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Electric vehicles as power and energy provider for the European electricity system - an electricity systems modelling study

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Summary

This study analysis the potential for electric vehicles (EVs) to contribute with power and energy to the electricity system by means of demand response, storage of electricity and contribution to the power reserve. The work applies real-time measurements of driving patterns and a cost-minimisation model of the electricity system assuming zero CO_2 emission and run for selected European regions. The results shows that EVs can (i) substantially reduce investments in peak power capacity, (ii) replace investments in other both short-term and long-term storage technologies (e.g., stationary batteries and hydrogen storage), and (iii) participate in the power reserve with large additional power capacity.

Keywords: V2G (vehicle to grid), modelling, energy storage, smart charging, smart grid

1 Introduction

Electrification of the transportation sector is considered to play a significant role in order to reach the European climate targets [1, 2]. An electrification of the transport sector will increases the yearly electricity demand and demand for power at certain hours [3-5]. An unregulated charging can cause an increase in the electricity load during times when there is already a high demand [4, 6]. Yet, if the integration of electric vehicles (EVs) include a strategy, the new demand can potentially offer benefits in terms of flexibility in the load, e.g. demand response services in the form of strategic charging and possibly also discharge back to the grid (i.e. vehicle-to-grid; V2G) according to what is most optimal from an electricity system point of view.

At the same time a transition of the electricity system towards more variable renewable electricity (VRE) are likely demanding a more flexible electricity consumption and production [2]. Solar power and wind power demands different types of flexibility from the electricity system. Solar power needs mainly a storage for 6 to 12 hours (to store electricity between day and night time) and for some regions also to store large amount of electricity between seasons. Previous studies have shown that batteries are typically preferable for this type of intra-day storage spanning over a couple of hours [7]. Wind power, on the other hand, have fluctuations in the energy production that spans over several days, as well as, between seasons. These fluctuations might be handled with long-term hydrogen storage or hydro power and not with investments in batteries, since energy needs to be stored for several days [7]. EV batteries can be used for storage of electricity by charging the batteries at hours with a high netload and discharge the EV batteries back to the grid (V2G) at hours with a low net load. The net load is the load that must be met by other electricity sources than variable renewable electricity, i.e., a low and even netload is favorable. Thus, electrification of the

transport sector can in different ways affect the electricity system both in terms of energy and power. Statistics shows that with today's driving patterns, the passenger vehicles are parked more than 95% of the time and on an average need to be charge for driving 1-2 hours per day [8, 9]. This shows that there might be a great potential to use the EV batteries for different electricity grid services. Thereby provide different type of flexibility services to the grid.

An optimised charging of EVs (i.e., charging the vehicles at hours when it is most optimal for the electricity system) and V2G could contribute to electricity system services such as:

• Storage of electricity to perform, e.g., peak power shaving and reduce cycling of thermal power plants

• Demand response

• Power reserve

• Ancillary services to help maintain security and quality of the electricity supply, such as frequency control

A possibility to store electricity between hours within a day and between days could help to integrate more VRE. The power reserve is used providing capacity within a short interval to meet demand in case of a sudden disruption of the electricity system. The power reserve is seldom used, but will most likely be expensive to provide in the future even if the power reserve will most likely be used more than today. When transforming the electricity system towards carbon neutrality, there will be a large share of VRE generation and there need to be new ways to provide flexibility services. EVs may contribute to this. Therefore, this study analysis and summaries the potential contribution of in EVs in the electricity system with respect to storage of electricity to stimulate an increase in the share of VRE, peak power shaving and contribution to the power reserve. In this study, we haven't analysed the possibility for EVs to provide ancillary services to help maintain security and quality of the electricity supply, such as frequency control.

2 Method

2.1 Model description

This study uses a cost-minimisation model of the electricity system called ENODE. The model has been developed to analyse the electricity system in countries in Europe when meeting a strict target on CO_2 emission. The model is of a Greenfield type (i.e. there is no generation capacity in place at the starting point) which takes investments in technologies to cover demand, as well as, optimise the hourly dispatch of different power technologies. The model is run for one year (Year 2050). There is no inter-connection between regions in the model. Fig. 1 gives a schematic of the main modelling elements applied in this work including input and output parameters. Table 1 shows the technologies and fuels for the model to invest in to meet an hourly electricity demand Year 2050. As seen in Fig. 1, the model provides output such as: (i) annual electricity production by fuel and technology; (ii) total system cost; (iii) charging profiles of the EVs; and (iv) marginal cost for electricity. A representation of road transportation demand on individual EV level (based on GPS driving measurements of 426 vehicles during ~2 months each) have been included in the model (see section 2.2 for a detailed description) [8, 9]. To represent the spread in the individual driving patterns is important in order not to overestimate the potential of V2G [10]. Different regions in Europe with different conditions for renewable energy (wind, solar and hydro power) have been modelled; south-Sweden (electricity price area SE3), Hungary, Ireland and central-Spain (electricity price area ES3). The hourly data are based on data from the European Network of Transmission System Operators for Electricity ENTSO-E (load) [11], and MERRA metrological data (solar [12, 13] and wind [14]). A full description of the model including all mathematically equations can be found in Göransson et al. [15] and the EV integration in the model can be found in Odenberger and Taljegard [10].

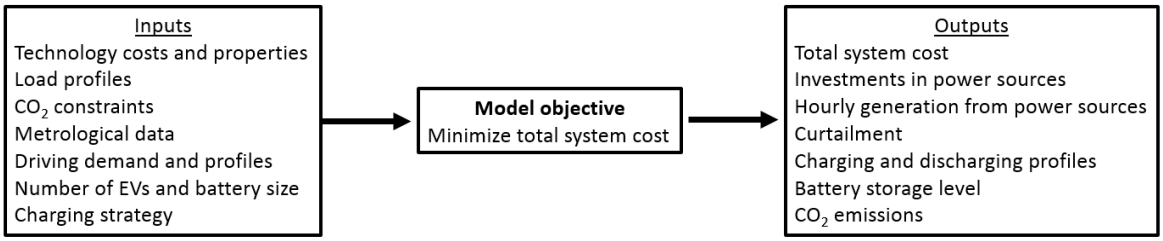

Figure1: Schematic of the main modelling elements applied in this work including input and output parameters

Table 1: Technologies and fuels included in the model

Thermal technologies	Condensing and combined heat and power (CHP) with and without carbon capture, gasifiers
Renewable technologies (excluding biomass)	On-shore and off-shore wind power, solar PV, hydro power
Fuels	Biomass, coal, gas, lignite, uranium, waste, biogas
Storage technologies	Flow batteries, Li-Ion batteries, hydrogen tank storage and hydrogen storage in lined rock caverns, EV batteries

2.2 Driving patterns and charging strategies

This study applies measured traveling patterns from a measurement campaign performed in the region of Västra Götaland (western part of Sweden), i.e. GPS measurements of about 770 randomly chosen gasoline and diesel vehicles that completed 107 910 trips between Years 2010 and 2012 [8, 9]. The vehicles were randomly selected from the Swedish vehicle database. The regions are reasonably representative for Sweden in terms of fleet composition, car ownership, household size, income and distribution of larger and smaller towns and rural areas. Out of the around 770 households that have had GPS equipment sent to them, about 529 of them were logged for more than 30 days and 426 of these 529 had highqiality data. Each vehicle were measured for a period of 30-73 days, yet different seasons for different measured vehicles. The measured driving period per vehicle were extrapolated from the original period to 12 months. This means that the driving data for each vehicle was used repeatedly with respect to days of the week so that the driving data has always the same weekday as the other load data. Fig. 2 shows the spread in the number of kilometre per year for the 426 vehicles used in the analysis after the extrapolation. The main concerns with using this type of data are twofold: it represents only a small sample of vehicles in one particular region and 274 of the vehicles were excluded from this analysis due to problem with the logging equipment and not enough data quality.

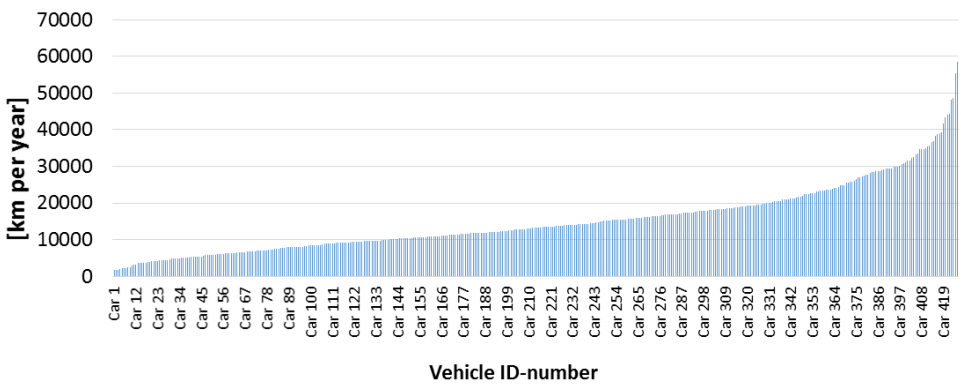

Figure2: Number of kilometers driving per year for the 426 different measured vehicles in the car movement database.

Three different charging strategies are assumed in the modelling. One strategy is uncontrolled charging of the vehicles directly upon parking (called *Uncontrolled* or *Direct charging*). Second strategy is to optimise the time of charging according to what is most cost-optimal for the electricity system while at the same time fulfilling an exogenously given hourly passenger EV transportation demand (called *Optimised*). Third strategy is both to optimise the charging and the discharging back to the grid (called *V2G*).

3 Results and discussion

3.1 Stimulating investments in more variable renewable energy

Fig. 3 shows the electricity generation by power sources for the four regions investigated in this study. An optimised charging of EVs (*Optimised*) increases the cost-optimal investments in renewable electricity to a minor degree, as seen in Fig. 3 (except for in IE where it instead reduces the investments in wind power, due to reduced curtailment of electricity). With *V2G* however, EVs stimulates investments in a higher share of renewable energy as seen in Fig. 3. In Hungary, the generation from variable renewables (dominated by solar power) increases from 38% in the model run with uncontrolled charging to 67% in the model run with V2G. Similar trend can be seen in central-Spain, where the share of variable renewables increase from 59% to 80% as seen in Fig. 3. In these two regions (central-Spain and Hungary), there is a reduced investment in mainly nuclear due to the increase in system flexibility with EVs. There is only a few percent increase between uncontrolled charging and V2G in the share of VRE in the two wind dominated systems central-Sweden and Ireland. This is mainly due to an already high share of VRE in Ireland without EV. EVs are instead in Ireland replacing investments in hydrogen storage. In central-Sweden, hydro power provides, instead of the EVs, the main system flexibility needed to stimulate investments in VRE. However, as seen in Fig. 3a and d, EVs with V2G are reducing investments and generation from peak power units.

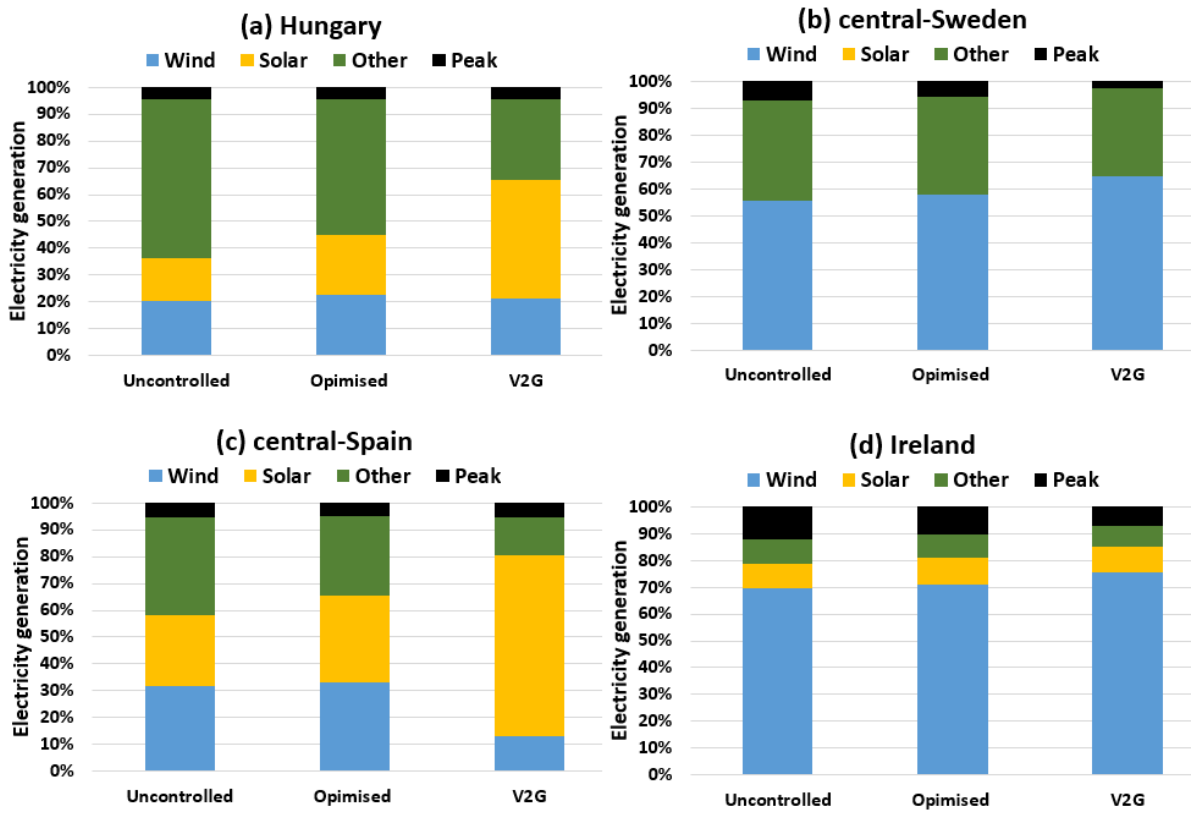

Figure3: Electricity generation by power sources for the four regions (a) Hungary, (b) Ireland, (c) Spain and (d) Sweden.

3.2 Storage in EV batteries to help the dispatch of the electricity system

Previous studies shows that storage technologies, such as stationary batteries and hydrogen storage, can help integrate a higher share of solar and wind power in the electricity system [7]. There is an investments in different storage technologies in the model runs without EVs in all investigated regions (Ireland, central-Spain, south-Sweden and Hungary). Fig. 4 shows the storage level of the aggregated EV batteries and hydrogen storage for a wind power dominated electricity system (Ireland). The curve for hydrogen storage in Fig. 4 is from a model run without EVs. The EV storage levels are from 3 model runs with EV assuming three different battery sizes. In the model runs with an optimised charging of EVs plus V2G in Fig. 4, the EV batteries can replace both stationary batteries and hydrogen storage. Larger EV batteries (85 kWh) is needed in order to fully replace long-term hydrogen storage. The same trends seen in Fig. 4 for Ireland can also be seen for the other regions investigated. In central-Spain, the EV batteries are mainly replacing investments in stationary batteries handling day-night time variation. The EV batteries can be used to a larger extent than the stationary batteries assuming that the investment cost for the EV battery is taken by the EV owner and not by the electricity system.

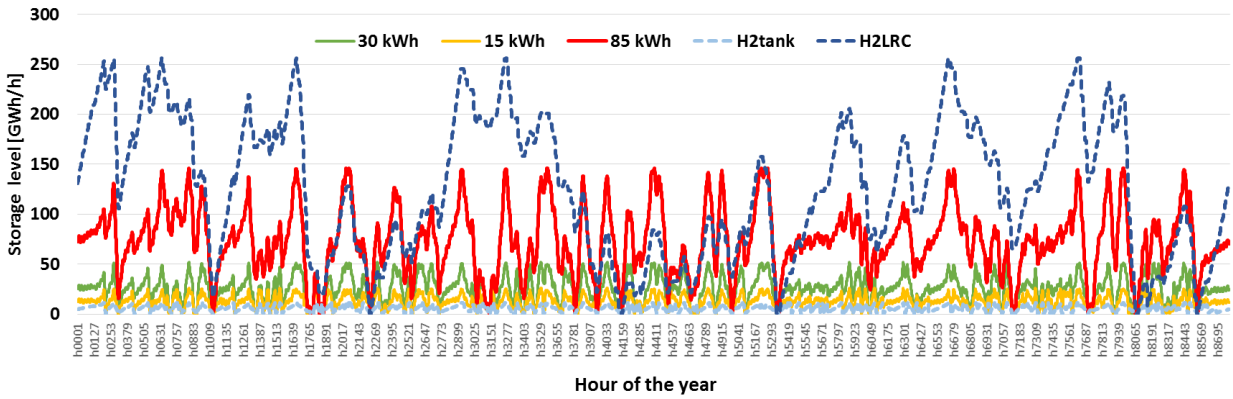

Figure4: Storage level of the aggregated EV batteries for different battery sizes all assuming optimised charging plus V2G and two different hydrogen storage (H2 tank and H2 LRC) for Ireland. The curves for hydrogen storage are from model runs without EVs. Abbreviations used: H2 LRC = hydrogen storage in the form of Lined rock caverns.

3.3 Cycling of batteries due to V2G

Fig.3 and Fig. 4 shows that V2G can help the electricity system with flexibility and thereby increase the investments in VRE and decrease investments in peak power and other storage technologies. A heavy cycling of EV batteries due to V2G would probably fasten the ageing of the batteries and thereby reduce their technical lifetimes. Fig. 5 shows the number of battery cycles per year due to V2G for the four investigated regions and the 426 driving profiles. The number of extra cycles per year due to V2G depends both on the vehicle driving profile and the region as seen in Fig. 5. Among the four investigated regions, central-Spain is the one with largest number of battery cycles due to V2G (Fig. 5). This is mainly due to good solar conditions in central-Spain where the EV batteries are used to handle day-night time variations. On average the vehicles in central-Spain are charged and discharged 3.7 times more with V2G, making the EV battery be used mainly for handling variations in the grid rather than driving. In wind-dominated regions, like Ireland, the number of cycles per vehicle are not increased as much as in solar dominated systems, as seen in Fig. 5. For example, the driving profile with most cycles from V2G in central-Spain is 260 compared to only 60 in Ireland (Fig. 5).

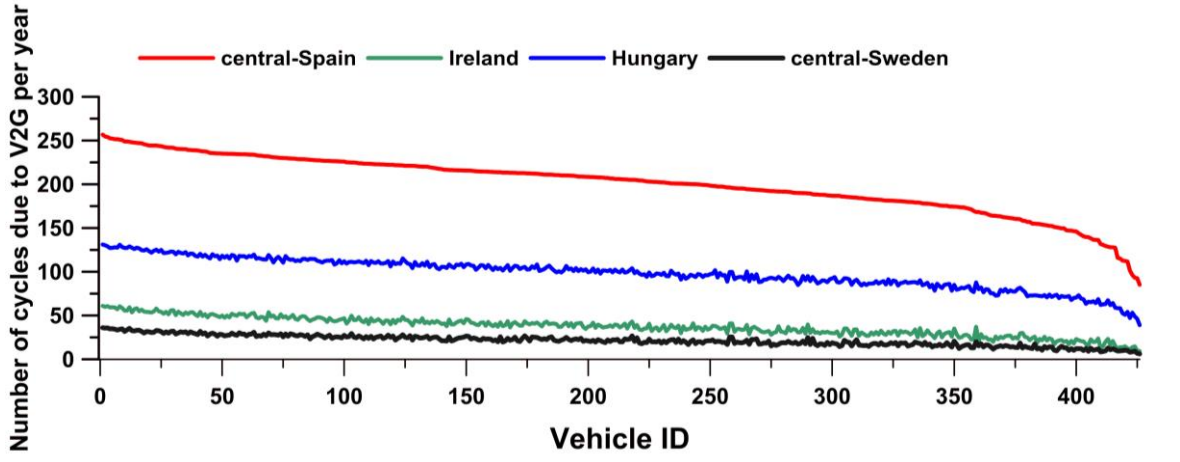

Figure5: The number of battery cycles per year due to V2G for the four investigated regions and the 426 yearly driving profiles assuming an EV battery capacities of 30 kWh and charging possibilities at all stops longer than 1 hour.

3.4 Peak power shaving

The modelling shows that when applying optimised charging of the EVs with V2G, the investments in peak power in the form of gas turbines running with low full load hours (some hundred hours a year during hours which have the highest net load) can be reduced in all investigated regions when applying an optimised charging and V2G. In Fig 3. a reduction in peak power can be seen especially for the wind dominated regions such as central-Sweden and Ireland. Fig. 6 shows the hours with the highest net load for central-Sweden Year 2050 without EVs and with different charging strategies for EVs. Fig. 6 shows that an uncontrolled charging directly when being parked will increase the peak power demand compared to an optimised charging strategy. An optimised charging with V2G can further reduced the netload and thereby investments in peak power. The results shows that EVs can facilitate investments in more base load by reducing the cycling of thermal power plants and increase the investments in more renewable energy by providing peak power at hours with low output from wind and solar power.

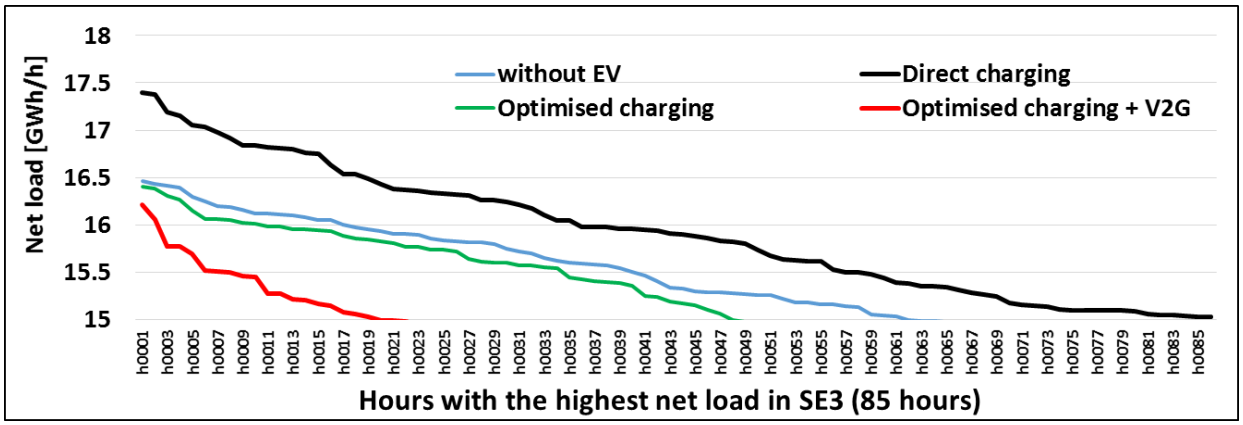

Figure6: Net load for south-Sweden assuming different scenarios (no electric vehicles, direct/uncontrolled charging directly when being parked; optimised charging and optimised charging with V2G). Only the 85 hours with highest net load is included.

3.5 Power reserve

Fig. 7 shows the maximum power available in the EV batteries for a certain hour in a region in central-Sweden assuming approximately 2 million electric cars in the region Year 2050. Thereby in Fig. 7 it is assumed that 60% of the fleet Year 2050 is participating in the power reserve. Individual driving patterns is always fullfilled, i.e., all trips can still be performed even though the vehicle is participating in the power reserve. So even if a vehicle is standing still a certain hour connected to the grid, the vehicle is only available

for the power reserve if the driving patterns coming hours are allowing for that. The power available depends on the proportion of EVs in the fleet willing to participate in the power reserve, the charging power at the outlet, driving profile and the battery size. The available power to the power reserve in central-Sweden is with a 30 kWh battery between 18 GW and 60 GW and between 9 MW to 30 GW with a 15 kWh battery (Fig. 7). This can be compared with the maximum net load of about 18 GW in the region in Fig. 7. Thereby, the EV batteries have a great potential to contribute to the power reserve even in the case with a small batteries of 15 kWh and at those hours of the day when most cars are out driving. At all hours of the year, at least 33% of the fleet are parked at the home location and at least 67% of the fleet are parked at any location. The similar results as in seen Fig. 7 can be seen for the other investigated regions (Hungary, Ireland and central-Spain), i.e., that the EVs are providing large amount of battery capacity at all hours of the year even when fulfilling the driving demand of all individual vehicles.

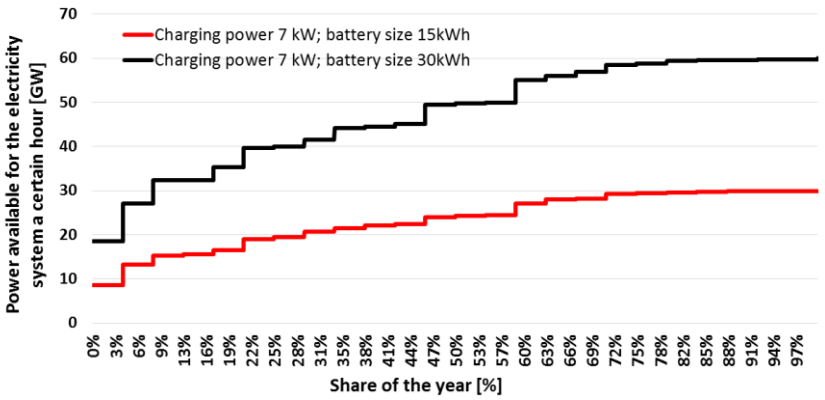

Figure7: Battery power available in the aggregated vehicle fleet a specific hour, assuming an electrification of 60% of the vehicle fleet in SE3 in south-Sweden (i.e. 2 million electric cars). The figure is sorted from the hour with the lowest power available to the hour with maximum power available. Attention in the modelling has been paid to different individual driving patterns.

4 Conclusions

The results shows that EVs with V2G can (i) substantially reduce investments in peak power capacity, (ii) replace investments in other both short-term and long-term storage technologies (e.g., stationary batteries and hydrogen storage), (iii) stimulate an increase in more VRW and (iv) participate in the power reserve with large additional power capacity since a large part of the fleet (at least 67%) are connected to the grid during all hours of the year. In this study, we are considering typical driving patterns and the driving demands are always fulfilled for all individual vehicle driving profiles in all model runs and calculations. A heavy cycling of EV batteries due to V2G would probably fasten the ageing of the batteries and thereby reduce their technical lifetimes. The study shows that the number of extra cycles due to V2G are considerable, especially for solar dominated electricity systems where EVs are handling day and night time variations. However, more battery modelling studies are needed to show the impact on the ageing and lifetime of the battery from V2G.

The development of autonomous vehicles might result in a substantial change in the way vehicles are used in the future. To what extent we will own our vehicles in the future might also heavily impact driving patterns and therefore also the results presented in this paper. This study assumes perfect foresight and a willingness to participate in a V2G scheme and the power reserve. Further studies are needed in order to analyse the willingness to participate in V2G by the EV owners, as well as, the practicalities in implementing and coordinating such charging strategy. The freedom to use the batteries for V2G also depends on assumptions of charging infrastructure access, number of EVs and the dimensioning of the battery relative to the daily driving distances. However, already with a 15 kWh battery (and definitely with a 30 kWh battery), the battery capacity is large compare to the average daily driving distance. Thereby there is no driving force from the electricity system perspective to invest in bigger EV batteries for providing system flexibility. In this study, we haven't analysed the possibility for EVs to provide ancillary services to help maintain security and quality of the electricity supply, such as frequency control. This might also be a possible contribution from EVs to the system flexibility.

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