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Impact of electric vehicles on the cost-competitiveness of generation and storage technologies in the electricity system

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Abstract

The increasing levels of variable renewable electricity (VRE) generation—such as wind and solar power—will create important opportunities for the charging of electric vehicle (EV) batteries during low-cost hours with a lot of VRE generation and for the discharge of EV batteries back to the grid (i.e. vehicle-to-grid; V2G) during high-cost hours. This study investigates how different EV charging strategies influence the cost-competitiveness of generation and storage technologies other than EV batteries in the electricity system, using a regional electricity system investment and dispatch model. The charging requirements of the EVs, which are used as an input to the optimisation model, are derived from the yearly driving patterns of 426 vehicles measured with global positioning system. The study is carried out for four regions in Europe with different conditions for wind, solar and hydro power generation. The results show that optimised EV charging with V2G can: (i) reduce investments in peak power capacity in all the regions investigated; (ii) reduce the need for short-term and long-term storage technologies other than EV batteries (i.e. stationary batteries and hydrogen storage); and (iii) stimulate increased shares of solar and wind power generation, as compared to direct charging in some regions (mainly Hungary). This study also shows that EV battery capacities as low as 30 kWh, which are connected to the grid only at their home location, can to a large extent contribute with flexibility to the electricity system in the way mentioned. The present study also investigates the influences of different shares of the fleet participating in V2G, and shows that the additional benefits for the electricity system level off when approximately 24% of the vehicle fleet participates in V2G.

1. Introduction

To meet the CO₂ emission reduction targets set out in the Paris Agreement [1] and the targets of the European Union (EU) [2, 3], the transportation and electricity sectors need to replace the use of fossil fuels with low-carbon options. The electricity system is already on its way to becoming decarbonised in many regions, mainly through increased shares of variable renewable electricity (VRE) generation, in particular wind and solar power when it comes to the EU. Electrification of road transportation is currently seen as one of the options (and perhaps the main option) to decarbonise road transportation [2, 4]. Un-controlled charging of electric vehicles (EVs) can increase the electricity system load during periods when there is already a high demand for electricity [5–11]. However, if the EVs are strategically integrated, the new demand for electricity might be able to offer benefits in terms of system flexibility, e.g. demand response services in the forms of strategic charging and possibly also discharging the EV batteries back to the grid (i.e. vehicle-to-grid; V2G) [12].

Solar power and wind power require different types of flexibility from the electricity system. Electricity systems that rely on large amounts of solar power benefit from storage between day and night, day and the next morning, as well as from support during cloudy days and some seasonal variations. Mileva et al [13] show that high levels of solar generation in the
electricity system can be cost-effectively integrated using a portfolio of technological options. Göransson and Johnsson [14] have shown that batteries are typically the preferred option for intra-day storage that spans over a couple of hours, while wind power generation needs storage for longer periods of variation [14].

In a system with large amounts of wind power, these variations may be handled by converting electricity during hours of high-level generation with wind power to another storable energy carrier, such as hydrogen. The hydrogen can subsequently be converted back to electricity or can be used elsewhere in the energy system. In regions with good conditions for hydro power, reservoir hydro power can also be used to compensate for hours of low generation. However, for these type of variations, investments in stationary batteries will not be a cost competitive strategy for handling long-term storage [15].

Previous studies using modelling of the system impact of variation management have been limited to investigating primarily one variation management strategy at a time. There are studies that have compared the impacts of a broader range of variation management strategies and their applications on the electricity system composition [7, 11, 16–21]. In a case study of California until 2027 by Fripp [7], the Switch-model shows that wind and solar power could potentially be used to reduce emissions by 90% compared to 1990 levels without losing flexibility in the system or raising the electricity system cost. Strategic charging of EVs vehicles were found by Fripp [7] to be important when having a high penetration level of solar and wind power in the California electricity system. Forrest et al [11] conclude that V2G can potentially eliminate the need for stationary energy storage in the California electricity system (i.e. a solar-dominated electricity system). Coignard et al [21] also analysed the integration of VRE using EV batteries to mitigate renewable intermittency. They found, similar to Fripp [7] and Forrest et al [11], that EVs support the California renewable integration targets while avoiding much of the tremendous capital investment of stationary storage. Kiviluoma et al [19] have investigated the possibility to use the transport and heat sector (via battery EVs and electric boilers) to provide flexibility in an energy systems heavily depending in wind power. They have shown that EVs have limited possibility to provide flexibility for the system compared to the heat sector. Schuller et al [22] used as mixed-integer optimisation model with the aim of minimising the amount of conventional generation. Their conclusion is that EV smart charging can provide balancing grid services on shorter time-scale (intra-day). In a power system with a large share of renewable generation this flexibility should be complemented by long-term storage. Furthermore, Schuller et al [22] conclude that a higher maximum charging power and more charging infrastructure will increase the flexibility of EVs.

An individual EV owner can only store about 15–85 kWh in their battery, whereas on an aggregated scale, EV batteries can provide substantial amounts of battery capacity and energy storage capacity for the system. The analysis of passenger vehicle driving patterns performed by Karlsson and Kullingsjö [23] has shown that even with relatively small EV battery capacities, a large part of the passenger EV fleet does not require battery recharging every day in order to manage the daily driving demand, as this part of the car fleet is typically parked for about 95% of the time [23]. It is, therefore, of interest to investigate EVs as a variation management strategy for both solar and wind power using real vehicle driving data.

Few, if none, of the studies mentioned have used individual driving patterns of passenger cars, which are representative for the whole fleet, in an electricity system model designed to analyse the potential of EVs to replace other types of storage technologies (e.g. stationary batteries and hydrogen storage). Previous work looking at the impact of EVs on the electricity system have typically based their driving demands on data derived from travelling surveys, standardised driving cycles or 1 day measured driving distances (e.g. [5, 7–9, 18, 19, 21, 22, 24–29]). However, Harris and Webber [30] have shown, by analysing GPS vehicle travel data from the Puget Sound Regional Council, that the driving patterns differs noticeably between weekdays and weekends, as well as between individual drivers, which could lead to erroneous V2G modelling results if not taking into account when doing electricity system modelling studies. There is a risk to over-estimate the potential of using the EV batteries for optimised charging and V2G if not including individual driving patterns, since a vehicle that is parked might be charging so as to supply an EV that is out driving.

This study investigates how EVs affect the cost-competitiveness of generation and storage technologies (both stationary batteries and hydrogen) in the electricity system when complying with zero-carbon emissions. A cost-minimising Greenfield model of the electricity system (called ENODE) is applied to four selected regions in Europe (Hungary, Ireland, central Spain, and central Sweden) that have different conditions for wind, solar and hydro power. Thereby, this study analysis both regions with good wind and solar conditions. Furthermore, this study uses, compared to previous electricity system modelling studies, individual driving patterns in the model, consisting of the GPS data obtained from about 426 randomly chosen gasoline- and diesel-driven vehicles measured during 30–73 days in a row per vehicle. Thereby, this study can analyse cycling of individual EV batteries due to V2G, as well as, the potential for V2G of different battery size on an individual vehicle level. Individual driving patterns also gives the possibility to analyse the cost-benefit of doing V2G for individual drivers depending on their driving patterns.
The analysis is focused on: (i) the types of generation and investments that are stimulated by the introduction of EVs; (ii) the EV charging and V2G discharging patterns; (iii) the value of using EV batteries as a storage option for the electricity system, as compared to using other storage technologies; and (iv) the impact on the number of full charging cycles from the application of V2G for individual driving profiles. The study is performed under assumptions related to different geographical regions, EV battery capacities, V2G implementation schemes, and charging infrastructure connections.

2. Methodology

2.1. Model description

We use a cost-minimisation model of the electricity system (ENODE) that is designed to assess the impacts of variability and investment management strategies on investments in the electricity system. The ENODE model analyses both investments in generation and investments in the electricity system. The ENODE model includes improved representation of thermal power plant flexibility; the introduction of EVs; hourly electricity demand and profile (excluding transport); CO2 emissions; meteorological data; technology costs and properties; and technology costs and properties.

![Figure 1. Schematic of the modelling applied in this work. Everything located inside the solid line is included in the model optimisation. CHP, combined heat and power; GT, gas turbine; CCCTG, combined cycle gas turbine; CCS, carbon capture and storage; V2G, vehicle-to-grid.](Image)

The full mathematical description of the model, including all constraints and equations, is presented in supplementary material (SM), which is available online at stacks.iop.org/EnvironResLett/14/124087/mmedia. Figure 1 presents the overall structure of the modelling applied in this work

$$\min C_{\text{tot}} = \sum_{p \in P} C_{\text{inv}}^{\text{p}} i_p + \sum_{p \in P_{\text{run}}} \left( C_{\text{run}}^{\text{p}} + C_{\text{cyc}}^{\text{p}} \right)$$

$$= \sum_{p \in P} \delta_{p, t} + \sum_{p \in P_{\text{run}}} \delta_{\text{run}}^{\text{p}} + \sum_{p \in P_{\text{run}}} D_{\text{grid}}^{\text{p}} + \sum_{p \in P_{\text{run}}} E_{\text{EV}}^{\text{p}} + \sum_{p \in P_{\text{run}}} \delta_{\text{charging}}^{\text{p}} \forall t \in T$$

where

- $C_{\text{tot}}$ is the total system cost
- $P$ is the set of all technologies
- $T$ is the set of all time steps
- $P_{\text{run}}$ is the set of driving profiles (426 in this study)
- $P_{\text{run}}$ is the set of stationary batteries and two types of hydrogen storages
- $P_{\text{run}}$ is the investment cost of technology $p$
- $i_p$ is the investments in technology $p$
- $\delta_{p, t}$ is the running cost of technology $p$ in time step $t$
- $D_{\text{grid}}^{\text{p}}$ is the electricity generation from technology $p$ in time step $t$
- $E_{\text{EV}}^{\text{p}}$ is the electricity with which the storage type is charged
- $E_{\text{EV}}^{\text{p}}$ is the electric vehicle charging for driving profile $p$ at time step $t$
- $D_{\text{grid}}^{\text{p}}$ is the demand of electricity at timestep $t$
- $\delta_{\text{charging}}^{\text{p}}$ is the electricity discharged to the grid with the storage type

Four different regions are selected to reflect different conditions of wind, hydro, and solar resources. The model is allowed to invest in the following storage
technologies: flow batteries; Li-ion batteries; hydrogen tank storage; and hydrogen storage in line rock caverns. The present work refines the model by adding the EV charging and discharging to the grid to the model structure (see the SM for a full mathematical description of ENODE).

Equations (3)–(7) are added to the previous model versions and are implemented with the aim of optimising the time of charging and discharging to the grid of the passenger EVs, while at the same time fulfilling a given hourly passenger EV demand. Time of charging and discharging to the grid of the EV batteries are restricted to: the maximum charging (equation (3)) and discharging power (equation (4)); the EVs needing to be parked at a location with charging infrastructure connections (equation (5)); and the maximum battery storage capacity (equation (7)). Equation (6) gives the hourly EV battery balance

\[
E_{\text{PEV}}^{\text{CPEV}} \leq N_{\text{CPEV}} \cdot CP \quad \forall \ dp \in DP, t \in T, (3)
\]

\[
E_{\text{DGrid}}^{\text{DGrid}} \leq N_{\text{CPEV}} \cdot BS \cdot n \quad \forall \ dp \in DP, t \in T, (4)
\]

\[
N_{\text{CPEV}} \leq FA_{\text{CPEV}} \cdot N_{\text{dp}} \quad \forall \ dp \in DP, t \in T, (5)
\]

\[
SL_{\text{PEV}}^{DPEV+1} = SL_{\text{PEV}}^{DPEV} + E_{\text{PPEV}}^{\text{CPEV}} \cdot n - E_{\text{DGrid}}^{\text{DGrid}} \cdot 1/nt
\]

\[
SL_{\text{PEV}}^{DPEV} \leq BS \cdot N_{\text{dp}} \quad \forall \ dp \in DP, t \in T, (6)
\]

\[
SL_{\text{PEV}}^{DPEV} \leq BS \cdot N_{\text{dp}} \quad \forall \ dp \in DP, t \in T, (7)
\]

where

- \( n \) is the charging and discharging efficiency of the electric vehicle battery
- \( N_{\text{CPEV}} \) is the number of electric vehicles that is connected to the grid for driving profile \( dp \) at timestep \( t \)
- \( CP \) is the charging power
- \( FA_{\text{CPEV}} \) is either 1 or 0 depending on whether or not the vehicles belonging to driving profile \( dp \) are connected to the grid at timestep \( t \)
- \( N_{\text{dp}} \) is the number of electric vehicles belonging to driving profile \( dp \)
- \( SL_{\text{PEV}}^{DPEV} \) is the storage level of the electric vehicle battery for driving profile \( dp \) at timestep \( t \)
- \( E_{\text{PPEV}}^{\text{CPEV}} \) is the electric vehicle discharging from the battery to the wheels for driving profile \( dp \) at timestep \( t \)
- \( BS \) is the battery capacity of the electric vehicle

The driving demand needs are prioritised in the model and need to be fulfilled at all times. EVs are implemented in the ENODE model using individual driving patterns that are based on GPS measurement vehicle data (see below for description). The following outputs from the model are analysed: (i) annual electricity by fuel and technology; (ii) charging and discharging profiles of the different storage options; and (iii) system cost. The number of EV batteries available for V2G is exogenously given in the model, and the investment cost for EV batteries is not included in the cost optimisation of the electricity system.

Technology data for energy plants are from the Danish energy agency [35], Brynolf et al [36] and Nykvist and Nilsson [37]. Power technology costs are taken from the World Energy Outlook assumptions of the International Energy Agency from the 2016 edition [38]. See the SM for the assumed investment costs and the properties of the different power and storage technologies and fuels. The hourly data are based on data from the European Network of Transmission System Operators for Electricity ENTSO-E (load) [39], and MERRA and ECMWF metrological data (generation profiles for solar [40, 41] and wind [42, 43]) for year 2012.

### 2.2. EV driving patterns

EVs are implemented in the ENODE model using individual driving patterns. Travelling patterns from a measurement campaign performed in the region of Västra Götaland (western part of Sweden) are applied, consisting of the GPS data obtained from about 770 randomly chosen gasoline- and diesel-driven vehicles that completed 107 910 trips in the period of 2010–2012 [23, 44]. The vehicles GPS-equipped, which were randomly selected from the Swedish vehicle database, are representative of Sweden in terms of a number of parameters (e.g. fleet composition, car ownership, house-hold size, and distribution of larger and smaller towns and rural areas). Of the 770 measured vehicles, about 426 were logged for more than 30 days and provided high-quality data (i.e. excluding some of the vehicles for which data were missing due to problems with the GPS equipment, such as loose contacts with the power supply or lost satellite connection).

Since none of the vehicles had a full year of logging, the measured period was extrapolate from the original period to 12 months. The same weighting factor is applied to each of the 426 driving profiles, which is used to scale-up to the number of EVs assumed in the study, which is set at 60% of the car fleet in each country. There is a large spread across the 426 cars in terms of the driving demand, hourly driving profile, and the number of hours being parked. Since the driving patterns are taken from measurements of conventional vehicles, the driving distance that is not covered by the EV battery, due to the battery capacity and driving pattern, is assumed to be covered by, for example, renting an internal combustion vehicle or taking the train.

The potential degradation of EV batteries due to V2G is not included in the optimisation. However, in some of the model runs, a cost for V2G was included and this varies within the range of 10–100 EUR/MWh. This cost can be seen as corresponding to different payments to the EV owners in return for using their EV batteries for electricity system services. Additional vehicle input data and specifications can be found in the SM.
### Table 1. Parameters that are varied in the ENODE model.

| Parameter                                      | Level                                                                 |
|------------------------------------------------|----------------------------------------------------------------------|
| Geographical areas                             | Central Sweden, Ireland, Hungary, and central Spain                  |
| Maximum available electric vehicle battery capacity (kWh per car)\(^a\) | 15, 30 and 85                                                        |
| Charging strategies                             | Direct; Opt; V2G                                                      |
| Charging infrastructure connection             | Parking at home location (home) and parking at all stops longer than 1 hour (all stops) |
| The share of electric vehicles (%) participating in an optimisation scheme\(^b\) | 0, 20, 40, 60, 80 and 100                                           |
| The share of electric vehicles (%) participating in a vehicle-to-grid scheme\(^b\) | 0, 20, 40, 60, 80 and 100                                           |
| Cost for vehicle-to-grid (EUR/MWh)             | 0, 10, 20, 30, 40, 50, 75, 100                                       |

\(^a\) Electric vehicle battery capacity available for the electricity system to use.

\(^b\) It is assumed that the owners of the vehicles with the shortest driving distances per year are those most willing to participate in an optimisation charging scheme with or without V2G.

#### 2.3. Parameters that are varied in the model analyses

Table 1 gives an overview of the model parameters that were varied in this study. All the cases are run for the four geographical regions: central Sweden (electricity price area SE3), which has large amounts of reservoir hydro power and good wind conditions; Ireland, with good wind conditions; central Spain, with favourable solar conditions; and Hungary, with relatively poor conditions for wind, hydro and solar generation. Three charging strategies were modelled:

1. Direct charging to a fully charged battery when parked (Direct);
2. Optimisation of the charging time to minimise the electricity system cost (Opt); and
3. Vehicle-to-grid (V2G), which compared to Opt also includes the possibility to discharge the EVs to the grid based on what is advantageous from the electricity system point-of-view.

In all the model runs, there is a requirement to fulfil a given individual EV driving demand, which is limited to driving distances that lie within the EV battery range. Furthermore, two assumptions regarding the charging infrastructure connections are made in the different model runs. The vehicles can be connected to the grid either at the home location only (home) or at all stops that are longer than 1 hour (all stops). Other parameters varied in this study (table 1) are the EV battery capacity, share of the fleet participating in optimised charging and in V2G, and the above-mentioned variation of the cost for V2G. If assuming a cost for V2G, the only discharging to the grid that will take place is the one which has more value for the electricity system than the V2G cost. The impact on the health status of EV battery from V2G will, of course, depend on the cycling behaviour, which is not reflected in the V2G cost, since an equal cost per energy unit of discharging back to the grid is assumed. Investments in the vehicle and the charging infrastructure equipment are not included in the model optimisation.

The cases are named according to following example: a case that involves a V2G charging strategy with a battery capacity of 30 kWh and charging at all stops longer than 1 hour is termed V2G-30 kWh-all stops.

#### 3. Results

##### 3.1. Investments in electricity generation and storage technologies

Figure 2 shows the investments in generation technologies for the four investigated regions. Figure 3 shows the electricity discharged to the grid from the EV batteries as a function of the share of the vehicle fleet participating in a V2G scheme. In all the regions, EVs with V2G reduce the need for investments in peak power capacity (i.e. fuel cells and biogas GT), as demonstrated in figure 2.

In Hungary, optimised charging of EVs (Opt) increases only minimally the cost-optimal investments in solar power, as compared to direct charging of the vehicles, as is evident in figure 2. However, with V2G, the EVs stimulate investments in large capacities of solar power in Hungary (figure 2). In Hungary, the generation from VRE increases from 50% to 71% in the model run with V2G and 30 kWh EV batteries, as compared to direct charging (see figures S5 and S6 in the SM). Thus, in this region, all investments in nuclear power are out-competed by additional investments in solar power when EVs supply V2G.

In central Spain and Ireland, the cost-optimal shares of VRE with direct charging are already at 86% and 94%, respectively. This is due to the storage of solar and wind electricity in stationary batteries and as hydrogen. V2G can to a large extent replace these investments in stationary batteries and hydrogen storage by using the EV batteries as an electricity storage. In central Sweden and Hungary, V2G can stimulate a minor increase in investments in wind power, as shown in figure 2 (see also figure S5 in the SM). In regions with good solar conditions, such as central Spain, V2G is increasing the value of investments in...
solar power at the expense of investments in wind power, as is evident from figure 2.

It is also clear from figures 3 and S6–S8 in the SM that already with 30 kWh batteries and 24% V2G participation (i.e. 60% of all vehicles are assumed to be electrified, 40% of which participate in V2G), most of the potential for variation management from V2G is achieved. Already with a 15 kWh battery, the battery capacity is large relative to the required daily driving distance for many of the vehicle profiles. However, the largest battery capacity, 85 kWh per EV battery, can stimulate a slightly higher share of VRE, as shown in figure 2. This is possible since the 85 kWh battery generally can endure several days of driving without charging. The longer endurance of the larger EV batteries makes them enhance the value of VRE better than an equal volume of smaller batteries.

In regions with high output from solar power (central Spain and Hungary), access to the charging infrastructure connection not only at home location is more important to be able to provide flexibility to the system. However, as seen in figure 3, the battery capacity (e.g. having 30 kWh instead of 15 kWh) plays a bigger role than the infrastructure connection. In the wind power-dominated regions (central Sweden and Ireland), having charging infrastructure connection at all stops longer than 1 hour is not as important for the electricity system point-of-view.

Table 2 shows the levels of discharge to the grid and storage capacities of the EVs and for the different storage options examined in the model. The results (table 2) show that EV batteries with V2G can, to a large extent, replace all other storage technologies, such as stationary batteries and hydrogen storage. However, simply optimising the EV charging is not sufficient to replace other storage technologies, as shown in table 2.

EVs with V2G stimulate a large increase in VRE investments in Hungary, since Hungary with poor conditions for wind and solar, require free storage to further increase the cost-competitiveness of solar and wind. In contrast, the wind and solar conditions in Spain are good enough to motivate investments in VRE together with stationary batteries already in case without EVs. In the present study, it is assumed that the investment cost for the EV battery is borne by the EV owner rather than the electricity system. The EV batteries have larger storage capacities than stationary batteries in all the regions (table 2). However, in Ireland, the battery capacity is smaller than the hydrogen storage level for most of the cases investigated. It is only in the case with an EV battery capacity of 85 kWh that the EV batteries can completely replace hydrogen storage. The large EV storage can be cycled more than the hydrogen storage and offers larger charge and discharge capacities, as investments in relatively
expensive electrolyzers and fuel cells are not necessary. The EV battery storage also benefits from higher electricity-to-electricity efficiency than the hydrogen storage system.

3.2. Dispatch levels of the storage technologies

In the case with direct charging, the electricity storage levels between night-time and day-time (mainly by stationary batteries) and over several days (mainly in the form of hydrogen) are shown in figures 4(a) and (b) for central Spain and Ireland, respectively. The long-term storage involves hydrogen caverns with small tanks, to reduce fatigue from cycling of the caverns. Daily variations are covered by Li-ion batteries. If V2G is allowed, all of the stationary battery storage and most of the hydrogen storage technologies are replaced by EV batteries assuming a battery capacity of 30 kWh (table 2).

Figures 4(c) and (d) show, for central Spain and Ireland, respectively, the storage levels of the EV batteries when assuming three different battery capacities. As shown in figure 4, the storage capacity offered by the EVs is much larger than the cost-optimal battery capacity without EVs and this makes it possible to utilise more solar PV electricity from sunny days. In central Spain and Hungary, where solar power is enhanced, the EV batteries handles mainly diurnal variations. As seen in figure 4(c), the charging in central Spain occurs in the middle of the day when solar power is generating electricity. In contrast, discharging back to the grid from EVs for all the countries occurs mainly during the peak hours in the morning and afternoon (see figures S9–S11 in the SM). But in the countries with low diurnal variations (Ireland and Sweden), as well as in all countries assuming 85 kWh batteries, the EV batteries are also handling wind variations with fewer charging and discharging cycles per year. The long-term storage potential of EV batteries is obviously limited by the individual driving demands.

The EV battery storage levels are thereby covering both daily variations and longer variations spanning over several days. However, battery capacities of 15 and 30 kWh per vehicle cannot fully replace the use of hydrogen in Ireland, as the small storage capacities are drained during driving. The 85 kWh EV batteries manage these longer variations, as can be seen in figure 4 where the EV storage level follows the charging and discharging pattern of the hydrogen storage

Figure 3. Discharging back to the grid from EV batteries as a function of the share of the fleet that is participating in a V2G scheme with varying battery capacity, charging strategy, and charging infrastructure connections.
Table 2. Available storage capacities, storage sizes, and levels of discharging to the grid per year for the EV batteries and the different storage technologies, (Li-ion batteries, and hydrogen) explored in the model. All the results assume 30 kWh of EV battery capacity and charging at all stops longer than 1 hour.

|                      | EV batteries | Li-ion batteriesa | Hydrogen |
|----------------------|--------------|-------------------|----------|
|                      | Direct Opt V2G | Direct Opt V2G | Direct Opt V2G |
| Central Spain        |              |                  |           |
| Storage capacity (GW)b | 5 13 28    | 40 28 0         | 2 1 0    |
| Storage size (GWh)   | 155 155 155 | 80 57 0         | 87 60 0  |
| Discharging to the grid (GWh yr⁻¹) | 0 0 29 500 | 22 900 15 800 | 1200 900 0 |
| Ireland              |              |                  |           |
| Storage capacity (GW)b | 2 3 5       | 3 4 0           | 3 3 1    |
| Storage size (GWh)   | 50 50 50    | 6 8 0           | 280 220 130 |
| Discharging to the grid (GWh yr⁻¹) | 0 0 1800 | 1100 330 0 | 3800 2800 1500 |
| Hungary              |              |                  |           |
| Storage capacity (GW)b | 3 6 11     | 8 4 0           | 0.5 0.1 0 |
| Storage size (GWh)   | 80 80 80    | 16 8 0          | 15 5 0   |
| Discharging to the grid (GWh yr⁻¹) | 0 0 7500 | 4600 2200 0 | 180 60 0 |
| Central Sweden       |              |                  |           |
| Storage capacity (GW)b | 3 5 8       | 3 1 0           | 1 1 0    |
| Storage size (GWh)   | 90 90 90    | 5 2 0           | 25 25 0  |
| Discharging to the grid (GWh yr⁻¹) | 0 0 1700 | 730 130 0 | 220 120 0 |

- All investments in stationary batteries in the model are in Li-ion batteries. Investments in the other battery type (flow batteries) were zero.
- Storage capacity for EV batteries is the maximum utilised hourly charging or discharging capacity.

(compare the decline at hours 270–320 and incline at hours 300–430 in figures 4(b) and (d)).

3.3. Cycling of batteries with and without V2G

A heavy cycling of EV batteries due to V2G will speed up the cycling ageing of the batteries and might, as a consequence, reduce their technical life-times. Figure 5 shows the number of full cycles per year for each driving profile in central Spain. The number of cycles per year has been calculated by dividing the total amount of charging per year by the maximum battery capacity for each driving profile, separately. Among the four investigated regions, central Spain is the one with the highest number of battery cycles (see figure S12 in the SM for comparison with the other regions). This is mainly due to the good solar conditions in central Spain, where the EV batteries are primarily used to handle day-/night-time variations of solar power. The average numbers of extra cycles per year with V2G, assuming a battery capacity of 30 kWh and connection to the charging infrastructure at all stops longer than 1 hour, are 200, 100, 30, and 25 for the regions of central Spain, Hungary, Ireland, and central Sweden, respectively. For the 426 vehicles in central Spain (also those with longest driving distance), the number of cycles from the EV battery is increased drastically in the case with V2G, as compared to optimised charging only (figure 5). On average, the vehicles in central Spain are charged and discharged 3.7 times more frequently with V2G than without V2G. In this case, the EV battery is mainly used to manage variations in the grid rather than for driving. For the vehicle with the longest driving distance per year, the number of cycles with V2G is increased by 25% in central Spain, as seen in figure 5.

In wind-dominated regions, such as Ireland and Sweden, the number of cycles per vehicle is not increased as much as it is in the solar-dominated electricity systems. For example, the driving profile with the most cycles from V2G, assuming a battery capacity of 30 kWh, in central Spain is 260 (figure 5), as compared to only 60 in Ireland (see figure S12 in the SM). A larger battery capacity (e.g. 85 kWh instead of 30 kWh) would significantly decrease the number of cycles per vehicle (as seen in figures 5 and S12 in the SM).

3.4. System value of V2G

A V2G costs in the range of 10–100 EUR/MWh have been tested in a sensitivity analysis assuming a battery capacity of 30 kWh. Figure 6 shows the amount of yearly discharging from EV batteries and from stationary batteries depending on the cost of V2G. Thereby, figure 6 shows the value for the electricity system of using V2G to replace stationary batteries in the electricity system. Figure S13 in the SM shows instead how V2G facilitate a greater share of VRE depending on the V2G cost.

As shown in figure 6, the potential cost of V2G has a strong impact on the amount of electricity discharged back to the grid from the EV batteries. For a V2G cost of ≥75 EUR/MWh, very little V2G discharge occurs in any of the electricity systems. If assuming a V2G cost of ≤30 EUR/MWh, EV batteries are more cost-efficient than stationary batteries (figure 6). With a higher cost for V2G in central Spain and Hungary, some of the V2G is replaced by stationary batteries, and in Hungary the VRE share is reduced and base-load generation and stationary storage re-enters the cost-optimal systems (see figure S13 in the SM. In Ireland, the share of VRE is almost
constant and is not dependent upon the V2G cost. However, investments in hydrogen storage and fuel cells in Ireland are increasing with increasing V2G cost.

Figure 7 shows the marginal cost savings with V2G per battery capacity depending on the share of the EV fleet participating in V2G compared to doing optimised charging. The marginal values in figure 7 are calculated by dividing the difference in system cost by the difference in battery capacity between the two cases investigated. The marginal value for V2G decreases towards zero as more vehicles provide battery capacity to the electricity system. The marginal value for V2G per year is up to 13 EUR per kWh of battery capacity for the regions and cases investigated as seen in figure 7 (corresponding to approximately 390 EUR per vehicle and year). S15 in the SM shows the reduction in total system cost with optimised charging with and without V2G compared to direct charging.

In central Spain and Hungary, EV batteries are mainly replacing stationary batteries in combination with some traditional base-load power plants. Whereas, in Ireland and central Sweden, EV batteries are replacing peak generation technologies such as fuel cells and biogas turbines. The replacement of peak generation in central Sweden and Ireland gives a higher marginal value per MWh as seen in figure S14 in the SM. However, each additional vehicle battery is used less throughout the year in Ireland and central Sweden compared to central Spain and Hungary, which explains the steeper decline in marginal cost savings per battery capacity seen in figure 7.

4. Discussion

Three major findings of this study are that EVs with V2G can: (i) reduce investments in peak power capacity in all the regions investigated; (ii) replace investments in both short-term and long-term storage technologies (e.g. stationary batteries and hydrogen storage); and (iii) stimulate an increase in VRE share, mainly in regions with poor wind and solar resources (Hungary). Earlier studies (e.g. Fripp [7] and Forrest et al [11]) also show that V2G can to some extent replace stationary storage and reduce investments in peak power. However, the results in this study shows that the replacement can be done, without infringing on the individual driving profiles.

The major findings hold true to a large extent even for an EV battery with a capacity of 30 kWh that is only connected to the grid at the home location. This is due to the fact that with a 30 kWh battery, the battery capacity is large compared to the average daily driving distance. Therefore, from the electricity system perspective, there is no incentive to invest in larger EV batteries (such as 85 kWh) for the purpose of
providing system flexibility. However, if the car owners buy large batteries relative to the daily driving distance, so as to cover the few long-distance trips they make per year, this study shows that the electricity system can use these large batteries to replace also investments in long-term storage.

The EV batteries are supporting the electricity system differently, depending if it is a wind- or solar-dominated electricity system. In a wind-dominated electricity system (like Ireland), EV batteries are working mainly as a storage of several days, with few cycles due to V2G. The EV batteries are mainly charged during night-time, therefore charging infrastructure connections on more locations than at the home location are not important to provide flexibility for such system. In a solar-dominated electricity system, EVs have a greater impact on the system composition and total system cost than a wind-dominated electricity system. The EV batteries are then working mainly as a day-/night-time storage (charging during mid-day and discharged during evenings), which results in many cycles due to V2G. In an electricity system with large share of hydro power (like central Sweden), V2G have little impact on the electricity system composition or total system cost. Even though, V2G at certain hours also in central Sweden can help reduce investments in hydrogen storage and thereby reduce the system cost to some extent.

Heavy cycling of EV batteries due to V2G would possibly accelerate the ageing of the batteries, thereby reducing their technical life-times. The present study shows that the number of extra cycles linked to V2G is considerable, especially for solar power-dominated electricity systems in which the EVs are handling...
day-/night-time variations. On the other hand, the EV batteries are charged and discharged with very low c-rates, which would be beneficial for the health of the battery. More battery life-time estimations, including real driving patterns and V2G, are needed to assess the impacts on battery ageing and life-time of V2G when including both cycling and calendar ageing. If the calendar ageing and/or the cycling ageing related to driving have substantial impacts on battery life-time, extra use of the battery due to V2G might be preferable. There could be both environmental and economic benefits associated with the use of the car battery for balancing the output from the grid, since it would avoid investments in stationary batteries dedicated exclusively to grid balancing.

This model includes no electricity trading between regions, and each region is modelled as a closed system. Therefore, this study may over-estimate the benefit of V2G given that transmission is a way in which flexibility can be provided to the system by smoothening the production and consumption of electricity over a larger geographical region [45, 46]. Furthermore, this study assumes perfect foresight for the electricity demand, weather patterns, and travelling patterns, as well as assuming a pre-defined willingness to participate in an optimised charging or V2G scheme. When we ran the model with different assumptions for the share of the fleet that is participating in V2G we found that the participation level does matter, especially for the two regions of Hungary and central Spain. However, the increase in benefit for the integration of VRE is minor if ≥24% of all passenger cars are participating in V2G.

In the present study, we consider typical driving patterns, and the driving demands are fulfilled for all individual vehicle driving profiles in all the model runs and calculations. The development of autonomous vehicles could change significantly the ways in which vehicles are used in the future. The extent to which we will own our vehicles in the future may also influence strongly driving patterns and, therefore, also affect the results presented in this paper.

Further studies are needed to analyse the willingness of EV owners to participate in V2G, as well as the practicalities associated with implementing and co-ordinating such a charging strategy. The freedom to use the batteries for V2G also depends on assumptions linked to charging infrastructure access, number

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**Figure 7.** Annual marginal cost savings with V2G per battery capacity depending on the share of the electric vehicle fleet participating in V2G for (a) central Spain, (b) Ireland, (c) Hungary, and (d) central Sweden.
of EVs, and the dimensioning of the battery relative to the daily driving distance. In this study, we have only analysed the benefits of optimised charging and V2G on long-term investment decisions and the day-ahead market. We have not evaluated the possibility for EVs to provide ancillary services to help maintain the security and quality of the electricity supply, e.g. frequency control. This might also represent a contribution from EVs to the flexibility of the electricity system.

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Data availability statement

The data that support the findings of this study are available from Dr Taljegard upon reasonable request. The article includes references to all datasets and sources used in this study.

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