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frontiers in Energy Research

ORIGINAL RESEARCH
published: 09 July 2021
doi: 10.3389/fenrg.2021.631200

Impacts of Electric Road Systems on the German and Swedish Electricity Systems—An Energy System Model Comparison

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Specialty section:
This article was submitted to Sustainable Energy Systems and Policies, a section of the journal Frontiers in Energy Research

Received: *19 November 2020*
Accepted: *14 June 2021*
Published: *09 July 2021*

Citation:
Olovsson J, Taljegard M, Von Bonin M, Gerhardt N and Johnsson F (2021) Impacts of Electric Road Systems on the German and Swedish Electricity Systems—An Energy System Model Comparison. Front. Energy Res. 9:631200. doi: 10.3389/fenrg.2021.631200

This study analyses the impacts of electrification of the transport sector, involving both static charging and electric road systems (ERS), on the Swedish and German electricity systems. The impact on the electricity system of large-scale ERS is investigated by comparing the results from two model packages: 1) a modeling package that consists of an electricity system investment model (ELIN) and electricity system dispatch model (EPOD); and 2) an energy system investment and dispatch model (SCOPE). The same set of scenarios are run for both model packages and the results for ERS are compared. The modeling results show that the additional electricity load arising from large-scale implementation of ERS is mainly, depending on model and scenario, met by investments in wind power in Sweden (40–100%) and in both wind (20–75%) and solar power (40–100%) in Germany. This study also concludes that ERS increase the peak power demand (i.e., the net load) in the electricity system. Therefore, when using ERS, there is a need for additional investments in peak power units and storage technologies to meet this new load. A smart integration of other electricity loads than ERS, such as optimization of static charging at the home location of passenger cars, can facilitate efficient use of renewable electricity also with an electricity system including ERS. A comparison between the results from the different models shows that assumptions and methodological choices dictate which types of investments are made (e.g., wind, solar and thermal power plants) to cover the additional demand for electricity arising from the use of ERS. Nonetheless, both modeling packages yield increases in investments in solar power (Germany) and in wind power (Sweden) in all the scenarios, to cover the new electricity demand for ERS.

Keywords: electric vehicle, energy system modeling, method, vehicle-to-grid, variability management, smart charging

INTRODUCTION

In Europe, fuel combustion in the transport sector accounts for about 23% of greenhouse gas (GHG) emissions (Eurostat, 2015), and this is the only sector for which emissions are still growing compared to 1990 (European Commission, 2017). The transportation sector needs to replace conventional fuels with low-carbon options for European countries to reduce CO_2 emission and fulfill the Paris agreement (UNFCCC, 2015) and the European Union directives (European Commission, 2011).

Electrification of 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 (Johansson, 2013; Fridstrøm and Alfsen, 2014; European Commission, 2017). The Swedish government initiated a study on how the transport sector can be made fossil-free, which revealed that electrification could play an essential role in reducing the fossil fuel-dependence of the Swedish transport sector (Johansson, 2013). The Swedish electricity system depends to 98% of non-fossil fuel sources, with 43% from hydro power, 43% from nuclear and 13% from wind power (Eurostat, 2019). The German electricity system consist to a large extent on combustible fuels (44%) and wind power (25%) with an increasingly share of solar power (9%) (Eurostat, 2019).

Electrification of road transport can be achieved using various approaches, including: 1) the use of battery electric vehicles (EVs) with static charging (i.e., charging while being parked); 2) producing hydrogen or electrofuels (i.e., power-to-fuel) by using electricity for on-board use in internal combustion engines or fuel cells; and 3) the installation of electric road systems (ERS). The types of technologies and fuels that will dominate future road transportation is not yet clear. It is likely that a mix of different technologies and fuels will be part of the solution in the transport sector.

Electric Road Systems

ERS, also called dynamic power transfer, are providing vehicles with electricity in motion and thus, give the possibility to reduce the size and weight of the on-board battery, as compared to static charging. This is especially advantageous for long-haul trucks and buses since 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 assuming current battery chemistries. Yet, substantial reduction in 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 ERS concept builds upon electricity being supplied to the vehicle by overhead transmissions or from the ground (road). Overhead transmission technology is conductive-based with the vehicle connecting to the transmission lines by a type of pantograph (Olsson, 2013a) whereas the ground-based technologies can be either conductive or inductive (Olsson, 2013b; Chen et al., 2015). When conductive, the supply is through a physical pick-up to connect to an electrified rail in the road. Inductive supply is achieved by using a wireless power transfer from a coil in the road to a pick-up in the vehicle. The ERS needs to be demonstrated, not only for a couple of kilometers as in Sweden and Germany, but on large-scale. The vehicles are assumed to be hybrids, meaning that outside the ERS, the vehicles use batteries or combustion engines fueled with biofuels or fuel cells using hydrogen.

There remain several challenges with ERS before scaling up, such as finding viable economical business models, agreeing on technology standards, and accommodating increases in technical, business, and systems complexities. In addition, ERS will increase the electricity load during hours for which load is already high. 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.

Furthermore, the cost and climate benefits of ERS that will be derived from an increase in the share of electricity used for transport will be determined by the impacts on the electricity generation system. The impacts will differ between countries, depending on the characteristics of the electricity system, such as the conditions for renewable electricity (Taljegard et al., 2019a; Taljegard et al.,2019b).

An electrification of the transport sector through EVs with static charging and/or ERS with dynamic charging places a new demand on the electricity system. This new load will impact the electricity system depending on the time of consumption and the amount of electricity used. The shapes of these new profiles will reflect different charging strategies, for example, whether the EVs are charged directly while parked or the charging is optimized according to what is the most favorable from the electricity system perspective. This will then have different effects on investments in the capacity of the electricity system. Depending on the electrification strategy applied, this new load may also create the potential for battery-powered EVs to provide demand-side management (DSM) to the power grid.

Relevant Studies From the Literature

The impacts on the electricity system of passenger EVs, e.g., the dispatch of electricity generation technologies, CO_2 emissions, and peak power demand, have been investigated in several scientific studies (Hedegaard et al., 2012; Jochem et al., 2015). Most of the previous studies that have employed linear optimization modeling of the electricity system have included the static charging of passenger vehicles only. In the scientific literature related to ERS, a large focus has been on technology improvements of the ERS road infrastructure, such as the inductive charging system efficiency (Wu et al., 2012), alignment tolerance of the inductive power transfer (IPT) transformer (Villa et al., 2007), and a new three-phase bipolar IPT (Covic et al., 2007). There have also been studies on life-cycle assessments of ERS, such as Boer et al. (2013), Connolly (2016), Gnann et al. (2017), Balieu et al. (2019) and Marmiroli et al. (2019) studied the economic potential for ERS and concluded that ERS have the potential to be more cost-competitive than both diesel and electric vehicles using only static charging in the future. Studies such as those of Stamati and Bauer (2013), Grahn et al. (2014), Jelica et al. (2017) and Taljegard et al. (2017) have investigated the electricity demand for ERS. Stamati and Bauer (2013) analyzed the options to meet the electricity demand for an ERS on highways in the Netherlands using renewable energy sources. However, none of the abovementioned studies used an optimization model for the electricity system.

Plötz et al. (2019) have shown, by using an energy system model of Europe, that ERS can reduce the CO_2 emissions from heavy road transport. Two similar modeling studies conducted by Taljegard et al. (2019a) and von Bonin et al. (2018) have investigated how electrification of the road transportation sector will influence investments in new electricity generation capacity and the dispatch of the electricity generation portfolio until Year 2050. In their studies, scenarios including both static charging and ERS in different countries under a stringent CO_2 cap is modeled. Their studies show that investments in mainly wind and solar power cover the additional demand when electrifying the transport sector. A study performed by Gerhardt et al. (2018) examined the decarbonization of the transport sector and the interplay between the energy system and Power-to-X, including static charging, ERS and vehicle-to-grid (V2G). The study by Gerhardt et al. (2018) shows that V2G reduces the need for stationary electricity storage and peak capacity and increases the installed solar PV capacity.

Aim and Scope

So far, we have mentioned three different energy system modeling studies that have analyzed the impact of ERS on the electricity system (Bonin et al., 2018; Plötz et al., 2019; Taljegard et al., 2019a). All three models used in these studies have been developed in order to consider different details, such as geographical scope, temporal scoop, trade between regions, number of sectors, greenfield, etc. It is, however, rarely so that model structure and results have been compared in depth towards identifying key factors that affect the outcomes. What results are consistent outcome no matter type of model or model structure? This study 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 models were designed for the purpose of analyzing future electricity systems under a stringent CO_2 mitigation target, but have also different structure on some important parts of the models (as explained in *Electrified Transport Sector in Electricity System Investment Model-Electricity System Dispatch Model and Energy System Investment and Dispatch Model*).

Furthermore, the aim of the present study was to apply the two different models to investigate and compare how electrification of the transport sector, through the implementation of static charging of passenger vehicles and an ERS for trucks and buses, would impact the Swedish and German electricity systems. We have chosen to show results for Sweden and Germany, since these two countries are now in the forefront for implementing ERS on large-scale. This study investigates both impacts on energy and power capacity assuming the same scenarios for both models. The methodologies and results are compared, towards identifying the key factors that affect the outcomes.

MATERIALS AND METHODS

Electricity system modeling has developed since the 1950's (Masse and Gibrat, 1957) and today encompasses a wide range of detailed techno-economic tools to analyze the transition of electricity systems. Optimization models of the electricity system can analyze changes in the form of, for example, planning of the dispatch of units, investments in new generation, and the trading of electricity between regions (Connolly et al., 2010). Such modeling is typically used to guide policy decisions and business development plans on the best economic and environmental approaches to meet electricity demand under a given set of constraints (Foley et al., 2010). In this study, the impact of ERS on the electricity generation mix in Sweden and Germany is investigated by using two different optimization model packages: 1) a model-package that consists of an electricity system investment model (ELIN) and an electricity system dispatch model (EPOD); and 1) an energy system investment and dispatch model (SCOPE).

General Description of the Models

The ELIN-EPOD model package developed at Chalmers University of Technology includes a cost-optimization investment model (ELIN) and an electricity dispatch model (EPOD) of the European electricity systems. This model package has previously been used to study the transformation of the European electricity system so as to meet European policy targets on CO_2 emissions (see Odenberger et al. (2009) and Unger and Odenberger (2011) for a description of the original model package, and Göransson et al. (2014), Nyholm et al. (2016), Taljegard et al. (2019a), Taljegard et al. (2019b) for further developments of the model package). **Figure 1** gives an overview of the ELIN-EPOD model package that includes, for example, important input and output data and the technologies in which investments are made.

ELIN-EPOD encompasses the electricity sector and part of the heating sector (i.e., heat pumps and combined heat and power (CHP) plants). ELIN (i.e., 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. A description of the current and historical European electricity system is used as a starting point for the modeling to 2050. The models calculate the annualized investments cost for different technologies by using the investment cost, technology lifetime and a discount rate of 5%/yr. Results from ELIN (i.e., the investment model), such as, the description of the power system, fuel and CO_2 prices and transmission lines for the investigated year, are used as an input to the optimization in the dispatch model (EPOD). EPOD are then determining the least-cost hourly dispatch of the system for one specific year (in this study, Year 2050).

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 has been described by Böttger et al. (2018) and Jentsch (2015). SCOPE is a cross-sectoral model that is designed to analyze and optimize the European energy system. The model has been developed by Böttger et al. (2018) to include also the optimal investments in vehicle technologies and fuels. The sectors included in the model are electricity, transport, and heat.

The objective of the modeling is to minimize the total system cost in the energy system for the investigated year, which in this

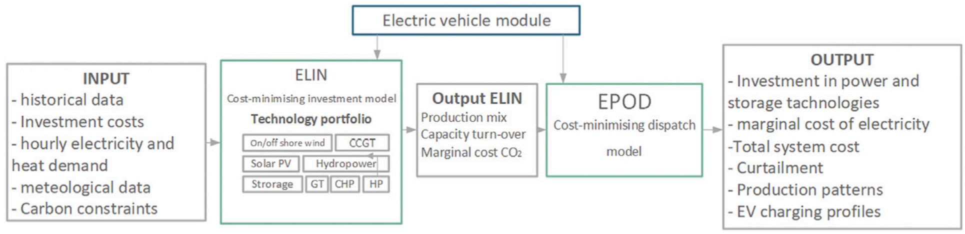

FIGURE 1 | Overview of the ELIN-EPOD model package indicating the input and output data and the technologies in which investment can be made. CCGT, Combined cycle gas turbine; GT, gas turbine; CHP, combined heat and power; EV, electric vehicle, PV, photovoltaic.

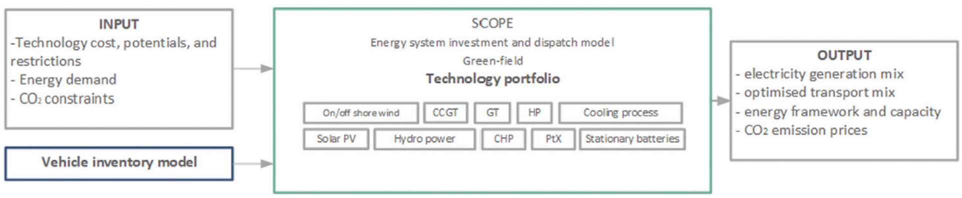

FIGURE 2 | Overview of the SCOPE-model, including the input and output data and the technologies in which investments can be made. CCGT, Combined cycle gas turbine; GT, gas turbine; CHP, combined heat and power; PtX, Power-to-X; PV, photovoltaic; HP, heat pumps.

study is assumed to be Year 2050. For Year 2050, a Green-field approach is assumed (i.e., an empty system as the starting point without any generation capacity in place, apart from hydropower and waste power plants). In **Figure 2**, a schematic representation of the SCOPE-model is given that includes the important input and output data and the technologies in which investments can be made. Input data describing the energy system are used to find the least-cost hourly system for the investigated Year 2050, while fulfilling the target of zero emissions of CO_2. The model is run for a full year with a 1 h time resolution. In addition to the electricity and gas markets, an overarching market for emissions allowances is included. Hydro power is modeled with historical data from Year 2012 for running water, storage water, and pumped storage power plants (Härtel and Korpås, 2017).

Electrified Transport Sector in the Models

The EVs can, in both ELIN-EPOD and SCOPE, provide system benefits for the electricity system in terms of flexibility. This flexibility can be provided by controlled charging and V2G, i.e., the possibility to discharge electricity back to the grid from the vehicle batteries when the system wants more energy. In the papers of Taljegard et al. (2019a), Taljegard et al. (2019b) and von Bonin et al. (2018), ELIN-EPOD was expanded to include static and dynamic charging of passenger vehicles, trucks and buses. A new load for static and dynamic charging has been added to both the investment model and the dispatch model. The traveling behavior of the aggregated passenger vehicle fleet used in the present study are based on 426 hourly real-world driving profiles (Taljegard, 2019). A detailed description on the modeling of passenger EVs in ELIN-EPOD can be found in Taljegard et al. (2021). The static charging and discharging back to the grid of the EVs are optimized with some constraints, such as prioritizing to fulfilling driving demand and limitations on battery capacity. There is no optimization of the number of EVs or battery capacity. A detailed description of how this is implemented in ELIN-EPOD can be found in Taljegard (2019).

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 1-day traveling observations (Trost, 2017). The vehicle inventory model simulates the future market penetration of alternative propulsion technologies for the road transportation sector. Böttger et al. (2018) provide a table with the different market shares of the different vehicle categories used in the SCOPE-model. An exhaustive model description can be found elsewhere (Trost, 2017). Simulations of the transport sector in SCOPE are performed based on the number of vehicles and vehicle kilometres traveled, as taken from the vehicle inventory model. Assumptions regarding electric driving share are based on the previous publications (Bergk et al., 2016) and (Günther et al., 2017). The numbers of other vehicles, such as buses, motorcycles and construction vehicles, are exogenously given.

Model Comparison

Table 1 shows a comparison of the SCOPE and ELIN-EPOD model packages, including some of the main model structures 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. The fact that the models differs to some extent, makes it interesting to compare the results. Almost all the

TABLE 1 | Key characteristics and a comparison of the SCOPE and ELIN-EPOD model packages.

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 time-step are optimized	Transmission of electricity per time-step is optimized but there is no new investment in capacity (fixed maximum capacity at year 2050)
Variation management strategies	Transmission, stationary batteries, V2G	Transmission, demand-side management (heat pumps and air conditioning), stationary batteries, power-to-X, V2G
Time resolution	ELIN is modeled every tenth year between 2020 and 2050 with 480 time-steps per year; EPOD is modeled for year 2050 with 1 h time-steps	Year 2050 with 1 h time-steps
Sectors	Electricity sector, electrified road transport sector, and part of heating sector	Electricity, heat and transport
Main inputs	Costs and properties of different fuels and technologies, hourly electricity and heat demand, CO_2 constraints, vehicle driving patterns	Costs and properties of different fuels and technologies, hourly energy demand, CO_2 constraints
Main outputs	Investments in power and storage technologies, total system cost, electricity generation mix, CO_2 shadow prices, electric vehicle charging profiles	Electricity generation mix, optimized transport mix, energy framework and capacity, CO_2 emission prices, total system cost
CO_2 target year 2050	Zero	Zero
CO_2 target	One target on European level	Targets on the European and national levels
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	wind, solar PV, hydropower, CHP, combined cycle gas turbines, gas turbines	On-/Off-shore wind, solar PV, power-to-gas (national) and power-to-X (import), hydropower, co-generation, cooling process, condensing plant, power-to-heat, CHP
Technology limitations	No new investments in nuclear	No new investments in nuclear and fossil-fired carbon capture and storage
(Area) limitations for renewable energy technologies	0.4 MW per km^2 (including available and non-available areas) for wind power and no area limitation for solar power	25 MW per km^2 (including available area) for wind power and area limitation for solar power in Germany (in Sweden, no investments in solar power are assumed).
Vehicle-to-Grid cost	10 EUR/MWh	10 EUR/MWh
Vehicle categories	Passenger car, light truck, heavy truck, bus	Small passenger car, medium passenger car, large passenger car, light commercial vehicle, heavy commercial truck
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 EVs is optimized 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	Aggregated vehicle fleet compiled from vehicle inventory model
Electric road system (ERS) implementation	ERS for light and heavy trucks and buses (in a sensitivity analysis, ERS for passenger cars and light trucks has also been assumed)	ERS for heavy trucks
Share of trucks using ERS	100%	Number of trucks using ERS is optimized in the vehicle inventory model

differences between the models is related to model structures, such as, time resolution, sector integration and starting system point (see **Table 1**). Optimal would of course be to include all these things in the same model. However, this is not feasible due to the model being to computational heavy to run. In this study, we have therefore chosen two models where one is very detailed on the electricity sector and connection between larger geographical areas (ELIN-EPOD), while the other one (SCOPE) includes instead several sectors. We have tried, as far as possible without changing the structure of the models, to have 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 (CCS). Therefore, this technology has been included in a sensitivity analysis.

The present study focuses on the modeling results for Sweden and Germany (although modeling of the neighboring 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 analyze the results not only for Sweden and Germany in isolation. There are indeed different bottlenecks in the electricity transfer regions throughout Europe (including transfers of electricity from and to Sweden and Germany), which are included in the modeling.

The national electricity demand is divided into regional demands, based on the statistics for gross domestic production (GDP) obtained from Eurostat (Eurostat, 2012) (ELIN-EPOD) and Cosmo EU (SCOPE). Both models use weather data from Year 2012 with an hourly time resolution (Global Modeling and

Assimilation Office, 2015a; Global Modeling and Assimilation Office, 2015). Wind power generation areas are limited to 0.4 MW per km^2 in ELIN-EPOD (including non-available areas) and 25 MW per km^2 in SCOPE (assuming available land area). Hydropower is modeled with historical inflow data in both ELIN-EPOD and SCOPE. A cap on CO_2 corresponding to a 100% reduction in emissions by Year 2050 (relative to the level of emissions in Year 1990) for the energy sector is assumed.

Model Limitations and Important Structural Differences Between the Models

The system starting points differ between the models, as ELIN-EPOD is based on historical data while SCOPE has a Green-field approach for Year 2050. In ELIN-EPOD, the development of the electricity supply system over time is based on phasing out the currently operating power plants based on projected technical life-times and then making new investments to meet the electricity demand in Year 2050. In SCOPE, decisions regarding new investments are taken without the influence of today's energy system. The benefit with a Green-field approach is that more details can be included in other parts of the model without making the model too computational demanding to run. For example, ELIN-EPOD includes only the electricity sector and part of the heat sector (heat pumps and CHP plants), and the electricity demand for transportation is exogenously given in ELIN-EPOD, while SCOPE includes all the sectors in the energy system (heat, electricity and transport). Therefore, SCOPE also includes an optimization of investments in fuels and technologies for the transport sector. ELIN-EPOD is modeling the electricity system, where the vehicle investment cost and ERS infrastructure investment cost are not included in the optimization.

In ELIN-EPOD, the transmission network between regions is modeled according to the current expansion plans with their specified capacities and limits. The investment model (ELIN) has the possibility to invest in additional transmission capacity between the modeled regions. In ELIN, battery storage is the only way to store the electricity produced; since ELIN only simulates 20 representative days, the stored electricity needs to be used during a 24 h window. In SCOPE, trade between regions is optimized, with a fixed upper limit of transmission capacity. SCOPE has the possibility to store electricity over time periods longer than 1 day, making it possible to exploit excess to electricity at a later time. The storage technologies that are allowed in SCOPE are Power-to-Gas (PtG) and stationary batteries.

In the ELIN investment model, only intra-day storage is possible, as only representative days are used. However, ELIN includes the possibility to invest in stationary batteries with intra-day storage. Both ELIN-EPOD and SCOPE assume a fixed demand as an input to the models. In SCOPE, heat pumps and air conditioning are modeled as flexible consumers, and thus, can shift consumption over time. This is not the case in ELIN-EPOD, where DSM of the heating sector is not included.

Scenarios

Table 2 presents 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) is run in both models. The models are run assuming three different charging strategies for passenger EVs: 1) fully recharge the battery directly when being parked and connected to the grid (Direct); 2) optimization of the charging time to minimize the cost of meeting the electricity demand (Optimized); and 3) optimized charging and discharge back to the grid (Optimized + V2G). In the strategy Optimized, the charging is optimized and scheduled to times when the electricity price is the lowest, while still making sure that the vehicle is sufficiently charged for the upcoming trip. Vehicle-to-grid is utilized in the charging strategy Optimized + V2G as a storage to balance demand and supply, resulting in that the vehicles are charged during low electricity prices periods and discharge power to the grid during high electricity price periods. ERS are included in three of the scenarios, in which ERS are assumed to be the main electrification option for trucks and buses. The use of electricity for ERS is a fixed parameter in the model and is thereby not optimized. Static charging of truck and buses, or use of hydrogen with fuel cells, are not included in this modeling work since we wanted to analyze the impact assuming a scenario with large-scale implementation of ERS. A reference scenario (RS) without ERS is modeled to allow comparison of the results.

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

RESULTS

The model results obtained from the two different models show that, when including static and dynamic charging of cars, trucks and buses, a Swedish and German electricity generation system without CO_2 emissions can be achieved in different ways. However, there are some differences in the results seen for the two models.

Investments in Electricity Generation Capacity

Germany

Figure 3 shows the total capacity installed in Germany in Year 2050 for the investment models ELIN (**Figure 3A**) and SCOPE (**Figure 3B**) and for all the investigated scenarios (i.e., RS, S1–S3). RS is a reference scenario without ERS that allow for comparison of the results with the three scenarios with ERS (S1–S3) in **Figure 3**.

The installed capacity for Germany differs considerably between the two models, as shown in **Figure 3**. The main difference is that SCOPE gives a higher installed capacity for

TABLE 2 | Descriptions of the 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)	Combination of 40% optimized charging and 60% direct charging, and ERS for trucks and buses
S3-V2G40%-ERS (S3)	Combination of 40% optimized charging with V2G and 60% direct charging, and ERS for trucks and buses

TABLE 3 | Parameters tested in a sensitivity analysis in ELIN-EPOD.

Scenario name	Parameter	Reference value	New value
S3-no fossils	No investments in fossil technologies	Possibility to invest in fossil-based fuels	No possibility to invest in fossil-based fuels
S3-ERS for cars	ERS for all transportation modes	ERS for all trucks and buses	ERS for all trucks, buses and passenger cars

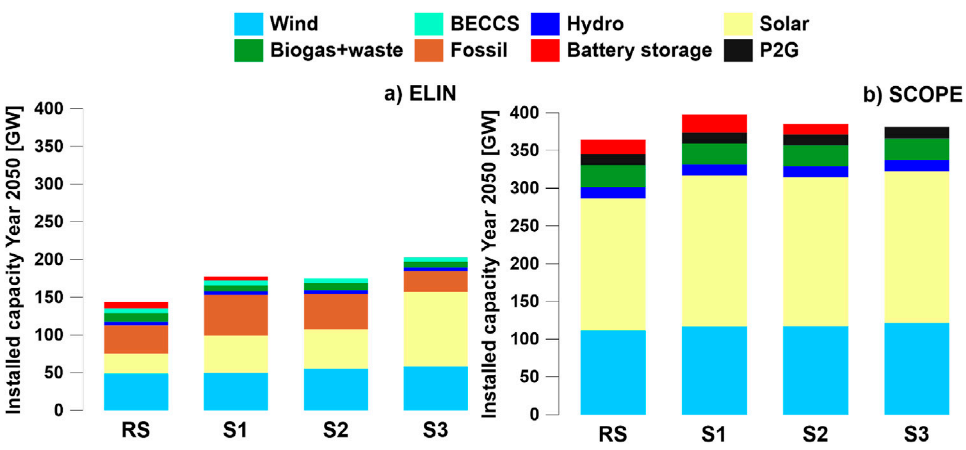

FIGURE 3 | Total capacity installed in Year 2050 in Germany for all the scenarios in **(A)** ELIN and **(B)** SCOPE. BECCS, biomass with carbon capture and storage; P2G, power-to-gas.

variable renewable energy (i.e., wind and solar power), whereas in ELIN there is more cost-efficient to have a mix of investments in bioenergy with carbon capture and storage (so-called BECCS) and power plants run with fossil fuels (mainly gas). BECCS (resulting in negative emissions) gives room for some investments in fossil fuel power plants in ELIN. This is the case, since ELIN, includes only the electricity sector and assuming zero emissions by 2050. Furthermore, lack of low cost flexible generation (e.g., the price of biogas has increased by Year 2050) gives thermal base load generation a competitive advantage relative wind power. At the same time, the sites with most favorable wind conditions in Germany have already been deployed. Note that the investment period in ELIN is 2020–2050, while that in SCOPE is only Year 2050.

As seen in **Figure 3**, a higher total installed capacity can be seen in SCOPE compared to ELIN. This is due to higher levels of installation of solar PV and wind power in SCOPE. In ELIN, it is more cost-efficient, compared to SCOPE, to invest in BECCS to cover part of the electricity demand in Year 2050. The difference in installed solar PV can also be explained by the need for the system to reach regional climate targets in the SCOPE model for all sectors, resulting in higher investments in renewable electricity sources in Germany. Installations for thermal power, as seen in ELIN, yield higher full-load hours and, thus, a lower total capacity is needed to supply the electricity demand. A further difference relates to the significantly higher level of installation of battery storage in SCOPE than in ELIN, which is used to handle the variability of solar power generation.

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

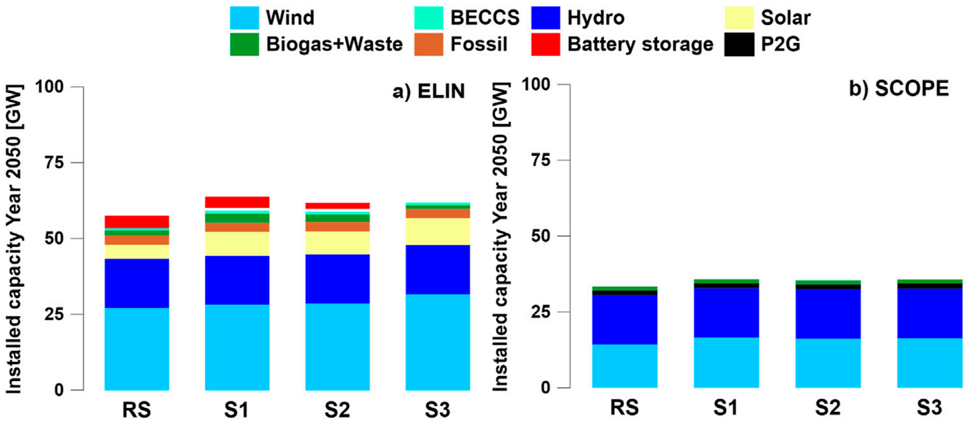

FIGURE 4 | Total capacity installed in Year 2050 in Sweden for all the scenarios in: **(A)** ELIN; and **(B)** SCOPE. BECCS, biomass with carbon capture and storage; P2G, power-to-gas.

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

The introduction of an ERS (i.e., scenario S1-Direct-ERS) implies an increase in electricity demand of about 74 TWh in Germany and 11 TWh in Sweden, which needs to be supplied by new investments in the electricity system. In both ELIN and SCOPE, the increased investments 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 optimization of 40% of the charging of the EV fleet (i.e., scenario S2-Opt40%-ERS) implies that the EVs are, if possible, being charged when electricity demand is lower, as compared to the case when all EVs charge directly while parked. This results in a lower total installed capacity of stationary batteries in both models. In ELIN, no investments are then made in stationary battery storage due to the flexibility for the electricity system offered by EVs. In addition, the flexibility offered by EVs gives a reduction in peak power by 30% compared to the S1 scenario with direct charging of passenger EVs. In SCOPE, there is a similar trend with fewer investments in stationary battery storage to handle solar variations due to the flexible charging of the EVs.

The option of using the electricity stored in the batteries of the EV fleet (i.e., passenger cars) through V2G (i.e., scenario S3-V2G40%-ERS) results, for both models, in no investments being made in battery storage, although the investments in solar power increase in both models. The EV batteries can in S3 performing the same storage services as stationary batteries, thereby no stationary batteries are necessary. In ELIN, fewer investments are also needed in gas turbines, and the system value of solar power increases in S3-V2G40%-ERS.

ERS for heavy vehicles increase the peak power demand compared to base-case scenario. The total investment and the investment in peak power will, if all heavy vehicles use ERS and discharging back to the grid (V2G) is applied for the passenger EVs (i.e., S3-V2G40%-ERS), decrease to a greater extent than if only optimizing the charging behavior (S2-Opt40%-ERS).

Sweden

Figure 4 shows the total capacity installed in Sweden for Year 2050 for the **Figure 4A** ELIN and **Figure 4B** SCOPE models for all the investigated scenarios. The total installed capacity for Sweden differs significantly between the models, as well as, the technology options in which investments can be made. The difference in installed capacity can be explained by the possibilities for long-term storage (in the form of P2G) and DSM in SCOPE, which are not possible in ELIN. In similarity to Germany, investments are made in biomass generation technologies in ELIN, while in SCOPE biomass is more economically beneficial to use in other sectors. An additional difference is in the installed capacity of solar PV and stationary batteries, which are not present in SCOPE. In SCOPE, the model does not invest in solar PV for Sweden, due to the technology limitation of solar insulation. The battery storage capacity in ELIN can be attributed to the investments in solar PV. If solar PV installations are combined with battery storage, the electricity produced by the PVs can be better exploited.

When analyzing the different scenarios in the two models, there is not much difference in installed capacity between the different scenarios in the SCOPE model, while the difference in installed capacity between the scenarios in ELIN is more evident. In ELIN, the increase in demand due to the introduction of ERS (S1-Direct-ERS) results in increased capacities of waste, wind power and solar power. Direct charging of passenger EVs and ERS will increase the peak power demand in Sweden, by charging EVs at hours when there is already a high demand for electricity. In the optimized charging scenarios (S2-Opt40%-ERS and S3-V2G40%-ERS) in ELIN, there is a lower demand for battery storage than in the direct charging scenario (S1-Direct-ERS),

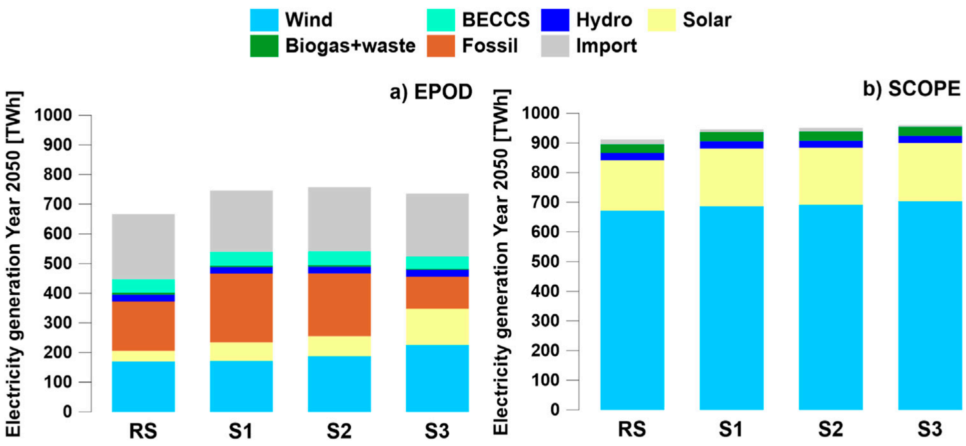

FIGURE 5 | Electricity generation in Germany in Year 2050 for all scenarios, as predicted by **(A)** EPOD and **(B)** SCOPE.

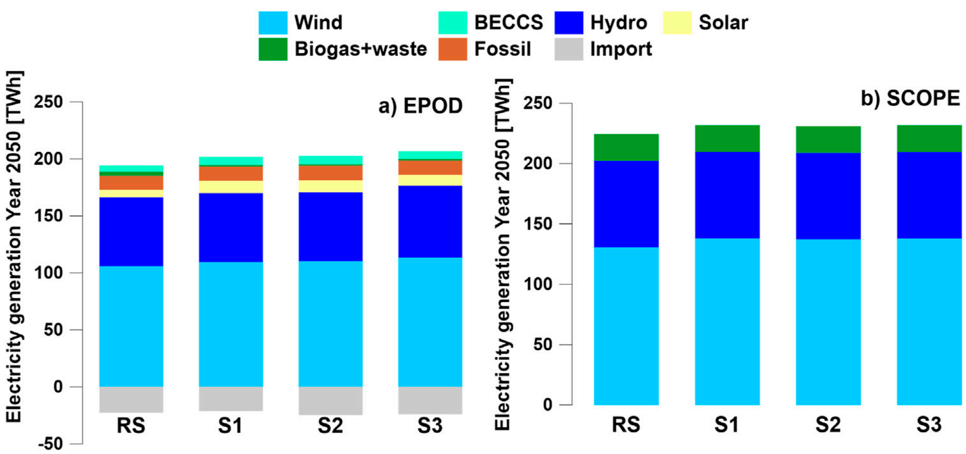

FIGURE 6 | Electricity generation in Sweden in Year 2050 for all scenarios, as predicted by **(A)** ELIN and **(B)** SCOPE.

since the demand for peak power in S2 and S3 will be lower than in S1.

Electricity Generation

The modeling results from ELIN-EPOD show that fossil fuels, wind power, and biomass with CCS dominate the German annual electricity generation in Year 2050 (see **Figure 5**). In SCOPE, however, solar PV and wind power dominate the annual electricity system in Germany. In SCOPE, the installed capacity in solar PV in Germany is about four-fold higher than in ELIN-EPOD.

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

Impacts of Electric Road Systems on the Net Load of Electricity

Figure 7 shows the net load (i.e., the load minus variable renewable electricity (VRE) generation) as obtained from the 1) EPOD and 2) SCOPE models. **Figure 7** illustrates the net load for 1 week in February in Germany and includes results from model runs including and excluding ERS and static charging of EVs assuming different charging strategies. In **Figure 7B**, the hourly resolution of P2G is also included to illustrate better the whole system, i.e., including long-term storage.

Under the condition that charging behavior is optimized with V2G, the passenger EVs are discharged to the grid when the net load is high, which reduces the investments needed in stationary

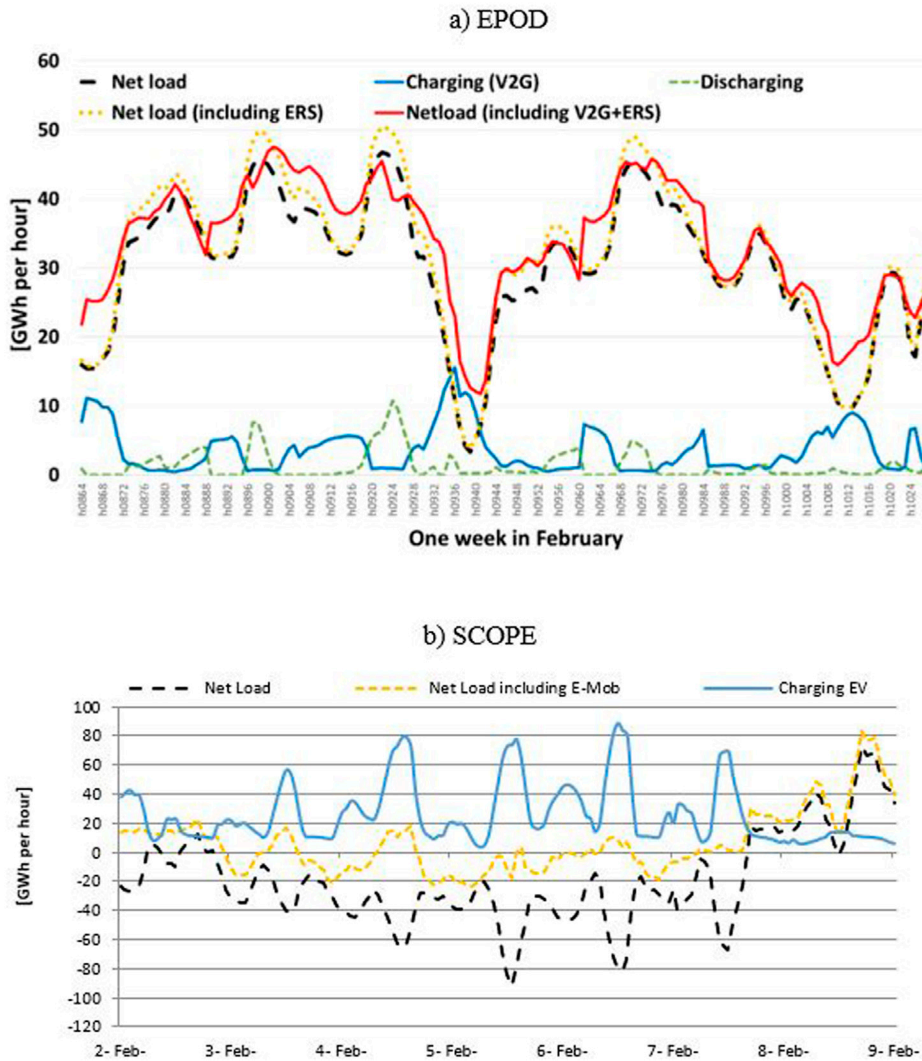

FIGURE 7 | Net load for one week in February in Germany assuming a number of separate model runs, including and excluding electric road systems (ERS) for trucks and buses, and the load from charging passenger EVs and V2G in the **(A)** EPOD and **(B)** SCOPE. SCOPE also includes hourly production of PtG.

batteries and gas turbines. In Germany for year 2050, the level of discharging to the grid from EV batteries is about 72 TWh, which can be compared to the total generation of approximately 900 TWh per year. The passenger EVs will flatten the net load curve by providing flexibility to the system.

ERS alone will, as shown in **Figure 7**, increase the current net load if one assumes the current traveling patterns. As seen in **Figure 7**, ERS would increase the peak in the net load curve if no V2G is applied.

There are some differences between EPOD and SCOPE. As can be seen in **Figure 7B** (SCOPE), there are many occasions on which there is a surplus of variable renewable power (i.e., negative net-load values). With optimized charging (blue line), this surplus can be used to charge the EVs. In SCOPE, a low or negative net load is also handled by carrying out P2G. A high or positive net load leads to the discharging of EV batteries back to the grid.

Sensitivity Analysis

A sensitivity analysis was conducted using ELIN-EPOD. **Figure 8** shows the results of the sensitivity analysis performed in ELIN-EPOD. The aim was to test how further changes in the parameters affect the design of the future electricity system that includes optimized charging and V2G (S3-V2G40%-ERS). In the sensitivity analysis, ERS for passenger cars has been introduced as an additional load in the system. We have also run the ELIN-EPOD model without the possibility for investments in fossil fuel-based technologies (which means that the motivation to invest in BECCS will be zero in this scenario).

As shown in **Figure 8**, introducing ERS for cars in the ELIN-EPOD model has a negligible impact on the outcome. The increase in electricity demand, when passenger vehicles are using ERS for the trips that are not covered by the 30 kWh battery, is about 2%. This relatively small increase in electricity

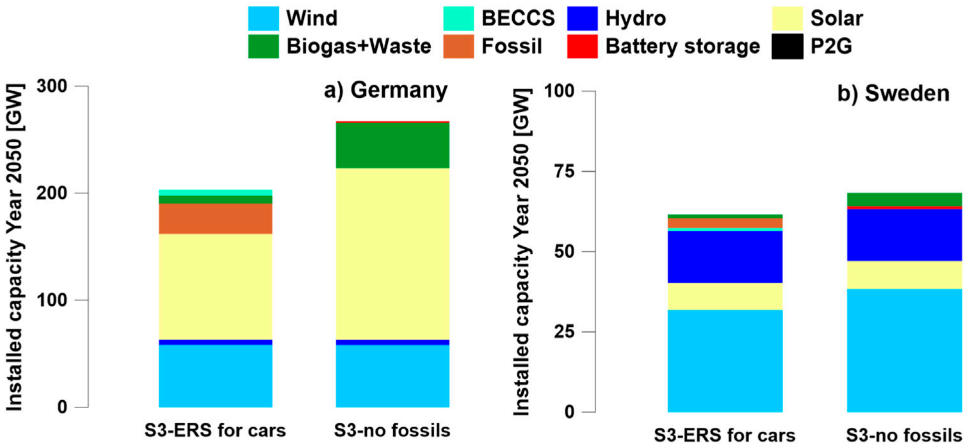

FIGURE 8 | Sensitivity analysis in ELIN-EPOD for Germany and Sweden. The same scenario as S3-V2G40%-ERS but with the addition of: **(A)** an introduction of ERS for passenger cars (S3-ERS for cars); and **(B)** no investments in fossil fuel-based technologies (S3-no fossils).

demand does not have a major impact on investments made in the electricity system, as compared to the case without ERS for passenger vehicles, as shown in **Figure 8**. The scenario without fossil fuels in ELIN-EPOD will increase the amount of solar power in the electricity systems in both Sweden and Germany. In addition, in Sweden, more wind power will be used instead of BECCS and natural gas. The use of biogas will also increase, helping to balance a higher share of VRE in the electricity system.

DISCUSSION

The present study examines the relationship between road electrification and investments in new electricity generation. The modeling outcome provides a deeper insight into how the implementation of ERS could influence the development of the future electricity system. This work shows the results for two different countries (Germany and Sweden) that have slightly different conditions for and access to resources, such as bioenergy, good wind spots and solar insolation. Here, two independently developed electricity system modeling tools reveal how electrification of road transport, with a special focus on ERS, might have an impact on the future electricity system. Although the modeling provides new information on the effects that electrification of road transportation (i.e., ERS and different EV charging strategies) could have on investments in the Swedish and German electricity systems, several parameters that could influence the outcomes remain uncertain. These parameters will be discussed in this section, as well as, the impact of the results due to differences in model structure between ELIN-EPOD and SCOPE.

The difference in the results between ELIN-EPOD and SCOPE is mainly due to 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 a more cost-efficient option for Germany with less investments in solar power and more investments BECCS in combination with fossil fuels in ELIN-EPOD compared to SCOPE. However, if prohibiting BECCS in ELIN-EPOD, as in the sensitivity analysis of this study, then more solar power in combination with batteries is also seen in Germany in ELIN-EPOD. A higher total investment 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 neighboring countries to Germany with better conditions for renewable energy. For Sweden, the differences between results in the two models can also be explained by some other model structures: 1) the possibility for long-term storage (in the form of P2G) and DSM in SCOPE, which is not possible in ELIN; 2) biomass distribution between sectors in SCOPE, while in ELIN the amount of biomass to the electricity sector is predefined; and 3) SCOPE having limitations in trade between countries.

In the future, autonomous driving and car sharing may change the way we transportation passenger and goods. For example, without the need for a driver, goods can be transported more during night-time, which will flatten the total load curve. Three are more factors, such as urbanization and car sharing, that might change the way that we transport goods and persons, which in turn affects the charging profile and the possibility to use V2G to reduce the need for peak power and handle more VRE in the electricity system.

In ELIN, access to resources (wind spots and bioenergy) has a strong impact on the investments made in wind power in Germany. Of course, it is difficult to estimate the exact level of resources available. Furthermore, investments in nuclear power and fossil power are allowed in all the regions investigated in ELIN-EPOD. We have assumed that an assessment of the roles of various generation technologies in the northern European electricity system transition is prioritized over a representation of the current political climates in the modeled countries. However, politicians in Germany are currently opposed to both of these thermal generation options.

In addition, both modeling frameworks show that the increase in the electricity net load from ERS could be handled by discharging EV batteries. However, the willingness and cost to use V2G is still uncertain. An optimization of the charging, results in that the vehicles are charged during periods of low electricity prices. In the case with V2G, there is also a discharging of electricity back to the grid during periods of high electricity prices. The S2 and S3 scenarios result in a lower electricity bill for the EV owner compared to direct charging.

CONCLUSION

The modeling results show that the additional electricity demand of about 74 TWh in Germany and 11 TWh in Sweden from large-scale implementation of ERS is met in large part (40–100% depending on model and scenario) by investments in wind power in Sweden and in both wind and solar power in Germany. Since ERS will take some time to scale up, the modeling shows that there should be sufficient time for the electricity system to be transformed so as to meet the demand for ERS while also meeting the goals related to the reduction of GHG emissions. However, actions to both transform the electricity system and building ERS is needed simultaneously to 2050.

It can be concluded that ERS are increasing the need for storage technologies and peak power units. Smart integration of other electricity demands, such as optimization 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 bearing in mind electrification technologies for passenger cars and other sectors, in particular for the industry sector where there are already plans for electrification (e.g., iron and steel, cement and petrochemical industries).

A comparison between the results from the different models shows that assumptions and methodological choices to some extent dictate the types of investments that are made (e.g., wind, solar and thermal power plants) to cover the additional demand for electricity arising from the use of ERS. For example, access to favorable resources of renewable electricity (i.e., good wind spots and bioenergy) has a strong impact on the investments made in wind power in Germany. Nevertheless, in all the scenarios and in both models, it is clear that increased investments in solar power (Germany) and wind power (Sweden) are required to cover the new demand for ERS.

Decision makers that plan to build a new ERS should, based on the results from this study, be aware of: 1) the problems with delivering enough power in the electricity system and the grid since ERS are using electricity at hours with already high demand; and 2) 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 (e.g., batteries). The local conditions for ERS in the grid always need to be analyzed for each separate ERS project.

DATA AVAILABILITY STATEMENT

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

AUTHOR CONTRIBUTIONS

Conceptualization, JO, MT, MV, NG, and FJ; methodology, JO, MV, and MT; software, JO, MV, and MT; validation, JO, MV, and MT; formal analysis, JO, MV, and MT; investigation, JO, MV, and MT; writing—original draft preparation, JO, MV, and MT; writing—review and editing, JO, MT, MV, NG, and FJ; visualization, JO, MT, MV, NG, and FJ.

FUNDING

This research was funded by the Norwegian Public Road Administration, the Swedish Transport Administration and German Federal Ministry of Environment, Nature Conservation and Nuclear Safety.

ACKNOWLEDGMENTS

We gratefully acknowledge the Norwegian Public Road Administration, the Swedish Transport Administration and German Federal Ministry of Environment, Nature Conservation and Nuclear Safety for financial support.

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.