	250 138	11	38	50
USA	4147	265 043	16	57	76
Canada	538	22 678	11	37	50
Japan	1012	91 377	23	80	107
Germany	575	46 474	21	72	96
France	478	32 005	17	59	79
Sweden	137	4 844	9	31	42
Great Britain	330	31 200	24	84	112
Norway	124	2 719	6	19	26

* Assuming a driving distance of 15,000 km per year and 0.17 kWh_e/km, 0.59 kWh_e/km, and 0.79 kWh_e/km for an electric vehicle, hydrogen vehicle using fuel cell, and a vehicle run on electrofuels in internal combustion engine, respectively. The number of passenger cars that is electrified is the same as the number of passenger cars in 2017.

5.1.3 Charging and discharging patterns of EVs

In the modelling described in **Papers III–VI**, three different charging strategies for EVs have been applied: direct; optimised; and optimised with V2G (for a description of the strategies, see Section 4.3). Figure 5.3 shows daily charging profile for a yearly average day for the three EV charging strategies in two different regions, Spain (5.3a) and Germany (5.3b). The electricity system modelled in Figure 5.3 assumes close-to-zero CO₂ emissions, resulting in a high share of VRE in the system. Spain represents an electricity system that, in the model results for 2050, has a high share of solar power, while Germany has a mix of wind, solar and thermal power.

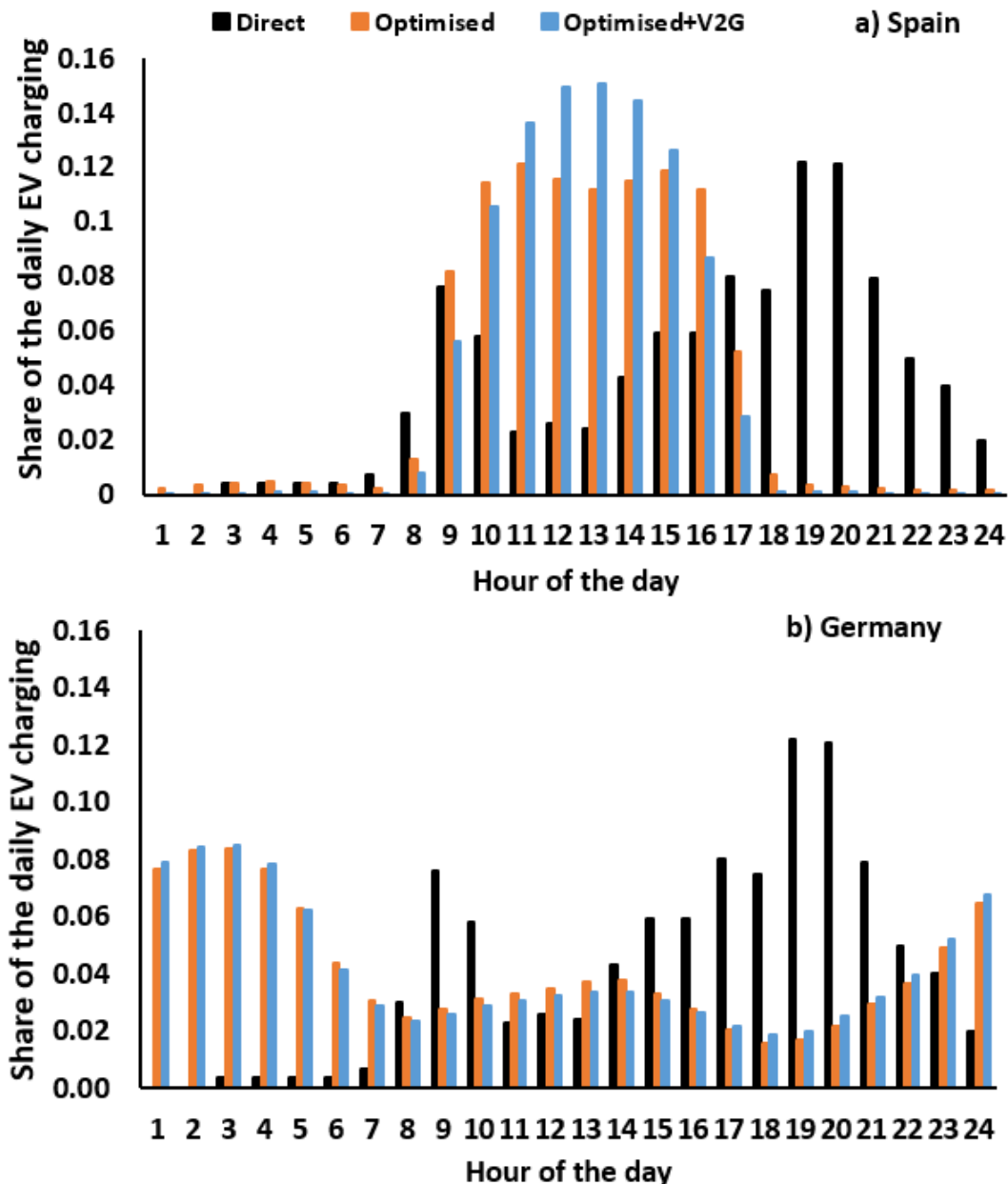


Figure 5.3: The daily charging profile for a yearly average day for direct charging, and optimised charging with and without V2G in: Spain (a); and Germany (b). The electricity system modelled assumes close-to-zero CO₂ emissions and 60% of the passenger fleet being electric vehicles.

As shown in Figure 5.3, the time of charging differs considerably between the direct charging strategy and the two optimised charging strategies. There are also differences between Spain (a system based on a high share of solar power) and Germany (a system based on a mix of wind, solar and thermal power). Thus, in Spain, there is a value associated with shifting the charging towards the middle of the day due to large share of solar PV, whereas in Germany the optimal trend is to charge during the night-time due to a continuous diurnal difference in consumption and the use of thermal power. It should also be noted that some vehicles, due to their individual driving patterns, require charging even during hours of the day when it is not optimal from an electricity system point-of-view.

In the case of V2G, the discharging back to the grid from passenger EVs in all the countries investigated occurs mainly during the peak hours in the morning and afternoon (see **Papers III** and **IV**). As a consequence, in an electricity system based on a high share of solar electricity generation, the presence of EVs that allow for V2G, i.e., moving peak solar electricity generation from mid-day to meet the evening and morning peak demand, can out-compete the traditional thermal and nuclear base-load. Countries that have other VMS than EVs, such as hydropower, have flatter charging (if assuming optimised charging) and discharging to grid curves than other countries without access to other cheap VMS (**Paper IV**).

As mentioned above, Figure 5.3 shows the average values for the overall vehicle fleet. However, the results from the modelling of individual EVs, i.e., YDP in this thesis, show that the charging and discharging of the individual EVs differ significantly across the 426 individual driving profiles included in the models. Figure 5.4 shows the levels of electricity discharged to the grid in relation to the number of kilometres driven per year (Figure 5.4a and 5.4b) and number of hours parked per year (Figure 5.4c) for the 426 yearly driving profiles. Although, in general longer driving distance means less V2G, there is also an influence of the individual driving profile seen in Figure 5.4.

The amount of V2G per vehicle also depends on the region modelled (5.4a), the battery storage capacity (5.4b), and access to the charging infrastructure (5.4c). This is described in **Paper V** and further discussed in Section 5.3. Figure 5.4 shows model results from the ENODE model, assuming zero CO₂ emissions from the electricity system by 2050 and 60% of the vehicle fleet being EVs using an optimised with V2G charging strategy.

The following three main conclusions can be drawn from the results in Figure 5.4:

- regions that have a large share of solar power (e.g., central Spain) will discharge the EV batteries with a higher energy volume per year than regions that have a large share of wind power (e.g., Ireland).
- larger EV batteries in the vehicles will increase the total level of electricity discharged to the grid per year (as well as per driving profile) for all the regions and battery capacities investigated.
- if the charging infrastructure is limited to the home location, most of the EVs will exhibit decreased discharging to the grid, whereas the EVs that are parked for most of the time will increase their V2G discharge.

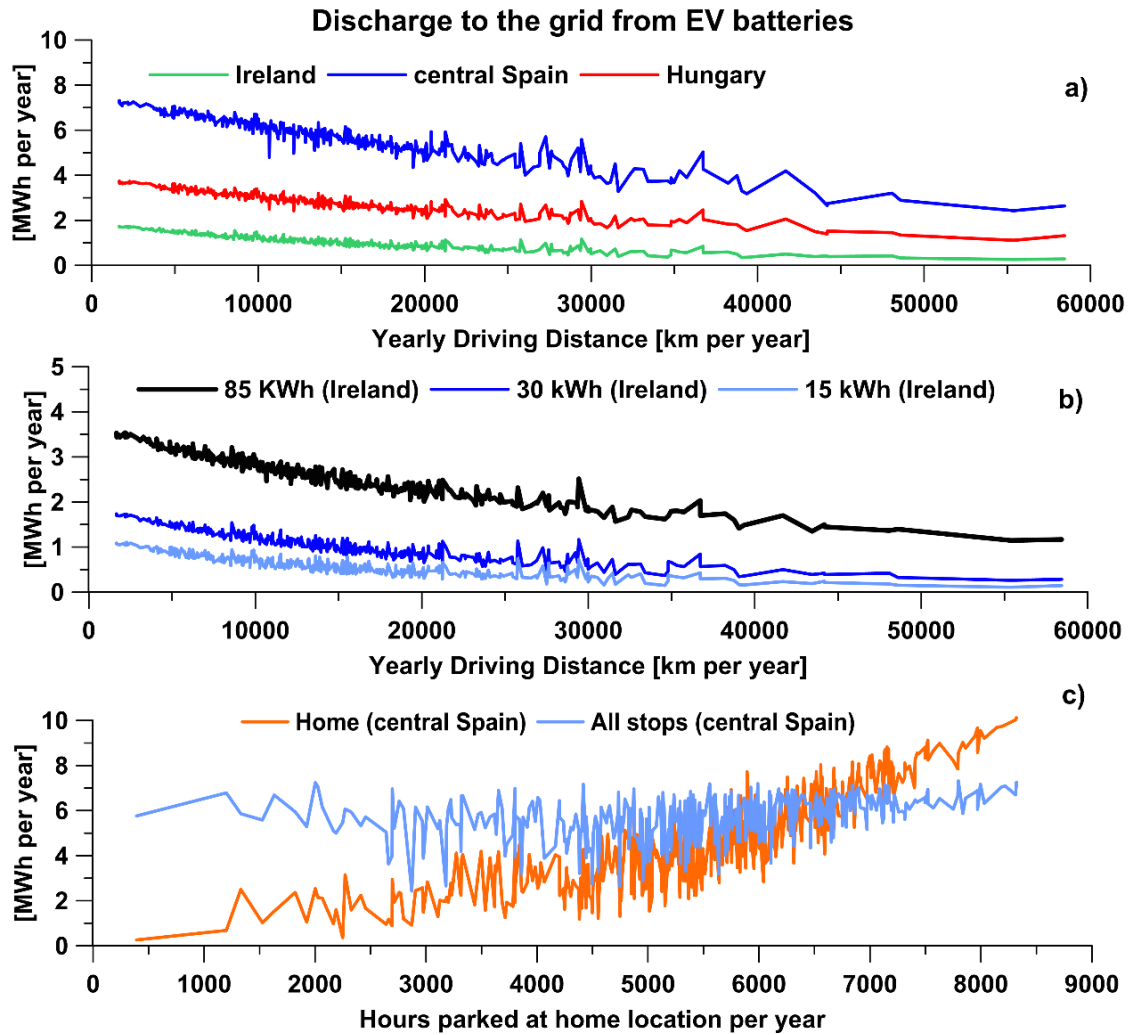


Figure 5.4: Levels of V2G discharge (in MWh per year and profile) back to the grid (y-axis) for the 426 individual EV driving profiles in the models. Level of discharge to the grid as a function of the annual driving distance of the EVs (a and b). Level of discharge to the grid as a function of hours parked at the home location per year (c). Panel (a) shows how much V2G is used in different regions, whereas panel (b) shows the V2G dependency on battery storage capacity. Panel (c) indicates the importance from the V2G perspective of being connected to the grid either at home or also at all stops longer than 1 hour. The results shown are from runs using the ENODE model (i.e., zero CO₂ emissions and 60% passenger electric vehicles) in Paper V. The GPS vehicle data-set used [103] are extrapolated from 30–73 days of driving per vehicle to a full year of driving.

5.2 Electric road systems and its large-scale implications

Papers I–IV investigate from different angles the electricity system impact of ERS and highlight the benefits and challenges linked to a large-scale implementation.

In **Paper I**, the conclusion is that ERS will entail an additional load to the current load profile, which is likely to increase demand during hours with a high net-load (Figure 5.2). In **Papers III** and **IV**, we investigate further how scaling up from a single road to a large-scale roll-out of ERS and massive deployment of EVs using V2G affects investments in new electricity generation capacity. ERS is assumed for trucks, buses and those trips by passenger cars that are not covered by the battery.

Electrification of the transport sector involving the combination of large-scale ERS and V2G is mainly met by increases in solar and wind power generation (depending on the region),

when assuming close-to-zero CO₂ emissions by 2050 (**Paper IV**). However, in a situation with limited V2G, the VRE generation is complemented by some thermal power in Germany as concluded in **Paper III** and **IV**.

The results from the modelling of large-scale ERS and optimised charging with V2G for passenger cars also shows that the need for system flexibility in the form of peak power units will decrease even with ERS, as compared to a scenario without EVs, assuming that V2G of passenger vehicles is allowed to increase system flexibility. If no V2G is applied, the ERS will increase the peak of the net-load curve by approximately 11 GW in Germany in year 2030 when electrifying 20% of all road transportation, which corresponds to a 14% increase in the net-load (**Papers III** and **IV**).

A large-scale installation of ERS on all the E- and N-roads in Norway and Sweden would potentially cover more than 60% and 50% of all the traffic and CO₂ emissions from internal combustion engines from all heavy and light vehicles, respectively. While full implementation of ERS is unlikely, these data are provided solely to demonstrate the future potential of ERS for the electrification of road transportation of people and goods. Large-scale implementation of ERS on 25% of the E- and N-road lengths in Norway and Sweden (i.e., ~6,800 km) would require a total investment of 2.7–7.5 billion €₂₀₁₆ (**Paper II**), assuming an investment cost of 0.4–1.1 M€₂₀₁₆ per kilometre [18, 43, 45-46].

The infrastructure investment cost per vehicle kilometre increases dramatically, as expected, for roads with an ADT of less than approximately 500 if assuming all vehicle types. Thus, electrifying roads with an ERS that only applies to heavy vehicles will increase the cost per vehicle kilometre for a road, as compared to using an ERS for both heavy and light vehicles. As shown in Figure 5.5, approximately 90% (all vehicles) and 40% (heavy vehicles) of the total E- and N-road lengths have a traffic volume of at least 500 vehicles per day (**Paper II**).

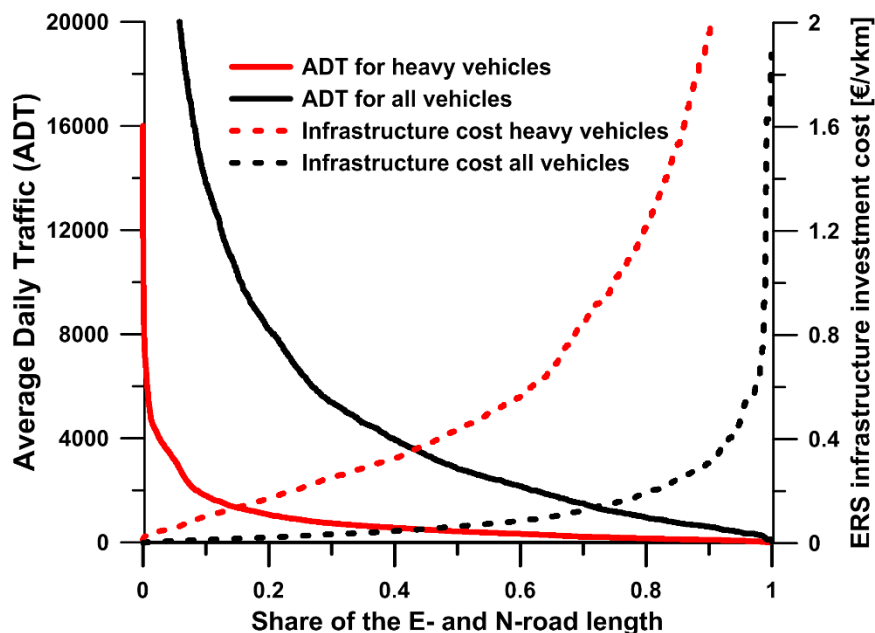


Figure 5.5: Electric road system (ERS) infrastructure investment costs per vehicle kilometre (right y-axis) and the present average daily traffic (left y-axis) as a function of the shares of the European (E) and National (N) road length in Norway and Sweden. The cost for the ERS infrastructure is assumed to be 1.1 M€₂₀₁₆/km (i.e., cost level 2 as defined in Paper II).

The extent to which ERS is a cost competitive strategy for reducing CO₂ emissions from road traffic depends, of course, on the cost of alternative drive-trains and fuels. The vehicle cost per kilometre (vkm) for ERS, i.e., cost for pick-up system and use of electricity, is in the range 0.2–0.4 €₂₀₁₆/vkm and 0.03–0.13 €₂₀₁₆/vkm for a truck and passenger car, respectively (**Paper II**). The total cost per vkm is the vehicle cost plus the ERS infrastructure cost. The ERS infrastructure cost per vkm varies depending on the number of vehicles using the ERS, as seen in Figure 5.5.

The results presented in **Paper II** reveal that for roads with an ADT of at least 1,200 vehicles using an ERS, total cost per kilometre for a truck using ERS (0.35–0.55 €₂₀₁₆/vkm) does not appear to be excessive, as compared to the current most-cost-efficient alternatives diesel, of approximately 0.7 €₂₀₁₆/vkm. Approximately, 15% and 75% of the total length of the E- and N-roads has a traffic volume of heavy and light vehicles, respectively, that exceeds 1,200 vehicles per day, as shown in Figure 5.5.

Figure 5.6 presents the results for passenger vehicles by comparing the costs of seven electrification strategies, where ERS is one option. Included in Figure 5.6 is the total annual cost, which includes the annualised vehicle cost, ERS and fast charging infrastructure cost, fuel production or electricity generation cost, and fuel/electricity distribution cost, excluding taxes and subsidies (see Grahn, Taljegard and Brynolf [42] for more assumptions). It can be seen in Figure 5.6 that the most cost-competitive solution for passenger vehicles for almost all the annual driving distances is to use a BEV with a relatively small battery and either stop to fast charge the battery or use an ERS for longer trips outside the range of the battery.

With a critical mass of ERS users, the ERS infrastructure cost makes up a relatively small proportion (~10%) of the total cost per vehicle kilometre for a passenger car using ERS. An ERS infrastructure cost of 0.05 €/vkm is assumed in Figure 5.6 (approximately 40% of all E- and N-roads have an infrastructure cost of 0.05 €/vkm, assuming all vehicle types are using the ERS as seen in Figure 5.5).

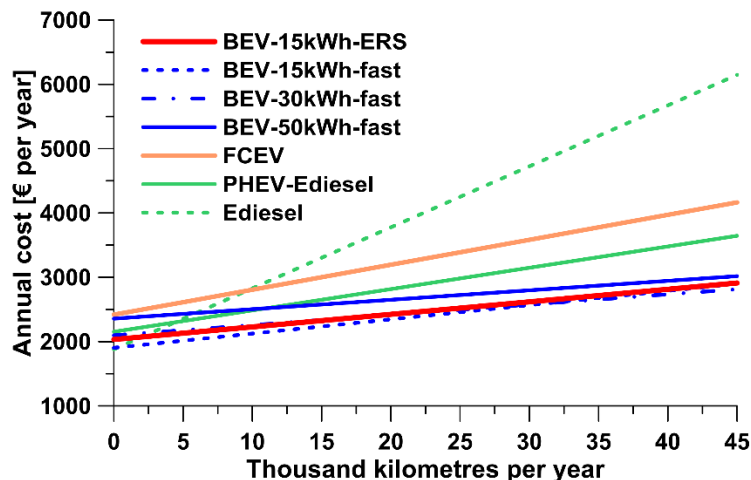


Figure 5.6: The figure is taken from the paper by Grahn, Taljegard and Brynolf [42]. The annual total cost per year (including costs for the vehicle and energy supply) as a function of the yearly driving distance for different ways of using electricity for passenger cars. The following assumptions related to costs are made: battery, 100 €/kWh; fuel cell, 30 €/kW; hydrogen tank, 575 €/kg; pick-up for ERS, 1000 €/car; ERS infrastructure, 0.05 €/vkm; fast charging, 0.06 €/vkm; electricity cost, 50 €/MWh. BEV, battery-powered electric vehicle; FCEV, hydrogen fuel cell vehicle; PHEV, plug-in hybrid vehicle using electricity and e-diesel; E-diesel, electrofuel in the form of diesel; ERS, electric road system.

To speculate, it is likely that many individual cars will be conducting trips on the whole main road network (i.e., not driving in a shuttle service), which would require that a large ERS network need to be built before it will be possible to reduce the size of the on-board battery.

Light vehicles appear to be important for bringing down the cost of ERS per vehicle kilometre by increasing the length of road with sufficiently high ADT. However, the passenger vehicles can cover most of the desired travel distances even with a small battery, so the need for an ERS for passenger vehicles is limited to only a few trips per year, assuming present travelling patterns.

There will be a trade-off between the extra cost for the vehicle equipment and using the ERS with the cost of the alternative solution (e.g., stopping and fast charging, taking another transport mode, and renting a fuel vehicle). While this trade-off could be based on economic criteria, for passenger cars it could also be based on other factors, such as convenience, accessibility, and comfort.

For trucks and buses, no individual driving patterns have been analysed in the work of this thesis. ADT is not the only important parameter to influence the design of an ERS (e.g., the willingness to use the ERS is also an important consideration). Individual driving patterns for trucks and buses might be of less importance, since those vehicle types has larger possibilities to optimise their logistics, to fully utilize the possibilities that ERS offers, e.g. smaller battery capacities.

The work of this thesis suggests that it might be economically viable to build ERS on some of the road network, so as to connect the main cities (**Paper II**). ERS on a larger-scale will result in a significant increase in the peak power demand in the regional and local electricity systems that cannot be ignored. On the other hand, there should be a potential to change the current driving patterns of individual trucks and buses, as opposed to passenger cars, especially if there is an introduction of autonomous vehicles (e.g. shift more of the transport to night time). The implementation of a large-scale ERS will require considerable up-front investment costs that will need to be handled using new business models.

The implementation depends of ERS also to a large extent on factors such as the: development of battery technologies; development of technologies for ultra-fast charging; future policy and investment climates for making decisions as to costly infrastructure investments; and bioenergy potential and allocation of biomass (assuming high bioenergy supply potentials, and conversion into biofuels, would offer a low cost alternative to electrification of the transport sector).

There might also be technical obstacles to building ERS that have not been included in this thesis. For example, the design and creation of a new infrastructure need to be co-ordinated with other countries, as many of the trucks are driving international routes, which in the case of ERS would require common standards. It will have to be profitable to use the ERS network also for a percentage of the individual yearly driving distance, as it takes long time to build a new infrastructure.

5.3 Impacts of electric vehicles on the electricity system

In **Papers III–V**, we model the European electricity system to investigate how large-scale deployment of EVs and ERS would affect investments in new generation capacity (Section 5.3.1), storage technologies other than EV batteries (Section 5.3.2), and the dispatch of the electricity system (Section 5.3.3). Different parameters that affect the system value of V2G, such as access to the charging infrastructure (Section 5.3.4) and battery capacities (Section 5.3.5), are also discussed in this section.

5.3.1 Impacts on capacity investments and electricity generation

Figure 5.7 shows the development of the electricity system in northern Europe (i.e., Scandinavia and Germany) from 2020 to 2050. The results are from the ELIN model, assuming direct charging (Figure 5.7, a and c) and optimised charging with V2G (Figure 5.7, b and d). Figure 5.8, which is based on modelling runs that included different countries in Europe, shows the share of wind (5.8a) and solar (5.8b) electricity generation for different charging strategies, assuming close-to-zero CO₂ emissions from the electricity system.

In 2050, a large part of the electricity generation consists of renewable electricity to meet the climate target of 99% reduction in emissions compared to 1990. The results show that with direct charging, the composition of the electricity system (Figure 5.7a and c) and the share of VRE in year 2050 (Figure 5.8) are similar to those in the scenario without EVs.

In all regions investigated, optimised charging of EVs leads to reduced investments in peak power units, as well as, nuclear and/or thermal power (in the form of natural gas with carbon capture and storage (CCS), biogas, and CCS coal co-fired with biomass), as compared to direct charging. This is mainly due to the allocation of EV charging to hours with a low net-load, thereby reducing the net-load variations.

The share of solar power increases with at least ten percentage points with the possibility to optimise the charging and to perform V2G in all the regions investigated (except for Sweden and Ireland), i.e., an optimised charging with V2G is acting as a variation management strategy. In some regions, those with either good solar conditions (e.g., Spain) or where less-efficient wind-power sites are deployed (e.g., Germany and UK), solar power increases at the expense of investments in wind power when assuming optimised charging with V2G, as compared to direct charging (Figure 5.8).

For a region with poor conditions for both wind and solar power, such as Hungary, the relative cheap EV batteries compared to other storage technologies, can increase the value of both solar and wind power in the system (Figure 5.8). The generation from VRE in Hungary increases from 50% to 71% (out-competing nuclear power) in the model run with optimised charging with V2G, as compared to direct charging.

As shown in Figure 5.8, optimised charging with V2G can also facilitate a few percentage points higher share of wind power in regions with good wind conditions (and poor solar conditions). For the purpose of facilitating wind power integration, a large battery (85 kWh) is beneficial for handling the long-term variations (see Section 5.3.5).

A difference becomes evident if comparing investments in new capacity between **Papers III and IV** for Germany. We have used the same model (ELIN-EPOD model package) in both papers. However, in **Paper III**, we used a rather conservative value for the area limitation of

solar power (134 kW/km²), which resulted in the same solar installation in Germany in year 2050 as exists today. In **Paper IV**, we have removed this area limitation, resulting in more investments in solar power in the scenario with V2G in Germany.

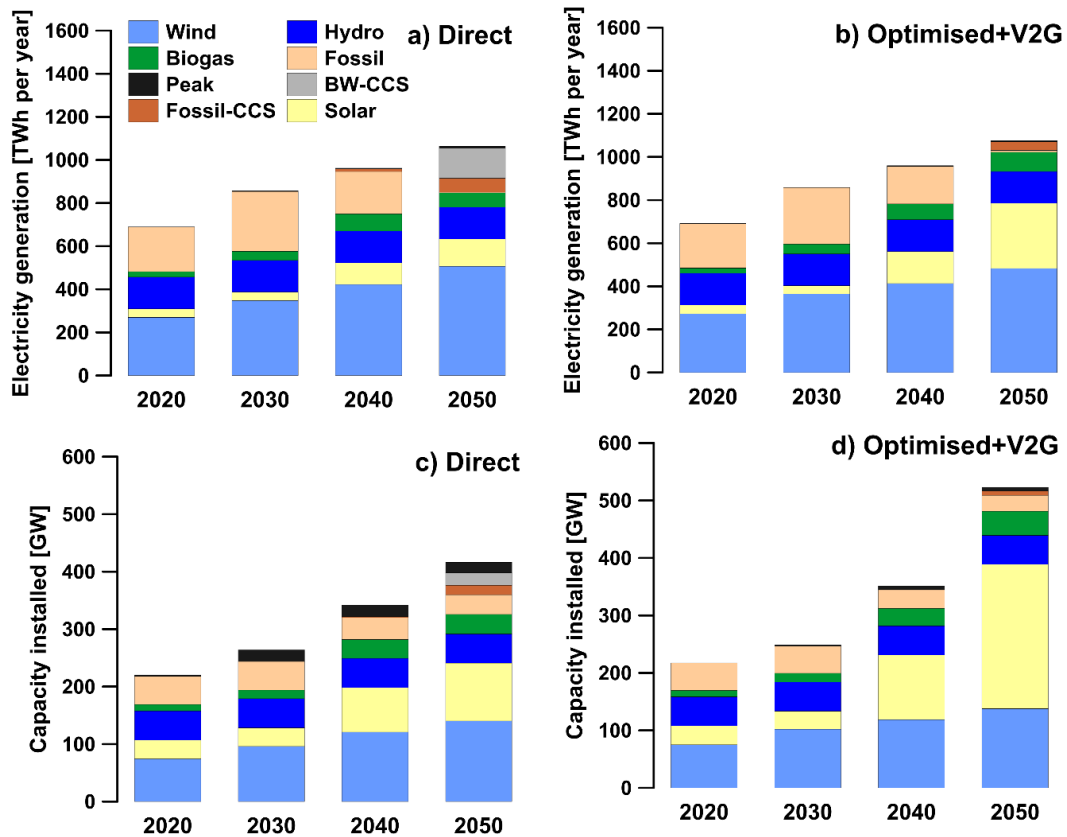


Figure 5.7: Electricity generation (a and b) and capacity installed (c and d) from different power sources from the scenario with direct charging of EVs (a and c) and optimised with V2G (b and d). The modelled regions are: Germany, Norway, Denmark and Sweden. It is assumed that there is a 99% reduction of emissions by year 2050 relative to year 1990 and 60% of the passenger fleet being electric vehicles (Paper IV). BW, fossil fuels co-fired with biomass; CCS, carbon capture and storage; V2G, Vehicle-to-grid.

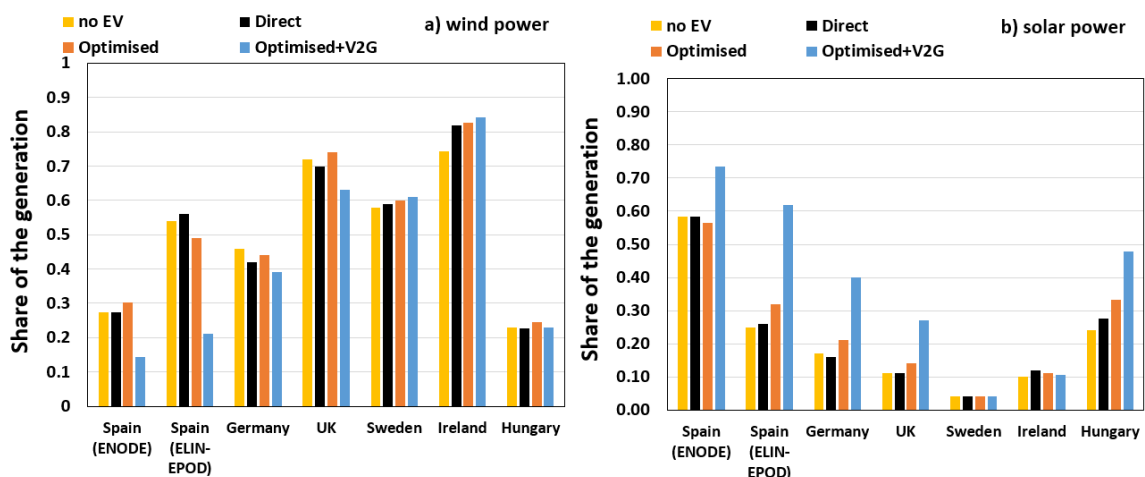


Figure 5.8: Shares of wind power (a) and solar power (b) in year 2050 for different countries and charging strategies. The results are obtained from both the ENODE (Paper V) and the ELIN-EPOD model packages (Paper IV). The electricity system modelled assumes close-to-zero CO₂ emissions and 60% of the passenger fleet being electric vehicles. The results for Spain without V2G differ between the models, mainly due to the fact that there are no stationary batteries in ELIN-EPOD.

Table 5.2 lists the impacts of direct charging, optimised charging with and without V2G, and ERS on the key system parameters investigated in this work: total system cost, share of VRE, curtailed VRE, possibilities to replace stationary storage by using EV batteries as storage, and the requirement for a back-up reserve.

Table 5.2: Impacts of passenger EV charging strategies and the electric road system (ERS) on some electricity system parameters. The results are derived from the modelling outcomes of **Papers III–V**.

	Direct charging of passenger EVs	Optimised charging of passenger EVs	Optimised charging with V2G for passenger EVs	ERS for light and heavy vehicles
Total electricity system cost	Higher than without EVs and higher than other EV passenger charging strategies.	Has the second-lowest total system cost. If not including V2G, EVs cannot replace investments in storage technologies to the same extent.	Has the lowest total system cost. This is mainly due to lower investments and use of other, more expensive, VMS.	Has the highest system cost, since this strategy includes all road transport, as well as, demands more VMS.
Share of variable renewable electricity (VRE)	The new EV demand is met by VRE in most regions. The share of VRE is about the same as that without EVs (depending on the solar and wind power resource availability).	Increases the share of VRE compared to direct charging in regions with poor conditions for VRE (since EVs is a cheap VMS that increases the value of VRE).	Integrates a higher share of VRE than direct charging at a lower system cost.	The new EV demand is met by VRE in most regions. The share of VRE is about the same as that without EVs (depending on the solar and wind power resource availability).
Curtailement	Increased	Decreased	Decreased	Increased
Possibility to replace stationary storage	No. Direct charging will instead increase the need for other VMS, such as investments in other storage technologies, as compared to a scenario without EVs.	Yes, to some extent. However, investments in other storages are still needed.	Yes. For many regions, this strategy can replace investments in most stationary batteries and some of the hydrogen storage.	No. ERS will instead increase the need for investments in more storage technologies, as compared to a scenario without EVs.
Peak power demand	Increases the peak power demand, as most of the charging takes place during hours with already high demand.	Neither increases nor decreases in the peak loads. EVs are not charged during those hours with peak load.	Decreases the peak power demand by charging the EVs at hours with low demand and discharges to the grid during peak hours.	Increases the peak power demand, as driving takes place during hours with already high demand.
Back-up reserve	Requires additional back-up reserve.	Cannot provide back-up reserve and does not demand additional back-up because it avoids charging during certain hours.	Can provide back-up capacity to the system by using the EV battery to store electricity for up to several days.	Requires additional back-up reserve.

5.3.2 Competition between stationary batteries, hydrogen storage, and EV batteries

Paper V evaluates how different EV charging strategies influence the cost-competitiveness of storage technologies other than EV batteries in the electricity system. In **Paper V**, we conclude that V2G can, to a large extent, replace investments in stationary batteries and hydrogen storage in all the investigated regions, assuming a cost for V2G of less than 30 €/MWh. This is possible because the aggregated EV battery capacity connected to the grid is significantly larger than the cost-effective investments made in stationary battery capacities in the model runs without V2G.

However, in Ireland, which represents a system with a high share of wind power (>90%) and no connections to neighbouring regions, the modelled EV battery capacity is smaller than the cost-efficient storage capacity for most of the cases investigated (with the exception of a situation with an EV battery with a capacity of 85 kWh). The large EV batteries can replace the need for investments in relatively expensive electrolysers and fuel cells, since EV batteries can be cycled more than the hydrogen storage and offers larger charge and discharge capacities.

Optimising the EV charging without V2G is not sufficient to replace stationary batteries or hydrogen storage, which means that V2G can be an important feature so as to accrue the full benefit from integrating EVs in the electricity system, as shown in **Paper V**.

Figure 5.9 compares the share of reduction in total electricity system cost for direct charging and optimised charging with and without V2G. The results are from the modelling performed in **Paper V** using the ENODE model assuming zero CO₂ emissions. The reduction in total electricity system cost depends on several parameters, such as the region investigated, the battery capacity, the charging strategy, and the share of the fleet participating in optimised charging/V2G (Figure 5.9).

The reduction in total electricity system cost in the case of optimised charging, as compared to direct charging, is mainly attributed to a lower investment cost (e.g., lower investments in stationary batteries and hydrogen storage), lower fixed operational and maintenance costs, and lower fuel costs. Optimised charging with V2G and a larger battery capacity provide the highest cost reductions, as shown in Figure 5.9.

The region with the smallest cost reduction is central Sweden, where V2G is of less importance for balancing an electricity system that has access to a cheaper VMS than EV batteries (i.e., hydropower).

In **Papers III** and **IV**, the differences in cost between the charging strategies are not as significant as those seen in **Paper V**. This is because ELIN applied in **Papers III** and **IV** does not see the full cost of variability and that trade is possible. It is also clear from Figure 5.9 that the whole fleet does not need to participate in V2G in order to derive most of the potential for variation management from V2G.

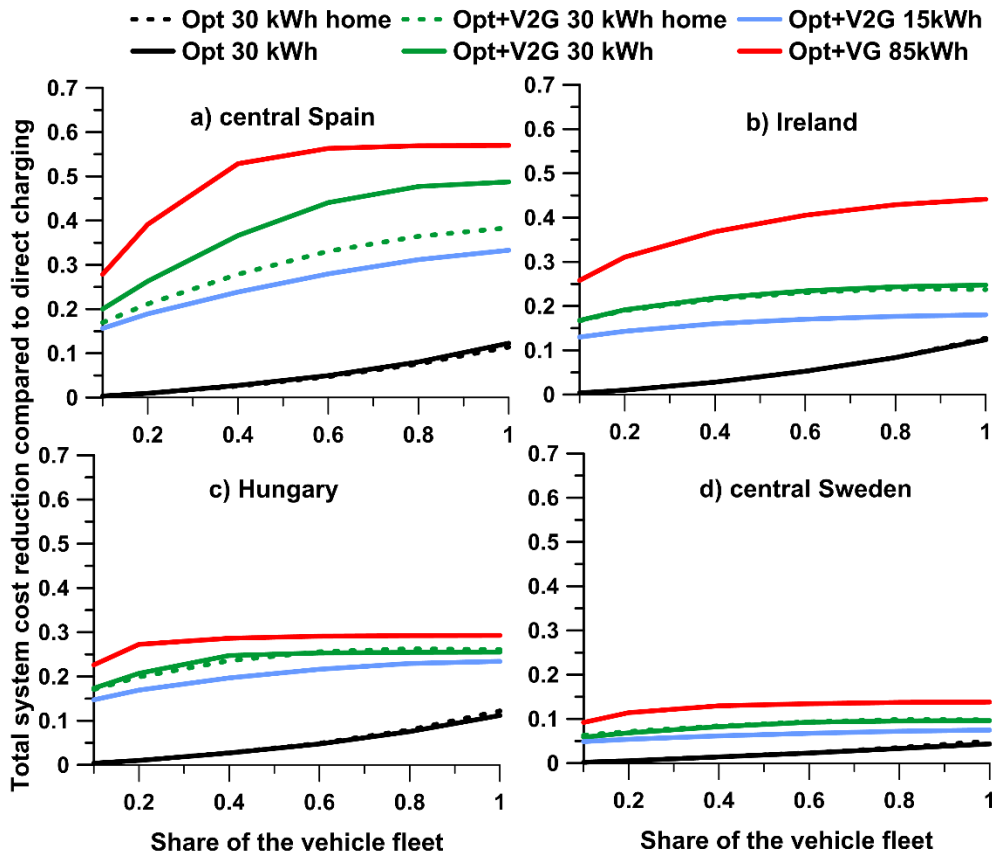


Figure 5.9: Share of the reduction in total electricity system cost ascribed to direct charging and optimised charging with and without V2G. The results are from the model runs with the ENODE model presented in Paper V (i.e., zero CO₂ emissions and 60% electric vehicles). The investment cost for EV batteries is assumed to be absorbed by the EV owners and no cost for V2G is assumed. Opt, Optimised; V2G, vehicle-to-grid.

5.3.3 Dispatch of the electricity system with electric vehicles and a high share of VRE

Figures 5.10 (Ireland) and 5.11 (Hungary) compare the hourly dispatches of the power plants in scenarios with direct charging and optimised charging with V2G during a 1 to 2 weeks period in January when achieving zero emissions. Figure 5.10 shows a system that is heavily dependent upon wind power (Ireland). With direct charging, hydrogen storage is used to meet the electricity load during hours with low wind-power output. The hydrogen storage is refilled at hours with high wind-power generation (Figure 5.10a).

In Figure 5.10b, it is shown that the EVs with V2G (assuming a battery capacity of 30 kWh) can, to a large extent, replace the charging and discharging patterns of the hydrogen storage. This is achieved by charging the vehicles (more than the driving demand) over a couple of days and then discharging the vehicles to the grid over one to a couple of days. The over-dimensioning of the EV batteries relative to their daily driving demands for many of the 426 individual driving profiles makes this charging/discharging pattern possible. As the EV batteries replace the majority of the hydrogen storage, biogas gas turbines are used to supply the system during some crucial hours of the year, as shown in Figure 5.10b.

In a region with less-favourable wind conditions (Hungary as opposed to Ireland), the presence of V2G increases the competitiveness of solar power, which can then out-compete nuclear power. In addition, having V2G requires no stationary batteries to handle the day-night time variations, as seen in Figure 5.11.

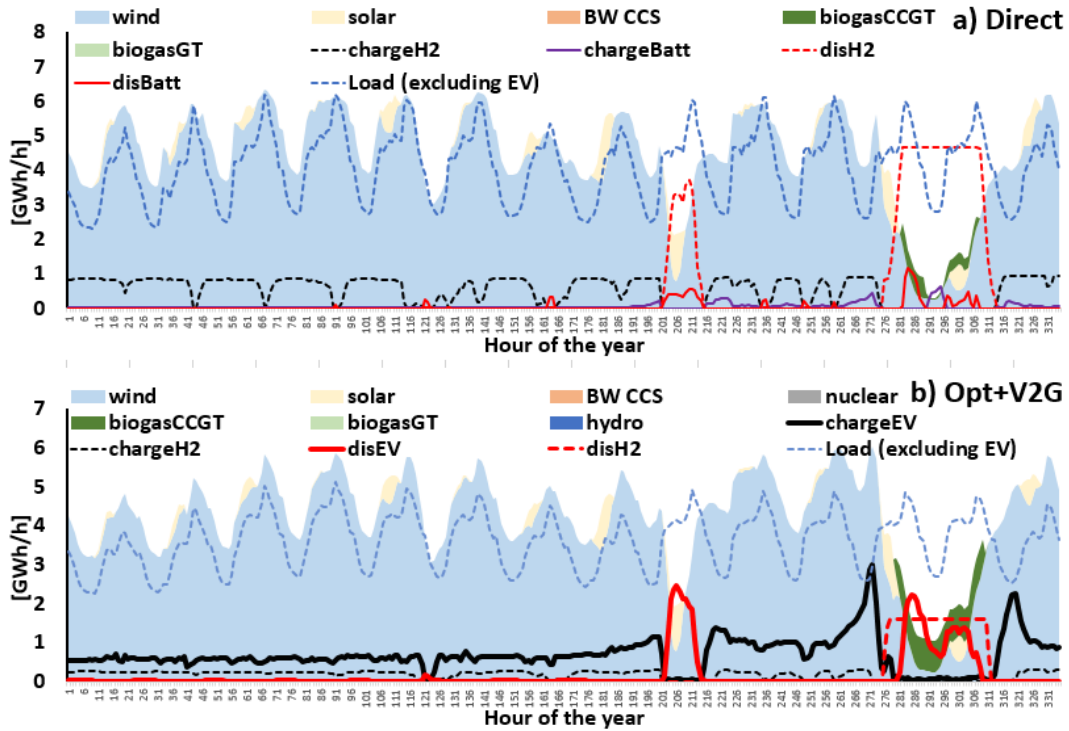


Figure 5.10: Model results for the generation of electricity and for the charging of EVs and the discharging from EVs and other storage technologies back to the electricity grid during a period of 2 weeks in January in Ireland for: (a) direct charging; and (b) and optimised charging with V2G. The results are from the ENODE model year 2050 assuming zero CO₂ emissions. BW, fossil fuels co-fired with biomass; CHP, combined heat and power; GT, gas turbine; CCGT, combined cycle gas turbine; CCS, carbon capture and storage; EV, electric vehicles; dis, discharge to the grid; charge, charging; H2, hydrogen; Batt, stationary batteries.

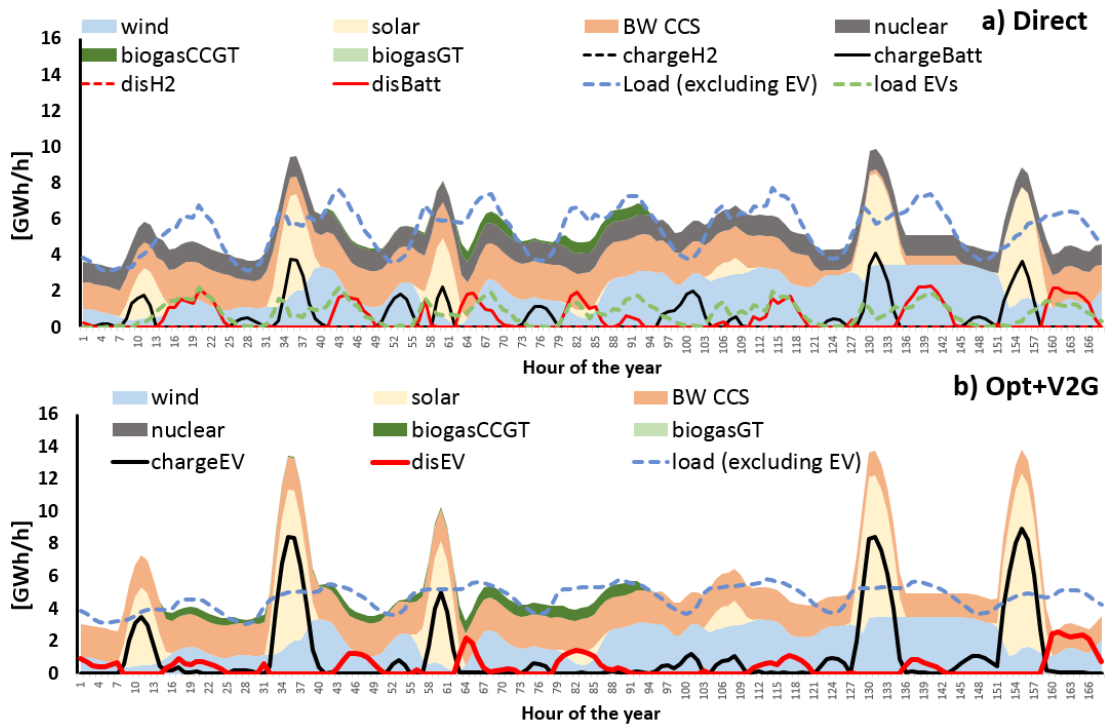


Figure 5.11: Model results for the generation of electricity and for the charging of EVs and the discharging from EVs and other storage technologies back to the electricity grid during a period of 1 week in January in Hungary for: (a) direct charging; and (b) and optimised charging with V2G. The results are from the ENODE model year 2050 assuming zero CO₂ emissions. See Figure 5.10 for abbreviations used.

5.3.4 Importance of the charging infrastructure and power

Large-scale implementation of a new charging infrastructure is associated with high up-front investment costs, even though the infrastructure cost is a small fraction of the total cost for the different transport solutions. **Papers V** and **Paper VI** analyses the system value of access to a charging infrastructure by modelling three scenarios: one with access to a charging infrastructure at all stops longer than 1 hour; one with access at all stops longer than 6 hours; and one with access to a charging infrastructure only when parking at the home location only.

Figure 5.12 shows the shares of charging (5.12a) and discharging (5.12b) that take place at the home location, as obtained from the modelling using the ENODE model, a battery capacity of 30 kWh, and under the assumption that the charging infrastructure is available at all stops longer than 1 hour. As shown in Figure 5.12, on average, approximately 50% in central Spain and Hungary (regions with relatively large shares of solar power) and 60% in central Sweden and Ireland (regions with relatively large shares of wind power) of the charging takes place at the home location. With respect to discharging, on average more than 60% takes place at the home location (Figure 5.12b). However, as shown in Figure 5.12, there is large variability between individual vehicles.

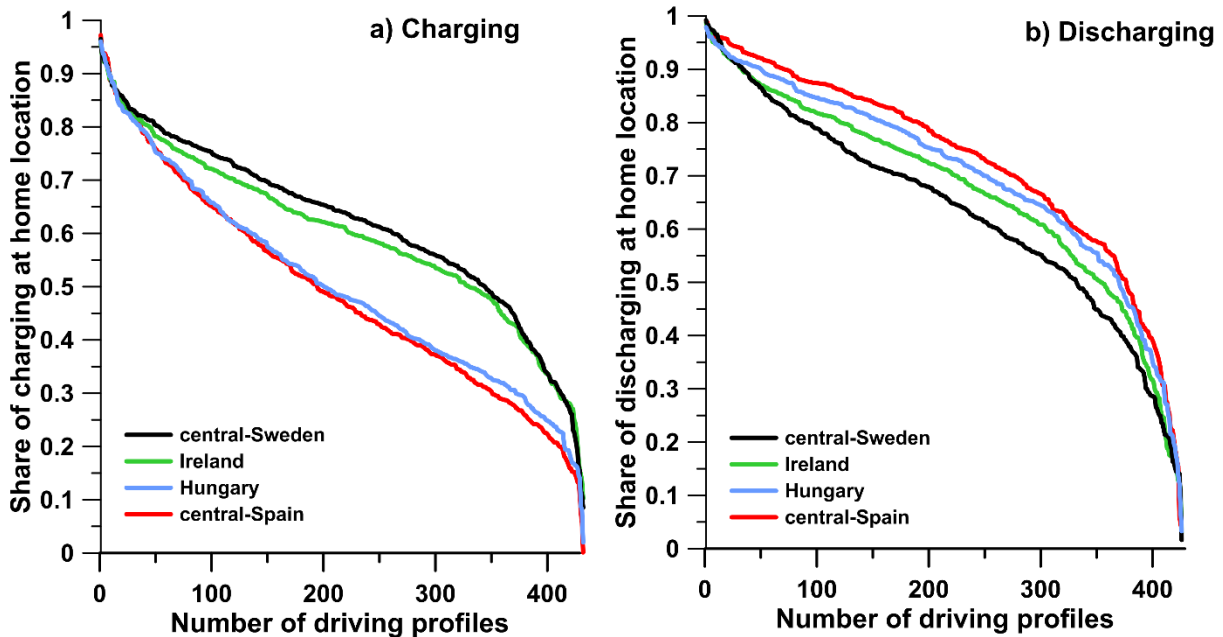


Figure 5.12: Shares per year of the charging (a) and discharging to the grid (b) that take place at the home location for the 426 individual driving profiles. The results are based on a model run with the ENODE model assuming no CO₂ emissions, an EV battery capacity of 30 kWh and access to charging infrastructure at all stops longer than 1 hour. The x-axis is sorted, among the 426 driving profiles, from the profile with most charging/discharging at the home location to least amount of charging/discharging at the home location.

In **Paper V**, we show that access to a charging infrastructure has an impact on the investments in and dispatch of the electricity system. Lower levels of charging and discharging are seen in central Spain and Hungary (two regions with high shares of solar power), when the charging infrastructure is limited to only the home location. This leads to slightly higher investments and the use of stationary batteries in central Spain and hydrogen storage in Hungary (see **Paper V**). This is explained by the close connection to solar power, i.e., if cars are not connected during day-time (parked at work) they cannot charge during the solar power peaks.

Therefore, the annual total electricity system cost savings with V2G will be lower in central Spain when a charging infrastructure is only available at the home location compared to charging infrastructure at all stops (i.e., there will be a higher total electricity system cost for such a system), as seen in Figure 5.9. However, the major flexibility benefits compared to direct charging (e.g., reduction in peak power investments and other storage technologies, and a higher share of VRE) are still achieved with a battery capacity of 30 kWh and connection to the grid only at the home location (**Paper V**). A deployment of charging infrastructure at all stops longer than 1 hour or all stops longer than 6 hours has minor impacts on the system flexibility.

Paper V concludes that a charging infrastructure is, to some extent, important also outside the home location for regions with a large share of solar power. Figure 5.9 shows that the charging strategy (i.e., including V2G), the battery capacity, and the number of EVs participating in V2G have much larger impacts on the system cost than the access to charging infrastructure. This is due to the fact that during all hours of the year, more than 30% of the fleet is parked at the home location (**Paper V**).

The maximum charging power in the model is assumed to be 3.7 kW in **Paper III** and 7 kW in **Papers IV–VI**. Fast charging at higher charging power has not been included in the optimisation conducted in this thesis. We found that given the EV penetration levels assumed in the investigated scenarios and an even distribution across all EVs, more than 98% of the charging and discharging is taking place at a power level <3.7 kW, also in the scenarios that assume a maximum power of 7 kW.

Thus, in this thesis, it is shown that with a sufficient number of EVs participating in V2G, it will not induce high c-rates (i.e., the amount of charging/discharging divided by the battery capacity) during the charging/discharging brought about by V2G. Avoiding charging and discharging with high c-rates is beneficial for the battery in terms of minimising battery degradation from cycling. However, for the electricity system, it is important for the EV batteries to be able discharge with high (maximum) power for a few hours per year, i.e., during the most crucial hours, the so-called ‘dimensioning hours’ of the systems.

It is important to note that in the ENODE model used for the study described in **Paper V**, no incentives are implemented in the model to charge certain vehicles in a specific way. The model does not include minimisation of the charging and discharging outside the home location, but rather the total amount of charging and discharging. In the same way, the model is not optimised to reach as low c-rates as possible. Another limitation of the study in **Paper III-VI** is that the regional and local grid infrastructures are not included in the cost optimisation.

5.3.5 System impacts of battery size - larger vs smaller batteries

Currently, the trend among EV manufacturers is to produce batteries with larger and larger capacities, either by adding more battery cells or by designing more space and weight efficient battery cells. This has resulted in an over-dimensioning of the batteries in relation to the daily driving needs, as shown by Kullingsjö and Karlsson [103]. In **Papers III** and **V**, the EV battery capacity has been varied in a sensitivity analyses to investigate how the potential of optimised charging with and without V2G changes with battery capacity. EV battery capacities of 15 kWh and 30 kWh per vehicle cannot fully replace the use of hydrogen storage in Ireland, as these battery storage capacities are depleted during driving. The 85 kWh EV batteries manage these longer variations without changing the driving patterns, as can be seen in

Figure 5.13, where the EV battery storage level follows the charging and discharging patterns of the hydrogen storage. The 85 kWh batteries thus enable the owners to choose low cost charging opportunities during periods of several days.

The conclusions drawn from **Paper V** are that from an electricity system point-of-view, batteries with higher capacities (85 kWh instead of 30 kWh) can:

- (1) increase the system value of wind power (in a region with poor conditions for both solar and wind power, such as Hungary);
- (2) increase the system value of solar power (in a region with relatively good conditions for solar power, such as central Spain, and in a region without hydropower and relatively poor conditions for VRE, such as Hungary); and
- (3) avoid investments in storage handling of fluctuations that persist for several days, e.g., hydrogen caverns (in a region with good wind conditions, such as Ireland).

Paper V also concludes that batteries with bigger capacities, obviously, will have significantly fewer full equivalent cycles per battery (even lower than with a 30 kWh battery and only optimised charging). In Hungary and central Spain, two regions that uses V2G a lot compared to e.g., central Sweden and Ireland, 85 kWh battery, instead of a 30 kWh battery, could reduce the amount of cycling by at least 50%.

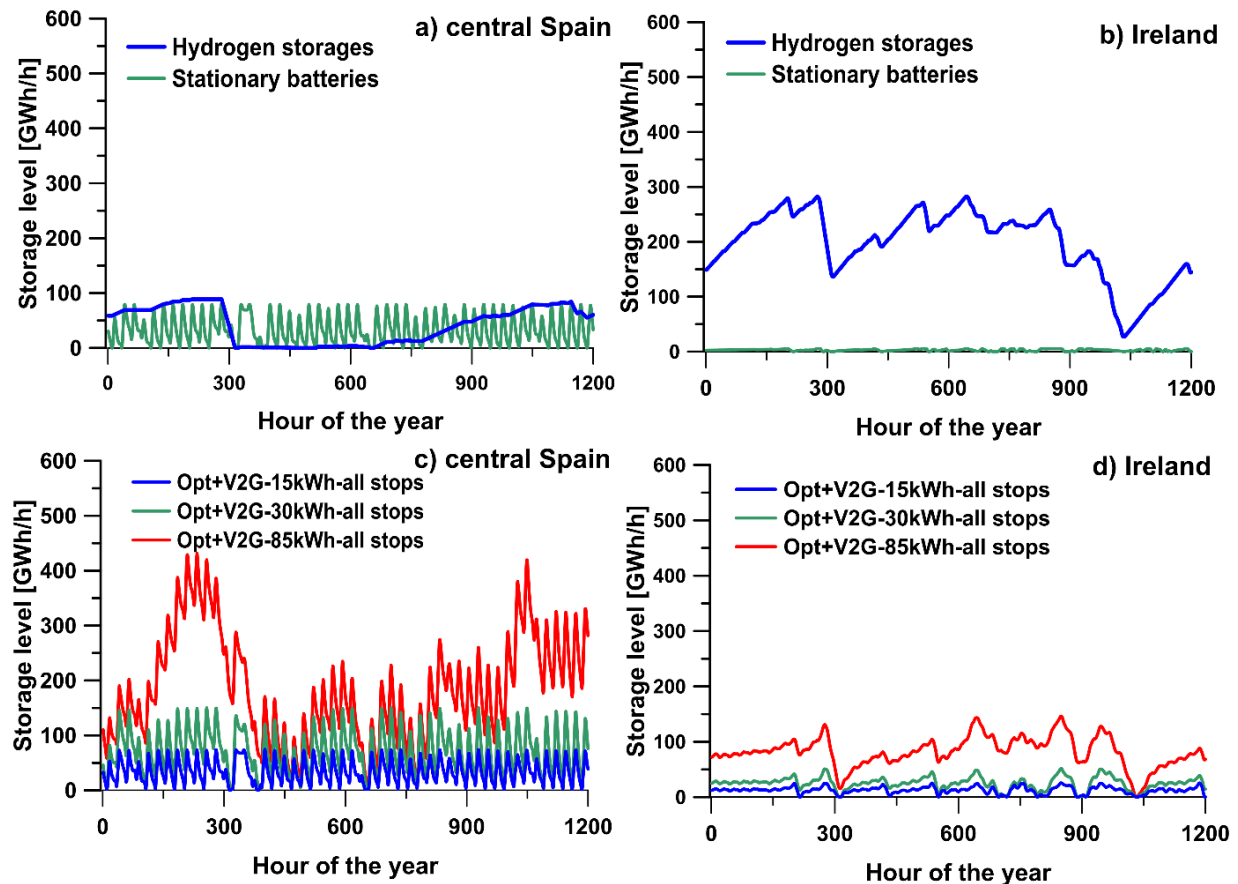


Figure 5.13: Storage levels of hydrogen and stationary batteries in the case with direct charging of EVs at all stops longer than 1 hour and with a battery capacity of 30 kWh for: (a) central Spain; and (b) Ireland, and the storage levels of aggregated EV batteries in a model run with V2G, assuming a charging connection at all stops longer than 1 hour and battery capacities of 15 kWh, 30 kWh, and 85 kWh for: (c) central Spain; and (d) Ireland (*cf.* Paper V). The results are based on a model run with the ENODE model assuming no CO₂ emissions.

In **Paper V**, it is shown that from the electricity system perspective there is no economic incentive to invest in larger EV batteries (such as 85 kWh) solely for the purpose of providing system flexibility. This is the case because other options for long-term storage are cheaper. However, if the car owners buy large batteries relative to their daily driving distance, we have shown that the electricity system can use these large batteries to replace investments in long-term storage.

One limitation of the studies described in **Papers III** and **V** is that the battery capacity is not optimised according to the individual driving needs. In these two studies, all 426 different driving profiles had the same battery capacities in a model run (but had different capacities between model runs, as described previously). The individual choice of battery capacity depends on the economic conditions, driving distances and patterns, and personal preferences.

Even if the trend during the last few years has been towards larger batteries, some drivers can reverse this trend. It could be difficult to produce the number of car batteries needed to satisfy the market demand for EVs. As mentioned in Section 4.3, batteries in the magnitude of 4,000 GWh per year will most likely need to be produced in year 2050 in Europe to satisfy the market demand. In the near future, this can also result in a scarcity of materials, e.g., cobalt [109] and increase the benefit of having smaller batteries that are recycled after being used in the vehicles. Expansion of the charging infrastructure, as well as ERS for passenger vehicles could lead to a new trend towards smaller battery capacities.

It might, therefore, be more environmentally beneficial and cost-efficient to adjust the capacity of the EV battery to the daily driving demand of motorists (and not to the few long trips taken per year). Then, the scope for using the EV battery for both driving and V2G becomes more limited, and it seems likely that in sunny regions, some stationary batteries might also be needed. However, regardless of whether we recycle or reuse the EV batteries, the results presented in this thesis show that there will most likely be very little need for stationary batteries, i.e., for the sole purpose of storing electricity (**Paper V**).

5.3.6 Total CO₂ emissions from electricity generation in an EV scenario

There has been an ongoing debate in recent years about the climate impacts of the production of batteries and the charging of EVs, due to fossil fuels in the electricity mix. The results described in **Papers III–V** can throw some light on this topic. In these papers, we have modelled the electricity systems of several European countries (e.g., Germany, Sweden, Norway, Spain, UK, Ireland, France), starting with today's electricity system and reaching close-to-zero emissions in year 2050. The modelling in this thesis takes into consideration the changes in electricity production that are due to electrification of the road transport sector (i.e., charging of EVs and ERS).

The results obtained from the modelling show that the total CO₂ emissions from the electricity system, as well as the CO₂ emissions related to the charging of EVs and ERS are, of course, expected to decline in all regions over the coming decades when meeting the climate targets. However, some regions with already low levels of emissions, such as Sweden, Ireland and Norway, will reach the target of CO₂ emissions in the electricity system prior to the target dates.

Figure 5.14 shows the total CO₂ emissions (Figure 5.14a) and the CO₂ emissions per unit of electricity generated (Figure 5.14b) from the electricity system between 2020 and 2050. The results in Figure 5.14 are obtained from the investments model ELIN assuming close-to-zero CO₂ emissions in year 2050 and no EVs.

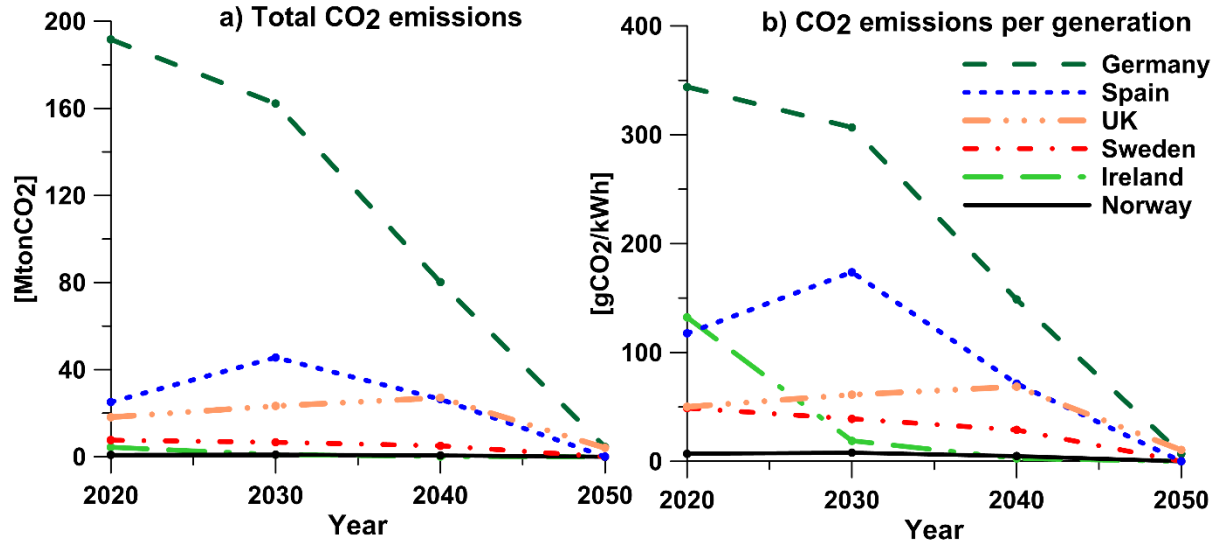


Figure 5.14: Total CO₂ emissions per year (a) and the average CO₂ emissions per generation unit from the electricity systems in different countries, as obtained from the runs with the ELIN model in Paper IV (see Table 4.1), assuming a target of 99% reduction of CO₂ emissions by year 2050, as compared to year 1990. The model run is without EVs, and the target for CO₂ emissions is constrained as one goal for all regions (i.e., not country-specific targets).

Figure 5.15 gives the CO₂ emissions per MWh and per kilometre (passenger cars) in Germany from charging EVs, assuming three different EV charging strategies and a 99% reduction of emissions by 2050, as compared to 1990. The highest level of CO₂ emissions in Figure 5.15 is 62 g/km (recalculated from 363 g/MWh applying an electricity consumption of 0.17 kWh/km). This can be compared with the average level of CO₂ emissions from newly sold passenger cars in Europe in 2018 of 120.5 g/km [110]. Direct charging, has slightly higher emissions than the other two options, due to more charging at hours where peak power units are used (Figure 5.15).

The emissions from charging EVs in Germany in Figure 5.15 has been calculated by taking the CO₂ emissions per GWh_{el} multiplied by the net EV charging each hour, followed by summing for all the hours of the year. It is evident from Figures 5.14 and 5.15 that as long as the transport sector is electrified at the same time as the power sector is decarbonised, the emissions from the charging of EVs will be low compared to current emissions from fossil-fuelled internal combustion engines, as well as, the European target for year 2021 of 95 gCO₂/km. This is confirmed by the model results in **Papers III–IV**, which show that with a cap on CO₂ emissions, the additional demand from an electrified transport sector is mainly met by an increase in generation from wind and solar power in Europe.

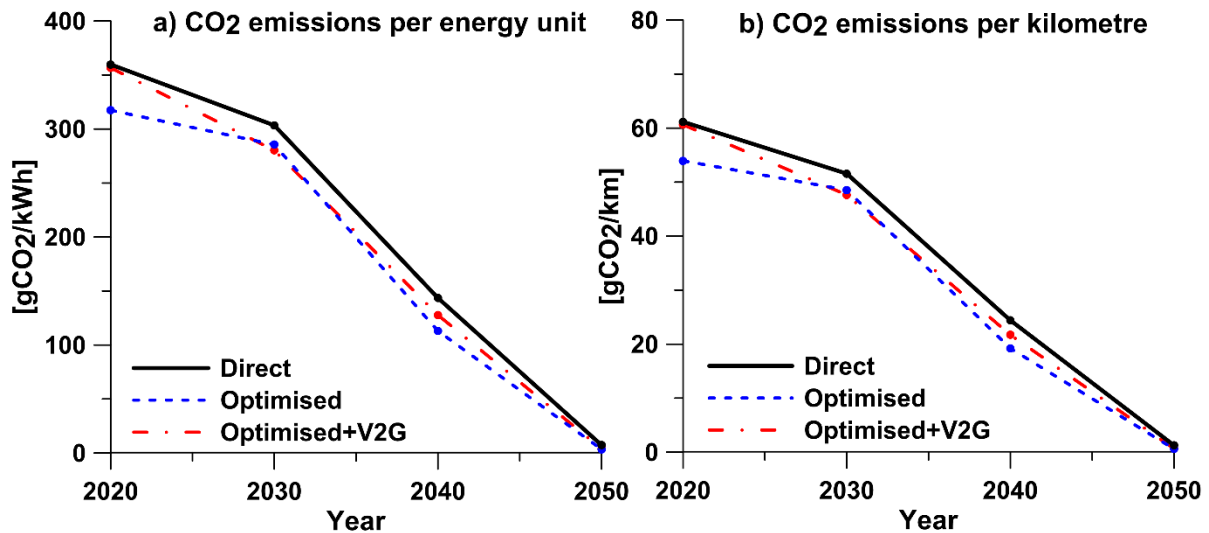


Figure 5.15: Average yearly CO₂ emissions for Germany per energy unit (a) and per kilometre (b) for charging EVs in the scenarios with direct, optimised, and optimised with V2G strategies. It is assumed a 99% reduction of emissions by 2050, as compared to 1990 and 60% of the passenger vehicles are electrified by year 2050. The values shown are calculated as the CO₂ emissions per GWh_{el} multiplied by the net EV charging each hour, followed by summing for all the hours.

Figure 5.16 shows the shadow prices for CO₂ extracted from the ELIN model, assuming 99% emission reduction to 2050 compared to 1990, for three different EV charging strategies (direct, optimised, and optimised with V2G) with and without EVs/ERS. As is evident in Figure 5.16, in order to maintain the CO₂ emissions below the given cap and include the new load from EVs, the lowest CO₂ price is induced with the V2G strategies (even lower than without EVs). ERS are increasing the CO₂ prices compared to a similar charging strategy without ERS (Figure 5.16). However, in the case with ERS, heavy road transport is also electrified, and the restrictions related to CO₂ emissions are shifted from the transport to the power sector.

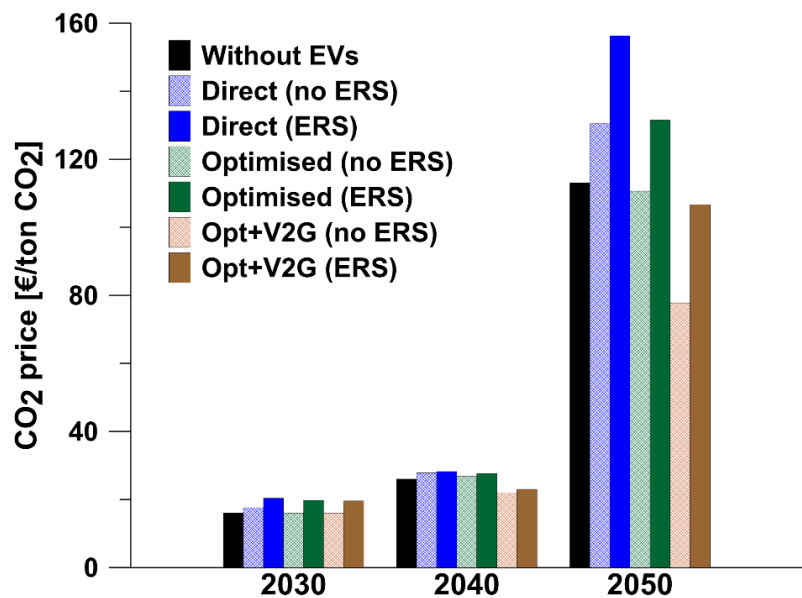


Figure 5.16: Prices for CO₂ in the absence of EVs and for three different charging strategies with and without an electric road system (ERS). All the scenarios assume that there is a 99% reduction in emissions by year 2050, as compared to year 1990, and that 60% of the fleet is electrified by year 2050. The modelled regions are: Sweden, Germany, Norway and Denmark. Opt, optimised.

The results from the modelling described in **Papers III–V** show the obvious fact that when one is determining the climate impact of EVs in the long-term, it is not sufficient to use statistics for the average CO₂ emissions, or the marginal electricity production, of the current electricity system. In many regions where the EVs are charging or their batteries are produced, current marginal production of electricity is from coal-fired power plants.

It is reasonable to suppose that the electricity generation system must be decarbonised if the world is developing in line with the Paris Agreement and, thus, the carbon intensity of the future electricity generation should be in line with the use of EVs to reduce emissions from the transport. Thus, assuming that the successful ramping up of both EVs and ERS will likely take several decades to reach a significant penetration level, its associated emissions will be strongly linked to the future electricity system, which, as pointed out above, will also have to be transformed over the same period. An electrification of the transport sector will increase the electricity generation within the EU-ETS.

5.4 Individual driving patterns vs. aggregated representation

Paper VI compares the implementation of EVs in the modelling using three different methodologies of integrating EVs, namely aggregated vehicle profile (AGG), yearly driving profile (YDP), and representative daily driving profiles (DDP), see Section 3.3 for a description. Some important parameters have been varied that might affect the choice of EV integration methodology, e.g., battery capacity, geographical scope, V2G implementation schemes, number of EVs, and charging infrastructure access. There may be additional parameters that are not yet investigated, and these might also affect the choice of methodology and should be beneficial to analyse.

Thus, when is an aggregated vehicle profile (AGG) good enough to estimate the value of V2G using electricity system models? The different parameters tested gave the same or similar results with an AGG and YDP representation of EVs in ENDODE (see **Paper VI**). One exception was when the charging infrastructure was limited exclusively to the home location in regions without access to hydropower, in which AGG over-estimated the V2G potential. This over-estimation affects investments in electricity generation capacity and/or storage technologies. For example, in the scenario with 15 kWh of battery capacity and grid access only at the home location, the AGG methodology over-estimates the V2G potential, resulting in a ~10% higher share of VRE in the Hungarian electricity system than in the case with YDP (**Paper VI**). Hungary is a region that needs cheap VMS to integrate more VRE. In central Spain (a region where stationary batteries helps increase the value of more solar power in the absents of V2G) the over-estimation of the V2G potential, when assuming a battery of 15 or 30 kWh and grid access only at home location, results in under-investment in stationary batteries and 11% lower system cost with AGG, as compared to YDP (**Paper VI**).

Is it then preferable to use DDP rather than YDP in models that reflect individual driving patterns? The DDP methodology has the advantages that 200 measured days out of a total of 27,879 days gives a good approximation of the driving profile/demand of the passenger car fleet. With this methodology, it is only important to have a data-set with many measured days, possibly with different cars. However, applying the DDP results in the modelling not being able to handle EV battery storage over more than 1 day.

In **Paper V** and in Section 5.3, we show that EV batteries can be used for storage over a time span longer than 1 day, to handle wind and solar power fluctuations (using YDP), which means that DDP cannot be used to resolve this. Therefore, the DDP methodology considerably under-estimates the flexibility potential of EVs, as shown in **Paper VI**. The results in **Paper VI** show that DDP either gives a lower share of electricity generation from VRE or requires greater investments in storage technologies other than EV batteries to achieve the same level of VRE as YDP/AGG, assuming the same scenario. Even with a battery capacity of 15 kWh, storage between days by the EV batteries (YDP and AGG methodology) can provide more flexibility to the system than intra-day storage (a result from applying the DDP methodology), as seen in **Paper VI**. This results, for example, in a 30% higher total electricity system cost in Ireland with DDP than the same scenario with YDP/AGG.

Some of the day-night variations can be captured with DDP, which is an important feature to understand how more solar power can be integrated into the electricity system, although both solar and wind power systems also need to store electricity between days. In the ELIN model, DDP is a good option, as the time resolution of the investment model is based on representative days and variation management over several days cannot be captured. In the EPOD and ENODE models with hourly time resolution for a full year, it is concluded in **Paper VI** that DDP is not a good proxy for investigating the system value of V2G using individual driving profiles.

YDP is the only methodology among the three applied in this work that allows the examination of certain research questions related to the battery health status, such as possible battery degradation from V2G. This is because AGG does not include individual driving profiles and DDP does not give any information as to how the representative driving days are linked in time. The main drawback with the YDP methodology is that it requires measurements of the same car over an extended time period, preferably of several months. Creating in a representative manner a data-set that contains a sufficient number of measured vehicles is both time-consuming and costly.

5.5 Reflections on the models and data

The vehicle energy consumption model developed and used in this thesis has several limitations, with the most important being that: (i) an average drive-train 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 may influence the results from the vehicle energy consumption model, although they are not varied in a sensitivity analysis, are driving behaviour, the extent to which the road is slippery, tyre pressures, weather, and the power-train configuration.

One obvious limitation associated with the types of optimisation models used in **Papers III–VI** is perfect foresight, with no uncertainty related to, for example, future costs, traveling patterns and demand, new technology developments, scheduling of charging and discharging to the grid of storage technologies and EVs, and the bioenergy potential for the production of biofuels. However, the applied electricity system models are not developed to predict the future but are instead 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 apply the modelling by minimising the total electricity system cost of the electricity system over the period studied. We are always seeking to identify the most cost-optimal solution (although the parameters are varied in a sensitivity analysis). It would be interesting to analyse also other solutions, e.g., using heuristics that are close in total system cost to see if the results change drastically. This is of interest since there are parameters that are not included in the modelling that could make the second-most optimal solution the preferable solution. Such parameters are for example the cost of the local grid, the esthetical values of wind power, environmental aspects other than CO₂ emissions, and the acceptance of EV owners to participate in V2G.

In **Papers III–VI**, we consider typical driving patterns and the driving demands are fulfilled for all individual vehicle driving profiles in all the model runs and calculations. Since data on individual driving patterns were available only for one region in Sweden and are applied to the other regions investigated, this will obviously not take into account national differences in driving profiles. Thus, there may be regional differences in working hours, leisure time activities, as well as geographical factors (e.g., Sweden being a low-population-density country compared to other countries).

There could also be regional differences related to access to a grid connection at parking spots and parking behaviours. For example, in countries in colder climates it is more common to have the vehicles parked in garages and to have access to an engine warmer, which usually means that there is already electricity available at the parking space. Parking on the street, perhaps also without having to pay a subscription to park in a certain spot, could make fast charging in cities attractive.

In this thesis, both the ELIN-EPOD model package and the ENODE model have been used to address the issue of the impact of EVs on the electricity system. One limitation with ENODE, which does not include trade, is that only local resources can be used, even though it can be beneficial to share resources across a large region. In contrast, the ELIN-EPOD model can handle trade between countries. However, the modelling of Germany in the present work included only Denmark and France as a neighbouring regions with inter-connections to Germany, which meant that other surrounding regions (Austria, Czech Republic, Poland, and Switzerland) were omitted. This was done because inclusion of all the neighbouring countries would have meant that it was computationally demanding to solve when also including individual driving profiles.

Southern Germany is a region with a high electricity demand and limited wind resources. The results in **Paper IV** indicate larger volumes of solar power than if trade with all neighbouring countries was included in the modelling, since a combination of solar power and trade with other regions, and thereby getting access to renewable energy resource also in neighbouring regions, would most likely be more cost-efficient.

5.6 Policy implications

There is definitely an urgent need to reach the European and national climate targets, especially for the transport sector, for which the CO₂ emissions have been almost stable since year 2000. This thesis is to a large extent focusing on reaching the climate targets using the most cost-optimal solution. However, one can consider whether we have the luxury of waiting for the optimal solution or if the most important thing is that we start to act now using the solutions currently available.

Electrification of transportation is shifting the regulation of the CO₂ emissions from the transport sector to the power sector. In Europe, with an absolute cap on CO₂ emissions from electricity generation (i.e., a total cap regardless of the level of electricity generation), electrification of road transport is likely to lead to real cuts in emissions. However, to accrue the full benefit from EVs, it could be important to create policy and/or market set-ups so that uncontrolled charging of passenger vehicles during hours when the electricity system is under strain is avoided. At present, this would mean avoiding charging during the morning and evening peak power demand periods on a daily basis, whereas in the not-so-distant future it will be advantageous to steer charging towards hours with high output from VRE and, hopefully, the willingness to participate in V2G will be high.

For electrification of the transport sector to become a reality, it should be important to establish an electrification road-map or strategy that includes the electricity generation, consumption and distribution of electricity; and increase the price imposed on CO₂ emission so as to ensure that the decrease in emissions from the European electricity system occurs in conjunction with electrification of the transport sector. An electrification road-map is needed to ensure that the electricity system is dimensioned for new types of electricity demands in the future. Otherwise, power shortages, instability of the grid, and over-loaded transmission lines may be the consequences of several un-planned and un-coordinated new loads. A road-map/strategy can also verify that the CO₂ emissions from the electricity system are not increasing when new sectors are undergoing electrification.

The power sector is included in the EU-ETS, where the present prices are significantly lower than the prices that are projected, in our model, as being required to reach climate targets in the future. If an optimised charging strategy and V2G are regulated, EVs can act as a powerful variation management strategy and eventually lower the EU-ETS prices compared to a scenario without EVs. It can be concluded that to reach the climate targets, the price for CO₂ emission needs to be higher in the EU-EST than it is today. The effect of on the CO₂ prices discussed are valid, thus the absolute levels of CO₂ prices will also be effected by other factors not included in our models, like, investments in local grid, electrification of industry, cost for V2G.

In the modelling work of this thesis, high shares of VRE are seen in many regions of Europe by 2050. In order to reach such high shares of VRE, the results show that several VMS and/or back-up generation are needed, such as V2G, peak power units, stationary batteries, hydrogen storage, and increased transmission capacity to allow for more trade. Investments in VMS/back-up generation, for example in gas turbines, will then be dependent upon high prices during some hours in order to obtain full cost coverage for a few hours of operation annually. A few hours of operation can be challenging from an investment point of view, as this back-up capacity is only needed from a system stability point-of-view.

The models assume an energy-only market with perfect foresight. However, a market with perfect foresight is not the reality. One measure to reduce the risk of power shortage, in for example Germany, France, Great Britain and Belgium, is to introduce a capacity market that complements the electricity market such that, for example, power plants or EV battery owners are getting paid for making capacity available. Electricity users, such as EV owners, can also get paid to reduce their levels of consumption (i.e., move the load to hours with a low net-load).

It is clear from this research that EVs with V2G can play important roles in balancing and stabilising an electricity system with high shares of VRE - on the time scales from an hour to several days and in many regions. V2G is still in an early phase of development, being tested in different pilot projects with the aim of improving the communication between the vehicle and the grid infrastructure. V2G is waiting for increase in the number of EVs and the emergence of electricity system balancing services for the higher VRE share. This study only looks at the techno-economical perspective. V2G on a large-scale involves not only a power flow between the vehicle and the grid, but also a flow of information. It is essential with attractive business models for the actors (EV owners and electricity system operators), as well as, an acceptance for V2G among the EV manufactures. To realise the V2G concept, an aggregator is needed that provides the interface between the system operator and the EV owners.

The automotive industry is a global business, in which technologies are shared, disseminated, and transferred between countries. It is, therefore, likely that we will have similar solutions to reach zero emissions for transport globally. This is especially true for passenger cars, which constitute a global mass market. Furthermore, ERS is a technology that is heavily dependent upon what the neighbouring countries are planning. Several technologies that are not compatible with each other exist for ERS. Since trucks and buses are travelling between countries in Europe, a common standard will be of the utmost importance. Nevertheless, there may also be scope for so-called 'closed systems', in which a shuttle service applies ERS between two fixed locations.

The 2030 Agenda for Sustainable Development, which was adopted by the United Nations Member States in 2015, calls for a substantial increase in the share of renewable energy in the global energy mix by 2030 [3]. The results of this thesis, presented in Sections 5.1 to 5.3, are contributing to reaching the targets of *SDG 7 Affordable and clean energy* and *SDG 13 Climate action*. An electrification of the road transport sector can help reduce the emissions of CO₂, as well as, improve the air quality in cities (SDG 3). The emissions are shifted from the transport to the power sector. In some countries, the new electricity demand from EV charging will have a significant impact on the total electricity demand. In addition, in some countries with limited renewable resources (like Japan and Germany), it will be a challenge to supply the new power demand from renewable electricity sources. However, an optimised charging strategy with V2G can help to integrate a higher share of VRE. This thesis shows the technical possibilities, but a realisation needs political will power.

CHAPTER 6

Conclusions

This thesis analyses and discusses the relationship between electrification of road transportation and the electricity generation system, applying several energy systems models. Our results show that electrification of road transport can have different impacts on the electricity system, depending on the electrification strategy used, the scale of the electrification and, especially, the time of consumption.

The modelling shows that direct electrification of passenger cars (i.e., involving static charging and/or ERS) can increase the national electricity demand by 6%–24%, depending on the country and assuming that the present fleet of passenger vehicles is electrified. This can be compared with an indirect electrification strategy involving the production of hydrogen or electrofuels, which would increase the electricity demand more than 4-fold compared to a direct electrification strategy, albeit with the increased possibility to distribute such demand both spatially and over time.

The results obtained by analysing a single road, highway E39 in Norway, show that the traffic on a single road exhibits large variations in both the geographical and time distributions of its energy and power demands. If assuming full direct electrification of the present-day traffic, the electricity demand is ~1 TWh per year (total annual vehicle kilometres for the E39: 2,600 million), with heavy vehicles accounting for 57% of this demand. Direct electrification of roads will increase the electricity demand during hours with already high demand, resulting in a 2% increase in the current power demand if electrifying a single road (such as the E39) and an increase of ~7% if electrifying all the E- and N-roads in Sweden and Norway.

ERS can play a role in decarbonising the transport sector, especially for trucks and buses, for two main reasons. First, the installation of ERS on 25% of the total combined E- and N-road length could connect some of the larger cities in Norway and Sweden with ERS, covering a large part (70%) of the current traffic demand on these roads. The 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 vehicles (buses and heavy trucks) and 50% of the demand from all light vehicles (cars and light trucks). Second, the cost of using the ERS infrastructure per kilometre is low compared to the total vehicle cost per kilometre, assuming a road on which at

least 1,200 vehicles use the ERS every day. However, it takes time to build new infrastructure, and with the high up-front cost, new business models are needed for large-scale implementation of ERS. ERS is also dependent upon a high user rate to bring down the ERS infrastructure cost per vehicle kilometre.

In this work, we have shown that the electricity demand from EVs in all the regions investigated are, when reaching close-to-zero CO₂ emissions in 2050, mainly met by an increase in generation from VRE (i.e., wind and solar power). A direct charging strategy or ERS will increase the electricity demand during hours with a high net-load, thereby increasing the need for greater flexibility in the system. However, an optimised charging strategy (without V2G) can help to smoothen the net-load curve by increasing the demand during hours with a low net-load, thereby reducing to some extent the need to invest in other peak-load and storage technologies, as well as, reducing curtailment of VRE.

An optimised charging strategy with V2G can provide greater flexibility than optimised charging on its own. It can do so by:

- Replace investments in stationary batteries to handle day-night time variations.
- Reducing investments in hydrogen storage for handling variations that span over several days (full replacement is envisaged in scenarios with a battery capacity of 85 kWh).
- Reducing investments in peak-power technologies (such as gas turbines and fuel cells).
- Reducing the total electricity system cost by 5%–60% relative to direct charging depending on the electricity system composition in the region, battery capacities, and the share of the fleet participating in V2G.
- Enabling an increase of up to 30% in the share of VRE compared to direct charging (depending on the electricity system composition within the region, and whether EVs together with VRE are more cost-efficient than thermal and nuclear power).

The magnitude of the system flexibility of EVs depends mainly on the conditions for renewable energy in the region, battery capacities, and the share of the fleet that is participating in V2G. V2G can, in most regions, increase the value of solar power so as to make it more competitive than other alternatives (i.e., thermal power, nuclear power or stationary batteries). EVs with battery capacities as low as 30 kWh, connected to the grid only at their home location, can contribute flexibility to the electricity system, as mentioned above. However, this thesis also shows that if the EV vehicles are equipped with large batteries (85 kWh), this can increase the value of VRE in relation to thermal and nuclear power. Yet, the investment cost for a larger battery (85 kWh instead of 30 kWh) are in this study assumed to be carried by the transport sector, and not by the electricity sector.

It is uncertain to what extent EV actors (i.e., manufacturers and car owners) will participate in a V2G scheme. This thesis shows that the additional benefits of V2G for the electricity system level off when approximately 24% of the EV fleet participates in V2G. V2G will increase the cycling of the EV batteries. As a potential cost for V2G, degradation of the battery could have a strong impact on the willingness to allow V2G, and thus, the amount of electricity discharged back to the grid from the EV batteries.

Finally, we conclude that it is important to represent the heterogeneity of individual driving patterns in electricity system optimisation models when the charging infrastructure is limited to the home location in regions with a high share of VRE and without access to

hydropower. The results from the modelling show that the charging and discharging patterns of the individual EVs differ significantly between the driving profiles modelled. On the one hand, individual driving patterns are needed when addressing research issues that have to do with individual EV performance, such as the impact of V2G on battery health status. On the other hand, current driving patterns of individual vehicles may look different to the driving patterns in year 2050, especially if there is an introduction of autonomous vehicles and/or more people start participating in car-sharing systems instead of personally own vehicles.

CHAPTER 7

Future work

There are, of course, many aspects of the electrification of the road transport sector and its implications for the electricity system that need to be studied further. This chapter gives examples of some of these aspects, most of which are related to the work performed for this thesis.

Hydrogen and electrofuels are in this study analysed from efficiency and total electricity demand perspectives following a discussion of the challenges and possibilities from the electricity system point-of-view (**Paper I**). Hydrogen/electrofuels will increase substantially the yearly electricity demand, although with a flexibility in relation to the time of consumption. In **Papers III–VI**, we have used an electricity system optimisation model that includes only direct electrification. Thus, a modelling study that analyses a combination of the different ways to electrify the transport sector, i.e., optimised charging with V2G, production of hydrogen and/or electrofuels for transport purposes, would be of interest. Such a study could then investigate the value for the electricity system of having more flexible use of electricity in the transport sector, with the drawback of a lower efficiency from the electricity source to the wheels.

V2G might increase the degradation rate of batteries, due to more frequent and deeper cycling. The cycling impact on the battery also depends on the battery capacity. Further research is needed to evaluate the battery degradation induced by V2G and its associated costs. It would be interesting to include a cost for degradation from battery cycling in the electricity system models, while taking into account the charging patterns of the cycling, including the state of charge (SOC) value, the depth of discharge (DOD), and the c-rates.

V2G is in this thesis investigated as a variation management strategy for the electricity system. In the modelling of this thesis, we assume that some of the EV owners in the fleet are willing to optimise their patterns of charging and discharging of the EV battery according to what is most optimal from the electricity system perspective. A study of the factors determining the willingness of EV owners to participate in V2G would give an additional perspective on the research performed in this thesis. The same goes for the willingness of vehicle owners (cars, trucks and buses) to use an electric road system in the future.

This work applies the traffic flow data (ADT) and real-time driving patterns for 426 vehicles in one region in Sweden for 30–73 days per vehicle as inputs to the modelling. 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 may result in a substantial change in the ways that vehicles (passenger cars, buses and trucks) are used in the future. To what extent we will own our cars in the future may also influence driving patterns and, therefore, also the results presented in this thesis. A study investigating the effects of more disruptive technology developments that change the travelling patterns and the distances that the vehicles are driven would complement the present work.

In the modelling of this work (**Papers III–VI**), we optimise investments in the national grid (i.e., grid connections for bottle-necks in the routes of transmission between regions). Investments and the usage of regional and local grids are not included in this work. Additional studies are needed to investigate the impacts on the regional and local electricity grids of road transport electrification. Such a study could include a cost analysis of the whole grid network comparing different charging strategies of passenger vehicles, ERS and using electricity to produce a fuel. A fuel, like hydrogen, can be produced centrally and transported with tankers or pipelines to the filling station. However, it could also be produced locally at the fuelling station, whereby the electricity grid infrastructure would provide electricity to local hydrogen stations using decentralised electrolyzers.

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