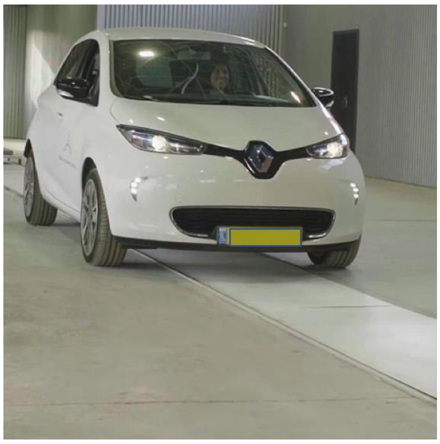
Swedish-German research collaboration on Electric Road Systems



Electricity supply to electric road systems

Impacts on the energy system and environment

Authors

Filip Johnsson, Maria Taljegård and Johanna Olofsson | Chalmers University of Technology

Michael von Bonin and Norman Gerhardt | Fraunhofer Institute for Energy Economics and Energy System Technology

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The research collaboration "CollERS" consists of the core members from the Swedish Research and Innovation Platform for Electric Roads and the two national German research projects Roadmap OH-Lkw and StratON:

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  - ifeu – Institut für Energie- und Umweltforschung Heidelberg
  - Fraunhofer IEE – Fraunhofer Institute for Energy Economics and Energy System Technology
  - Heilbronn University of Applied Sciences
- **Swedish research partners**
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  - Chalmers University of Technology
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  - Trafikverket – Swedish Transport Administration
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Summary

This study analyses how an electrification of the transport sector, including static charging and electric road systems (ERS), could impact the Swedish and German electricity system. The integration of ERS in the electricity system is analysed using: (i) a model-package consisting of an electricity system investment model (ELIN) and electricity system dispatch model (EPOD) and (ii) an energy system investment and dispatch model (SCOPE). The models are run for the same sets of scenarios and methodological differences and results are compared. The modelling results from the CollERS project show that the additional electricity demand from a large-scale implementation of ERS (i.e., a German-Swedish ERS corridor and connecting main road network) is mainly met by investments in wind power in Sweden and both wind and solar power in Germany. Since ERS will take some time to scale up, **the modelling shows that there should be enough time for the electricity system to be transformed to meet demand for ERS while also meeting the goals on greenhouse gas reduction**.

It can be concluded that ERS are increasing the peak power demand (i.e., the net load) in the electricity system. Therefore, there is a need for more investments in peak power units and storage technologies when using ERS. A smart integration of other electricity demand, such as optimisation of the static charging at the home location of passenger cars, can facilitate an efficient use of renewable electricity also with ERS. Thus, **it is important that ERS are evaluated and assessed in connection to corresponding assessment of electrification technologies of passenger cars and other sectors**, including the industry sector where there are already plans for electrification (e.g. iron and steel, cement and petrochemical industry).

The model comparison shows that different assumptions and methodological choices impact what kind of investments are taken, such as in wind, solar and thermal power plants to cover an additional demand from the use of ERS. However, an increase in investments in solar power (Germany) and wind power (Sweden) can be seen in all scenarios to cover the new demand for ERS.

Keywords: electric vehicle; energy system modelling; method; vehicle-to-grid; variability management; smart charging

Content

1. Introduction

In Europe, fuel combustion in the transport sector is responsible for about 23% of greenhouse gas (GHG) emissions [1] and is the only sector with emissions still growing compared to 1990 [2]. To meet CO_2 emission reduction targets in line with the Paris agreement [3] and the European Union [4], the transportation sector needs to replace conventional fuels with low-carbon options. Electrification of the road transportation together with an increased share of renewable electricity generation, is being proposed as an option for reducing CO_2 emissions in the transport sector [2, 5, 6]. The Swedish government initiated a study on how the transport sector can be made fossil-free, which revealed that electrification has the potential to play an essential role in reducing the fossil fuel dependence of the Swedish transport sector [6].

Electrification of road transport can be achieved by using various approaches, including: (i) battery electric vehicles (EVs) with static charging; (ii) the usage of electricity to produce fuels (e.g. hydrogen or synthetic hydrocarbons) for on-board use in internal combustion engines or fuel cells; and (iii) an electric road system (ERS). ERS can provide dynamic power transfer to vehicles in motion and has thus the possibility to reduce the size and weight of onboard battery, compared to EV's with static charging. This is especially advantageous for long-hauled trucks and buses. The CollERS report "Overview of ERS concepts and complementary technologies" includes a more detailed overview of the different approaches.

Technologies and fuels that will dominate future road transportation is not yet clear and it is likely that a mixture of different technologies and fuels, both within and between different vehicle categories will be part of the solution. The cost and climate benefit from an increase in the share of electricity used for transport will be determined by its impact on the electricity generation system. The impact will be different between countries, depending on the characteristics of the electricity system such as the conditions for renewable electricity [7, 8].

An electrification of the transport sector through EVs with static charging and/or ERS with dynamic charging introduces a new demand to the electricity system, and hence, will create new load profiles depending on the time of consumption and the amount of electricity used. The shape of these new profiles is depending on different charging strategies, for example if the EVs are charged directly when being parked or if the charging is optimised according to what is optimal from an electricity system perspective. This will then have different effects on the investment in capacity of the electricity system. Depending on electrification strategy, this new demand may also introduce a potential for battery-powered EVs to provide demand-side management to the power grid.

Several studies have used linear optimisation investment models and/or dispatch models to investigate the impacts of passenger EVs on, for example, the dispatch of electricity generation technologies, CO_2 emissions, and peak power demand [9, 10]. Most of the previous studies using optimisation modelling of the electricity system have included static charging of passenger vehicles only. Studies such as Grahn [11], Stamati and Bauer [12] and Taljegard et al. [13] and Jelica et al. [14] have investigated the electricity demand for ERS. Stamati et al. [12] investigated the possibility to meet the electricity demand for the highway traffic flow on an average day in the Netherlands, with renewable energy sources. However, none of the mentioned studies used an optimisation model for the electricity system.

Two modelling studies by Taljegard et al. [7, 8] investigated how electrification of the road transportation sector in different countries, including both static charging and ERS, under a stringent CO_2 cap will influence investments in new electricity generation capacity and the dispatch of the electricity generation portfolio until 2050. Their studies show that investments in mainly wind and solar power are made to cover the additional demand when electrifying the transport sector. A study performed by Gerhardt et al. [15] investigated the decarbonisation of the transport sector and its interplay between the energy system and Power-to-X, including static charging, ERS and discharging back to the grid (i.e., vehicle-to-grid; V2G). The study by Gerhardt et al. [15] shows that V2G reduces the need for stationary electricity storage and peak capacity and increases installed solar PV capacity.

This report presents a comparative study of two electricity system analysis models ELIN-EPOD and SCOPE – individually developed at Chalmers University of Technology and Fraunhofer Institute for Energy Economics and Energy System Technology – both designed for the purpose of analysing future electricity systems under a stringent CO_2 mitigation target.

The aim of this report is to apply the two different models to investigate and compare how an electrification of the transport sector, through the implementation of static charging of passenger vehicles and an ERS for trucks and buses, could impact the Swedish and German electricity system with respect to energy and power. The same sets of future scenarios have been applied to both models. Methodologies and results are compared with the purpose of identifying important factors affecting the outcome as well as similarities and differences in how the electrification of the transport sector can be accomplished under ambitious CO_2 mitigation targets.

2. Method

The integration of ERS in the Swedish and German electricity system is analysed using (i) a model-package consisting of an electricity system investment model (ELIN) and electricity system dispatch model (EPOD) and (i) an energy system investment and dispatch model (SCOPE).

2.1 Description of ELIN-EPOD and SCOPE

The ELIN-EPOD model package developed at Chalmers includes a cost-optimisation investment model (ELIN) and an electricity dispatch model (EPOD) of the European electricity systems. This model package has been used to study the transformation of the European electricity system to meet European policy targets on CO_2 emission (see Odenberger et al. [16] and Unger et al. [17] for a description of the original model package and Göransson et al. [18], Nyholm et al. [19] and Taljegard et al. [7, 8] for further developments of the model package). Figure 1 gives an overview of the ELIN-EPOD model package including, for example, important input and output data and technologies to invest in.

ELIN-EPOD consist of the electricity sector and part of the heating sector (i.e., heat pumps and combined heat and power plants). The investment model has an hourly resolution with 20 representative days and an investment period of every 10th year from 2020 to 2050. The dispatch model EPOD is run for a full year (2050) with an hourly time resolution. The models are based on current and historical data and information of the European electricity system. The results from the investment model (ELIN) (i.e., the description of the power system, fuel and CO_2 prices, transmission lines) for the investigated year are used as an input for the optimisation in the dispatch model (EPOD) to determine the least-costly hourly dispatch of the system for one specific year (in this study 2050).

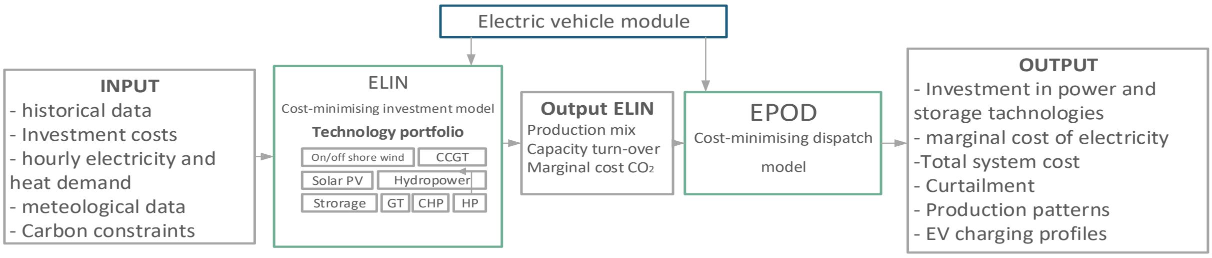

Figure 1. Overview of the ELIN-EPOD model package including the input and output data and technologies to invest in. CCGT, combined cycle gas turbine; GT, gas turbine; CHP, combined heat and power; EV, electric vehicle.

The energy system model SCOPE has been developed at Fraunhofer Institute for Energy Economics and Energy System Technology within the project "Interaction of Electricity, Heat and Transport", and the model is described in Böttger et al [20] and Jentsch [21]. SCOPE is a cross-sectoral model designed to analyse and optimise the European energy system. The model has been developed by Böttger et al. [20] to also include the optimal investments in vehicle technologies and fuels. Sectors included in the model are electricity, transport and heat.

The model objective is to minimise the total system cost in the energy system for the investigated year, which in this study is assumed to be 2050. For 2050 a green-field approach is assumed (i.e., an empty system as a starting point without any generation capacity in place besides hydropower and waste power plants). In Figure 2 a schematic representation of the SCOPE-model is given including important input and output data and technologies to invest in. Input data describing the energy system is used to find the least-cost hourly system for the investigated year 2050, while fullfilling zero emission of CO_2. The model is run for a full year with a 1-hour time resolution. In addition to the electricity and gas market, an overarching market for emission allowances is included. Hydro power is modelled with historical data from year 2012 for running water, storage water and pumped storage power plants [22].

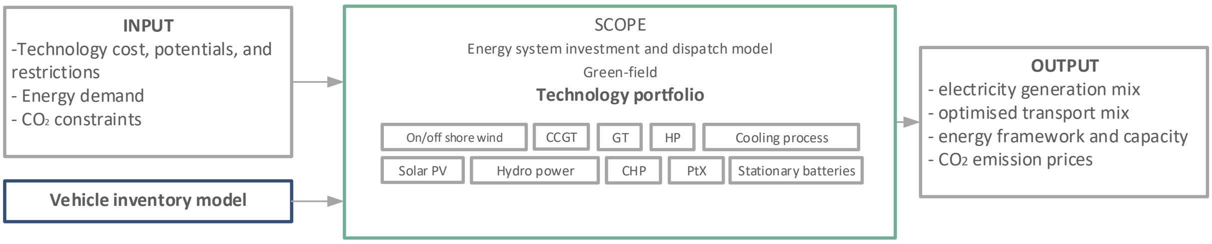

Figure 2. Overview of the SCOPE-model including the input and output data and technologies to invest in. CCGT, combined cycle gas turbine; GT, gas turbine; CHP, combined heat and power; PtX, power-to-X.

2.2 Model comparison

Table 1 shows a model comparison between SCOPE and ELIN-EPOD model package including some of the main model structure and assumptions. As seen in Table 1, the model structures and assumptions are in many aspects similar, but there are also fundamental differences between the models that will impact the results of this study. Almost all of the differences between the models are related to model structures, such as, time resolution, sector integration and starting system point (Table 1). We have tried, as far as possible without changing the structure of the models, to apply the same assumptions, same set of technology options and scenarios for ERS. In Germany, there is a policy debate about using fossil-fired carbon capture and storage. Therefore, the this technology has been included in a sensistivity analysis.

This study focuses on the modelling results for Sweden and Germany (although modelling of the neighbouring countries is included in both ELIN-EPOD and SCOPE). It should be stressed that Europe has an integrated electricity market and, thus, in order to provide a meaningful analysis, it is important to model and analyse results not only for Sweden and Germany in isolation. There are indeed different bottlenecks in electricity transfer regions throughout Europe (including transfer from and to Sweden and Germany) which is included in the modelling.

The national electricity demand is divided into regional demand, based on the statistics for gross domestic production (GDP) obtained from Eurostat [23] (ELIN-EPOD) and Cosmo EU (SCOPE). Both models are using weather data from year 2012 with an hourly time resolution [24, 25]. Wind area are limited to 0.4 MW per km^2 in ELIN-EPOD (including areas not available for wind power) and 25 MW per km^2 in SCOPE (assuming available land area). Hydropower is modelled with historical inflow data in both ELIN-EPOD and SCOPE. A cap on CO_2 corresponding to 100% emission reduction by 2050 relative 1990 emissions for the energy sector is assumed.

Table 1. Model comparison between SCOPE and the ELIN-EPOD model package.

Parameter	ELIN-EPOD	SCOPE
System starting point	Historical data	Green-field
Geographical Scope	Sweden, Germany, Norway, Denmark, Netherlands, Belgium, France, Switzerland, Austria, Czech Republic, Poland	European Union (excluding Malta and Cyprus), Norway and Switzerland
Transmission	Investments in transmission capacity and transmission of electricity per timestep is optimised	Transmission of electricity per time step is optimised but no new investment in capacity (fixed maximum capacity 2050)
Variation management strategies	Transmission, stationary batteries, vehicle-to-grid	Transmission, demand side management (heat pumps and air conditioning), stationary batteries, power-to-X, vehicle-to-grid
Time resolution	ELIN is modelled every tenth year between 2020 and 2050 with 480 timesteps per year, EPOD is modelled for 2050 with 1 hour timesteps	Year 2050 with 1 hour timesteps
Sectors	Electricity sector, electrified road transport sector and part of heating sector	Electricity, heat and transport
Main inputs	Cost and properties for different fuels and technologies, hourly electricity and heat demand, CO_2 constraints, vehicle driving patterns	Cost and properties for different fuels and technologies, hourly energy demand, CO_2 constraints
Main outputs	Investments in power and storage technologies, total system cost, electricity	Electricity generation mix, optimised transport mix, energy framework and

	generation mix, CO_2 shadow prices, electric vehicle charging profiles	capacity, CO_2 emission prices, total system cost
CO_2 target Year 2050	Zero	Zero
CO_2 target	One target on European level	Both targets on European and national level
Total electricity demand year 2050	~800 TWh in Germany and ~225 TWh in Sweden	~950 TWh per year in Germany and ~225 TWh in Sweden
Power generation technology options	on/off shore wind, solar PV, hydropower, combined heat and power, combined cycle gas turbines, gas turbines	On/off shore wind, solar PV, power-to-gas (national) & power-to-x (import)[1] [26], hydropower, cogeneration, cooling process, Condensing plant, Power-to-Heat, HP
Technology limitations	No new investment in nuclear and fossil-fired carbon capture and storage	No new investment in nuclear and fossil-fired carbon capture and storage.
(Area) limitations for renewable energy technologies	0.4 MW per km^2 (incuding available and non-available area) for wind power and no area limitation on solar power	25 MW per km^2 (incuding available area) for wind power and area limitation on solar power in Germany (in Sweden no investments in solar power is assumed).
Vehicle-to-grid cost	10 EUR/MWh	10 EUR/MWh
Vehicle categories	Passenger cars; light trucks; heavy trucks; bus	small passenger car, medium passenger car, large passenger car, light commercial vehicle, heavy commercial trucks
Number of electric vehicles (EVs)	Exogenously given EV penetration rate (20% by 2030 and 60% by 2050; 60% by 2030 and 100% by 2050);	Number of EV is optimised in vehicle inventory model
EV battery capacities	30 kWh for passenger cars (only ERS is assumed for trucks and buses)	35 kWh for small passenger cars, 60 kWh for medium passenger cars, 80 kWh for large passenger cars, 45 kWh for light commercial vehicles
Traffic demand/implementation	Aggregated vehicle fleet based on data from individually driving profiles [27]	Aggregated vehicle fleet compiled from vehicle inventory model [24]
Electric road system (ERS) implementation	ERS for light and heavy trucks and buses (in a sensitivity analysis, ERS for passenger cars light trucks has also been assumed)	ERS for heavy trucks
Share of trucks using electric road system (ERS)	100%	Number of trucks using ERS is optimised in the model

2.2.1 *Model limitations and important model structural differences*

The system starting points differ between the models since ELIN-EPOD is based on historical data while SCOPE has a green-field approach for 2050. In ELIN-EPOD the development of the electricity supply system over time is based on phasing out current power plants based on projected technical lifetimes and then making new investment to meet the electricity demand in 2050. In SCOPE, new investments are taken without the influence of today's energy system. ELIN-EPOD includes only the electricity sector and part of heat sector (heat pumps and combined heat and power plants) whereas the electricity demand for transportation is exogenously given. SCOPE includes all sectors in the energy system (heat, electricity and transport). Thereby, SCOPE also includes an optimisation of investments in fuels and technologies for the transport sector.

In ELIN-EPOD the transmission network between regions is modelled according to the current expansion plans with their specific capacities and limits. The investment model has the possibility to invest in additional transmission capacity between the modelled regions. In ELIN battery storage is the only way of storing electricity produced, since ELIN only simulates 20 representative days, the stored electricity need to be used during

[1] The national potential for power-to-gas is very limited, international power-to-x refers to countries with high Wind and PV resources.

a 24 hour window. In SCOPE, trade between regions is optimised with a fixed upper limit of transmission capacity. SCOPE has the possibility to store electricity over time periods longer than one day, making it possible to make use of abundant electricity at a later time. The storage technologies that are allowed in SCOPE are power-to-gas (PtG) and stationary batteries.

In the investment model ELIN, only intra-day storage is possible since only representative days are used. However, ELIN includes the possibility to invest in stationary batteries with intra-day storage. Both ELIN-EPOD and SCOPE assumes a fixed demand as an input to the models. In SCOPE heat pumps and air conditioning are modelled as flexible consumers and could hence shift consumption over time, which is not the case in ELIN-EPOD, where demand side management (DSM) is not included.

2.2.2 Electrified transport sector in ELIN-EPOD and SCOPE

The EVs can in both ELIN-EPOD and SCOPE offer benefits for the electricity system in terms of system flexibility, e.g. in the form of controlled charging and possibly also to discharge electricity back to the grid according to what is most optimal from an system point of view. In Taljegard et al. [7, 8] ELIN-EPOD were expanded with an add-on module to include also an electrified road transport sector in the form of static and dynamic charging of passenger vehicles, trucks and buses. Thus, a demand for electric transportation has been added to both the investment model and the dispatch model as a new load. The travelling behaviour of the aggregated passenger vehicle fleet used in this study are based on 426 hourly real-world driving profiles. The charging and discharging of the EVs are optimised, while at the same time fulfilling a given hourly demand with the number of EVs, the battery capacity, and the hourly EV demand being exogenously given. There is no optimisation of the number of EVs or battery capacity. A detailed description on how this is implemented in ELIN-EPOD can be found in Taljegard et al. [7, 8].

The transport sector in the SCOPE model is based on data provided from a vehicle inventory model that uses a travel survey consisting of 70 000 vehicles in Germany with one day traveling observation [28]. The vehicle inventory model simulates future market penetration of alternative propulsion technologies for the road transportation sector. Böttger et al. [20] provide a table with the different market share of different vehicle categories used in the SCOPE-model. An exhaustive model description can be found in Trost [28]. Simulations of the transport sector in SCOPE are performed based on the number of vehicles and vehicle kilometre taken from the vehicle inventory model. Assumptions regarding electric driving share are based on [29] and [30]. The number of other vehicles, such as busses, motorcycles and construction vehicles are exogenously given.

3. Scenarios

Table 2 gives a description of the scenarios run in ELIN-EPOD and SCOPE. The same set of scenarios (i.e., the share of vehicles being electrified and using the ERS) are being run in both models. The models are run assuming three different charging strategies for passenger EVs: (i) a direct charging of the EVs according to their driving patterns (Direct); (ii) an optimisation of the charging time to minimise the cost of meeting the electricity demand (Optimised); (iii) optimised charging and a passenger V2G strategy including the possibility to discharge the EVs to the grid (Optimised+V2G). ERS are included in three of the scenarios, in which ERS is the main electrification option for trucks and buses. Static charging of truck and buses are not included in this modelling work. A references scenario (RS) without ERS is modelled for comparison.

Table 2. Description of scenarios for ELIN-EPOD and SCOPE.

Scenario name	Properties
Reference Scenario (RS)	Direct charging of EV without ERS
S1-Direct-ERS (S1)	Direct charging of EV and ERS for trucks and buses
S2-Opt40%-ERS (S2)	40% optimised charging and 60% direct charging and ERS for trucks and buses
S3-V2G40%-ERS (S3)	40% optimised charging with V2G and 60% direct charging, and ERS for trucks and buses

A sensitivity analyses of some of the parameters presented in Table 1 is performed for ELIN-EPOD. Table 3 shows the parameters tested in a sensitivity analysis. For example, the sensitivity analysis varies the possibility to invest in fossil-based electricity generation technologies and ERS also for passenger vehicles in ELIN-EPOD.

Table 3. Parameters tested in a sensitivity analysis in ELIN-EPOD

Scenario name	Parameter	Base case value	New value
S3-no fossils	No investments in fossil fuelled electricity generation technologies	Possibility to invest in fossil fuelled electricity generation with CCS	Not possible to invest in fossil-based fuels with CCS
S3-ERS for cars	ERS for all transportation modes	ERS for all trucks and buses	ERS for all trucks, buses and passenger cars

4. Results

The model results from the two different models show that there are different ways to receive an electricity generation system with zero emissions for Sweden and Germany, when including an electrification of the transport sector. However, there are also results that are similar in both models.

4.1 Investments in the electricity generation capacity

4.1.1 Germany

Figure 3 shows the total electricity generation capacity installed in Germany year 2050 for the investment models ELIN (3a) and SCOPE (3b) and for all investigated scenarios (i.e., RS, S1-S3). As can be seen, the installed capacity for Germany differs considerable between the two models. The main difference in installed capacity is that SCOPE gives a higher installed capacity in variable renewable energy (i.e., wind and solar power with lower full load hours), while in ELIN there is also investments in bioenergy with CCS (so called BECCS) and fossil fuel power plants (mainly gas). BECCS results in negative emissions that make it possible to invest in fossil fuel technologies while still reaching the climate targets.

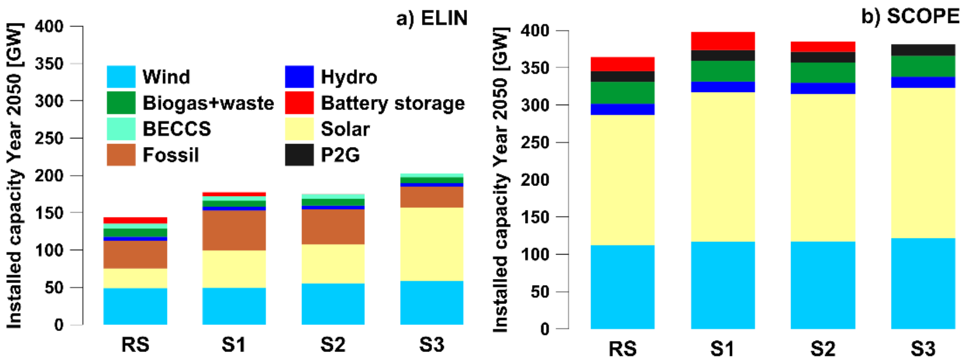

Figure 3. Total electricity generation capacity installed Year 2050 in Germany for all scenarios in (a) ELIN and (b) SCOPE.

The SCOPE model yields higher total installed capacity compared to ELIN. The main reason for this is due to the higher installation of solar PV and wind power in SCOPE. In ELIN, it is more cost-efficient, compared to SCOPE, to invest in bioenergy carbon capture and storage (BECCS) to cover part of the electricity demand in 2050. The difference in installed solar PV can also be explained by the need for the system to reach reginal climate targets in the SCOPE model in all sectors, resulting in higher investments in renewable electricity sources in Germany. Installations in thermal power, as seen in ELIN, yields higher full load hours and thus a lower total capacity needed to supply the electricity demand. Further differences is the significant higher installation of battery storage in SCOPE than in ELIN to handle the variability of solar power generation.

A higher share of variable energy sources (i.e., wind and solar power) in the electricity system in SCOPE, compared to ELIN, can be integrated due to demand-side-management provided by heat pumps and air conditioning, as well as, more investments in stationary batteries in SCOPE. Germany are running out of spots with good wind conditions in the ELIN model and need to invest during the investment period (i.e., 2020 to 2050) in other technologies such as thermal based technologies (biomass and natural gas).

The installed capacity in gas differs also between the models. In ELIN the CO_2 target is on a national level, which opens up the possibility for other regions to compensate for emission from thermal power plants, which is not the case for the SCOPE model, where the regions need to meet regional CO_2 targets. In ELIN installation in biomass are made, which is not the case in the SCOPE model. In SCOPE, biomass is used in other sectors to supply demand, while ELIN only includes the electricity sector, i.e. biomass is used to cover electricity demand. In ELIN BECCS is used to compensate for emission made by natural gas turbines and coal power plants.

The introduction of an ERS (S1-Direct-ERS) implies an increase in electricity demand which needs to be supplied by new investments in the electricity system. In both ELIN and SCOPE it can be observed that increased installations are made in solar PV, wind power and battery storage. In ELIN there is also an increase in investments in natural gas turbines.

Introduction of optimisation of 40% of the charging of the EV fleet (S2-Opt40%-ERS), implies that the EVs if possible are being charged when electricity demand is lower compared to the case when all EVs charge directly when being parked. This results in less total installed capacity in both models. In ELIN no investments are made in battery storage and reduction in peak power with 30%. In SCOPE there is a similar trend with less investments in battery storage.

The option of using electricity stored in batteries of the EV fleet (i.e. passenger cars) through V2G results in both models in investments in battery storage, although the investments in solar power increases in both models. In ELIN less investments are also needed in gas turbines and the system value of solar power increases in S3-V2G40%-ERS. With ERS for heavy vehicles the peak power demand inceases compared to the base case scenario. However, if all EVs (passenger cars) use dynamic power transfer and V2G is applied for the passenger EVs (i.e., S3-V2G40%-ERS), both the total investment and the investment in peak power will decrease to a larger extent compared to only optimising the charging behaviour (S2-Opt40%-ERS).

4.1.2 Sweden

Figure 4 shows the total capacity installed in Sweden for year 2050 for both investment models (a) ELIN and (b) SCOPE for all investigated scenarios. The total installed capacity for Sweden differs significantly between the models, as well as, technology options invested in. The difference in installed capacity can be explained by the possibility for long-term storage (in the form of P2G) and DSM in SCOPE, which is not possible in ELIN. Similar to Germany, investments are made in biomass generation technologies in ELIN, while in SCOPE biomass is more economical valuable to use in other sectors. Another difference is the installed capacity of solar PV and stationary batteries, which are not present in SCOPE. In SCOPE the model has not the option to invest in solar PV for Sweden, due to technology limitation of solar insulation. Battery storage capacity in ELIN can be explained by the investments in solar PV. If solar PV installations are combined with battery storage, the electricity produced by the PVs can be made better use of.

When analysing the different scenarios in the two models, there is not much of a difference in installed electricity generation capacity between the different scenarios in the SCOPE model, while the difference in installed capacity between the scenarios in ELIN is more pronounced. In ELIN, the increase in demand due to introduction of ERS (S1-Direct-ERS) results in increased capacity of battery storage, waste and wind power. In the optimised charging scenarios (S2-Opt40%-ERS and S3-V2G40%-ERS) in ELIN, there is a lower demand for battery storage compared to the direct charging scenario (S1-Direct-ERS).

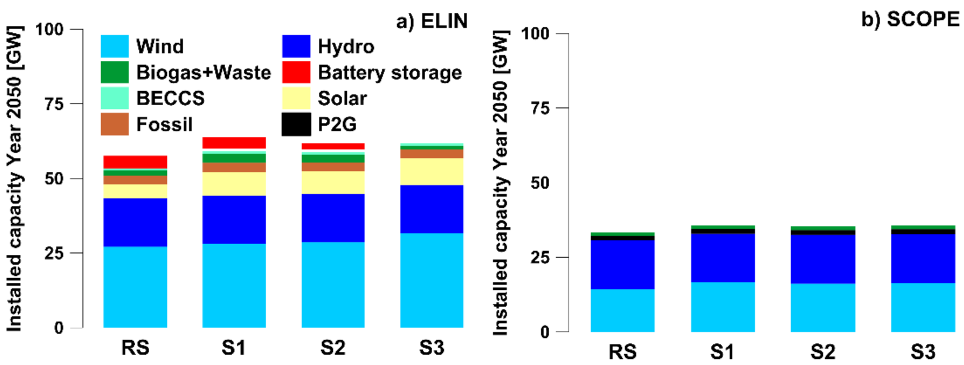

Figure 4. Total electricty generation capacity installed Year 2050 in Sweden for all scenarios (a) ELIN and (b) SCOPE. BECCS, biomass with carbon capture and storage; P2G, power-to-gas.

4.2 Electricity generation

The modelling results in ELIN-EPOD show that fossil fuels, wind power and biomass with CCS (resulting in negative emissions) dominate the German annual electricity generation in 2050 (see Figure 5). In SCOPE, however, solar PV and wind power dominate the annual electricity system. This can be explained by the large difference in installed PV capacity in the system. In SCOPE, the installed capacity in solar PV is about four times higher compared to ELIN.

Both models show that Germany will import electricity to meet electricity demand. In ELIN about 20% of the yearly demand is met by electricity being imported, while the share in SCOPE is much lower (16 TWh compared to 220 TWh). This can be explained by the predefined maximum limit on transmission capacity in the SCOPE model (i.e., tranmission investments is not part of the optimisation). The modelling results in both the models show that hydro and wind power dominate the annual electricity generation in Sweden in 2050 and that Sweden will be exporting electricity (ca 20 TWh) (see Figure 6).

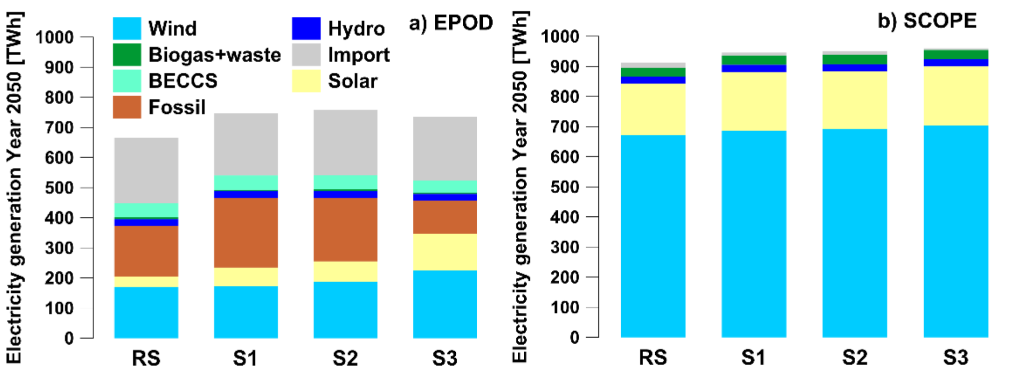

Figure 5. Total electricity generation for Germany in Year 2050 a) EPOD and b) SCOPE.

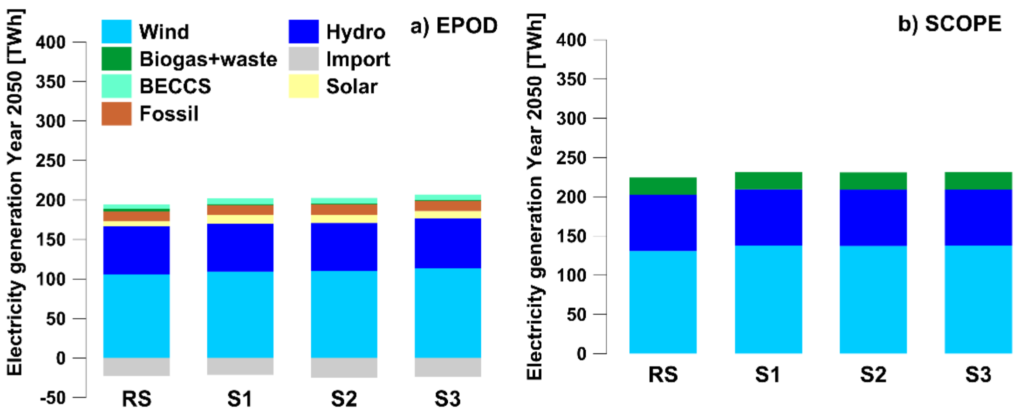

Figure 6. Total electricity generation for Sweden in 2050 for all scenarios a) ELIN and b) SCOPE.

4.3 Impact of electric road systems on the net load

Figure 7 shows the net load (i.e. load minus variable renewable electricity generation) as obtained from the models a) EPOD and b) SCOPE. Figure 7 illustrates the net load excluding and including loads from ERS and V2G, as well as, the EV charging and discharging back to the electricity grid for one week in February in Germany. In Figure 7b, the hourly resolution of P2G is also included to better illustrate the whole system, i.e., including long term storage.

Under the condition that charging behavior is optimised, the passenger EVs are discharged to the grid when the net load is high, which reduces investments needed in peak power capacity. The amount of discharging is about 72 TWh in Year 2050 for Germany. This number is small compared to the total generation of approximately 900 TWh per year, although it gives a flexibility to the system which is important for reducing peak power demand and curtailment of wind power. For example, passenger EVs will smoothen the net load curve in the German electricity system.

ERS alone will on the other hand, as seen in Figure 7, increase the current net load assuming the current traveling patterns. If no V2G is applied, the ERS would then increase peak in the net load curve.

There is a difference between EPOD (Figure 7a) and SCOPE (Figure 7b). As can be seen in Figure 7b (SCOPE) there are many occasions when there is a surplus of variable renewable power (negative net load values), a result not seen in the EPOD results (Figure 7a). With a controlled charging algorithm (blue line) this surplus can be used to charge the EVs. In SCOPE, a low or negative net load is also handled by doing P2G. A high or positive net load leads to discharging of EV batteries back to the grid, which is more pronounced in the EPOD results.

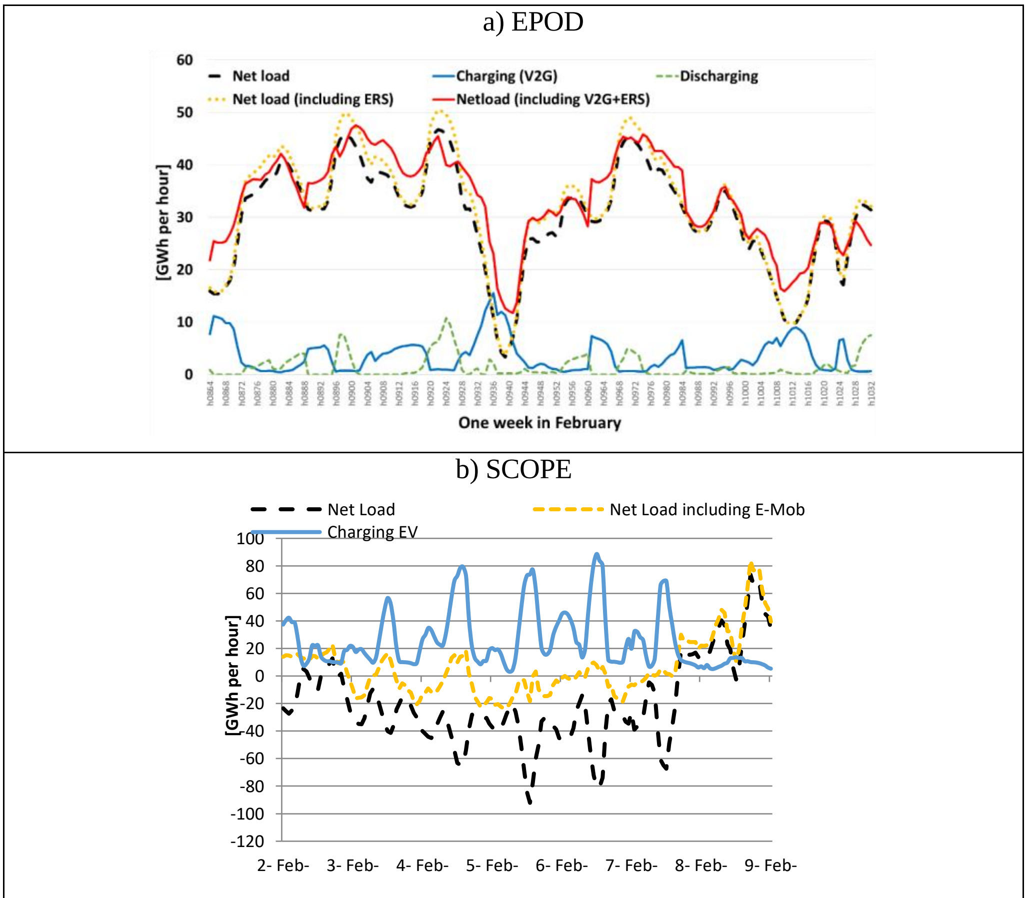

Figure 7. Net load (i.e., load minus wind and solar generation), including and excluding electric road systems (ERS) for trucks and buses, and the load from charging the EVs and the discharging back to the grid for one week in February in Germany in (a) EPOD and (b) SCOPE. SCOPE also includes hourly production of PTG.

4.4 Sensitivity analysis

Figure 8 shows the results of the sensitivity analysis performed in ELIN-EPOD. The aim is to test how further changes in parameters affect the design of the future electricity system including optimised charging and V2G (S3-V2G40%-ERS). In the sensitivity analysis ERS for passenger cars has been introduced as an additional load in a system. We have also run the ELIN-EPOD model without the possibility to investment in fossil fuel based technologies (thereby the motive to invest in BECCS will be zero).

As seen in Figure 8, introducing ERS for passenger cars has a minor impact on the outcome. The increase in electricity demand, when passenger vehicles are using ERS for the trips not covered by the 30-kWh battery, is about 2%. The relatively small increase in electricity demand does not have a large impact on investments made compared to the case without ERS for passenger vehicles, as seen in Figure 8. The scenario without fossil fueled electricity generation in the model package ELIN-EPOD will increase the amount of solar power in the electricity system in both Sweden and Germany. In Sweden, also more wind power will be used instead of BECCS and natural gas. The use of biogas will also increase to help balance a higher share of variable renewable energy.

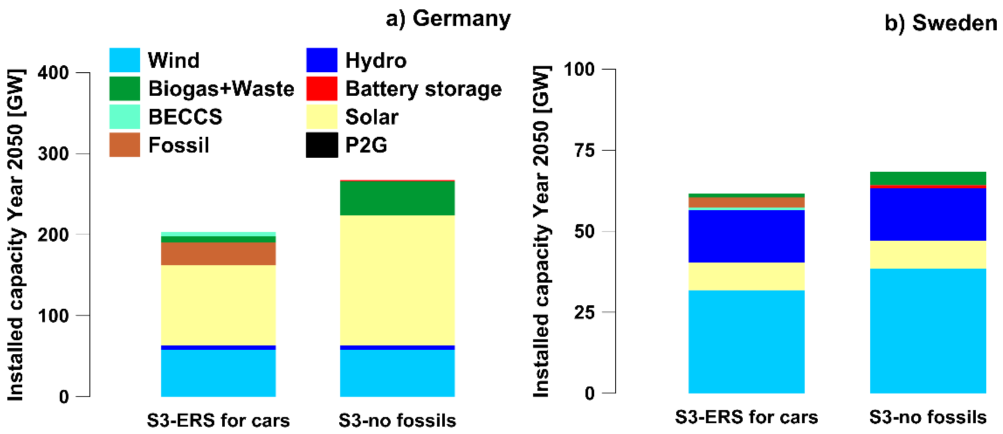

Figure 8. Sensitivity analysis in ELIN-EPOD. Comparison of S3-V2G40%-ERS with (i) introduction of ERS for passenger cars, (ii) no solar PV limitation and (iii) possibility to invest in fossil-fuelled electricity generation technologies and bioCCS.

5. Discussion

This study deals with the relation between road electrification and investments in new electricity generation. The modelng outcome have resulted in deeper insight on how the implementation of ERS could impact the development of the future electricity system. This work shows results for two different countries (Germany and Sweden) with slighly different conditions for and access to resources, such as bioenergy, wind locations and solar insolation. Two independently developed electricity system modeling tools gives in this study more insights on how an electrification of road transport could impact the future electricity system. Although, the modeling provide insights into the influence that electrification of road transportation (i.e., ERS and different EV charging strategies) could have on investment in the Swedish and German electricity system, several parameters that could influence the outcomes remain uncertain. These parameters are discussed in this section.

The difference in the results between ELIN-EPOD and SCOPE is mainly due difference in the model structures. SCOPE includes the distribution of biomass between all sectors, which is not the case for ELIN-EPOD. This results in that ELIN-EPOD obain biomass as a more cost-efficent option for electricity generation in Germany, with less investments in solar power and more investments BECCS in combination with fossil fuels compared to SCOPE. However, if prohibiting BECCS in ELIN-EPOD, as in the sensitivity analysis of this study, then more solar power incombination with batteries is also seen in ELIN-EPOD. The higher total investments in renewable capacity in SCOPE, compared to ELIN-EPOD is because in SCOPE, maximum transmission is predefined and the SCOPE includes national targets on CO_2. ELIN-EPOD finds a more cost-optimal solution by importing more electricity from neighbouring regions with better conditions for renewable energy. For Sweden, the differences between results in the two models can also be explained by some model structures: (i) the possibility for long-term storage (in the form of P2G) and DSM in SCOPE, which is not possible in ELIN ; (ii) biomass distribution between sectors in SCOPE, while in ELIN the amount of biomass to the electricity sector is predefined; and (iii) SCOPE has not the option to invest in solar PV for Sweden, due to technology limitation of solar insulation.

In the future, autonomous driving and modal systems might change part of the transporting of goods to night time, which will smoothen the load curve from trucks and buses using ERS. Other factors that might impact the way we transport goods and persons are urbanization (including new car ownership structure such as car-sharing), globalization, working hours, etc. which might have an impact on the charging profile and thereby also on the possibility to use V2G to reduce the need for peak power and handle more VRE in the electricity system. The models have limited and predefined technology options which might exclude future possible combination and investments in new technologies that might make it easier to implement of ERS in a future electricity system, although new loads (from other sectors) may also make it more more difficult.

The access to resources (places with good wind conditions and bioenergy) has an large impact on the investments in wind power in Germany in ELIN. It is obviously difficult to estimate the exact amount of resorces available. In ELIN and EPOD, a broad assessment of the role of various generation technologies in the north European electricity system transition is prioritised over a representation of current political climate in the modeled countries. Thus, investments in nuclear power and fossil power is allowed in all regions investigated. However, the German politicians have decided against both of these thermal generation options at the moment.

In addition, both modelling frameworks show that the increase of the net load from ERS could be handled by discharging EV batteries. A major part of the static charging occurs during night time to avoid correlation with the net load. However, the willingness for V2G is still uncertain.

6. Conclusions

The modelling results from the CollERS project shows that the additional electricity demand from a large-scale implementation of ERS (i.e., a German-Swedish ERS corridor and connecting main road network) is mainly met by investments in wind power in Sweden and both wind and solar power in Germany. Since ERS will take some time to scale up, **the modelling shows that there should be enough time for the electricity system to be transformed to meet demand for ERS while also meeting**

the goals on GHG reduction. However, there is still an urgent need to transform the electricity system and ramping up ERS until 2030 and to 2050 if taking advantage of the positive effects seen in this work.

It can be concluded that ERS are increasing the peak power demand (i.e., the net load) in the electricity system. Therefore, it is a need for **more investments in peak power units and storage technologies when using ERS**. A smart integration of other electricity demand, such as optimisation of the static charging at the home location of passenger cars, can facilitate an efficient use of renewable electricity also with ERS. Thus, **it is important that ERS are evaluated and assessed together with an assessment of electrification technologies of passenger cars and other sectors**, in particular the industry sector where there are already plans for electrification (e.g. iron and steel, cement and petrochemical industry).

The model comparison shows that different assumptions and methodological choices impact what kind of investments are taken, such as in wind, solar and thermal power plants to cover an additional demand from the use of ERS. However, an **increase in investments in solar power (Germany) and wind power (Sweden)** can be seen in **all scenarios** to cover the new demand for ERS.

Descision makers that plan to build a new ERS should, based on the results from this study, be aware of (i) the problems with delivering enogh power in the electricity system and the grid since ERS are using electricity at hours with already high demand; and (ii) that to meet the new ERS demand it is cost-efficient to invest in solar (Germany) and wind power (Sweden) in combination with demand-side management/power-to-X or some storage technology (batteries). The local conditions for ERS in the grid always needs to be analysed for each separate ERS project.

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