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Application of Rechargeable Batteries of Electrical Vehicles as Time Dependent Storage Resource for the Public Electricity Grid

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Abstract

This study investigates the potential to use the EES storages of a fleet of privately owned Electrical Vehicles (EV) as time dependent storage source connected to the electrical grid. The example of the national German electricity grid is examined. Calculations are done as time series on a complete yearly set of quarter-hour data for generation and consumption, as obtained from the national regulatory authority ("Bundesnetzagentur"). Future scenarios foresee targets that have been publicly stated by the German government, e.g. the projected discontinuation of electricity generation by nuclear power, the envisaged shares of renewables within the electricity mix per 2030 or 2050, and a projected evolution of the number of EV. Besides, the technical evolution like introduction of new types of EES like the Li-Air-storage promising higher storage capacity in the future is expected. The model assumes that private users of EV will provide the storage capacity within their EV to the public grid following a certain time pattern. A minimum reserve for the user is always granted and moreover it is assumed that the electrical system operator will make compensation payments to the user of the EV. In a scenario beyond 2030 where 6 Mio EV are projected, the number of EV is assumed to be 20 Mio EV in 2050. This results in a considerably large distributed storage to help dealing with a future more and more volatile electricity provision by more and more renewable energy sources, especially wind and PV. According to our preliminary results, an optimum for this model can be obtained at moderate power levels for charge and discharge, avoiding the necessity for a comparable high invest of "fast charging" stations.

Keywords: Electrochemical Storage (EES); Vehicle2Grid (V2G); Electricity Generation Mix

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Nomenclature

CAPEX	Capital expenditure (initial invest for a project)
EV	Electrical Vehicle
LEV	Light Electrical Vehicle (passenger vehicle, not for mass transport)
LV	Low Voltage
MV	Medium Voltage
PV	(solar) Photovoltaic
SOC	State Of Charge (of a rechargeable battery)
VRE	Variable Renewable Energy (wind and solar PV)
V2G	Vehicle to Grid
A_{V2G}	(Economic) advantage of the V2G concept in EUR
$a_{bot,export}$	Interdependency factor export price, bottom
$a_{top,export}$	Interdependency factor export price, top
$a_{bot,\mathrm{import}}$	Interdependency factor import price – VRE generation, bottom
$a_{top,\mathrm{import}}$	Interdependency factor import price – VRE generation, top
$\bar{C}$	Average battery capacity of one EV. in kWh
C_{max}	Total battery capacity of all EV participating in V2G, in kWh
$E_{lack,t}$	Lacking electric energy due to insufficient generation at time interval t in MWh
$E_{\mathrm{sur},avg}$	Average surplus energy of an entire year in MW
$E_{\mathrm{sur,t}}$	Surplus energy at a given time interval t in MW
$E_{VRE,t}$	Energy generation by VRE wind and solar at time interval t in MWh
$E_{VRE,avg}$	Annual average energy generation by VRE during a time interval MWh
G_v	Gains from foreign trade in EUR
$G_{v,V2G,consumption}$	G_v: V2G is applied and EV are supplied from the energy stored by V2G
$G_{v,V2G,no\ consumption}$	G_v: V2G is applied and EV are supplied from public grid as additional load
$G_{v,no\ V2G,no\ consumption}$	G_v: No V2G, but EV are supplied from public grid as additional load
k	Correlation factor for weather between the national and extraterritorial regions
n_{EV}	Total number of EV participating in V2G
$P_{bat,max}$	Maximum charging/discharging power of a battery (average) in kW
$P_{bidir,max}$	Max. nominal power of bidirectional infrastructure for charging/discharging in kW
$p_{export,avg}$	Average retail price / export price of an entire year in €/MWh
$p_{export,t}$	Retail price / export price at a given time t in €/ MWh
$p_{import,avg}$	Annual average import price during a time interval t in €/MWh
$p_{import,t}$	Import price at a given time interval t in €/MWh
t	Number of time interval in time series
Δt	Resolution of the time series (typically quarter-hour)

1. Introduction

The concept to use battery capacity of electrical vehicles as electricity storage for the electrical grid has been presented more than one decade ago [1] and has been followed up continuously since. The approach called “Vehicle-to-grid” (V2G) is building on the fact that private cars most of the time (90% … 95%) are not used for transport [2] and can offer additional storage for buffering or ancillary services to the grid operators. On the other hand, V2G can also be looked from a point of business models for electrical vehicles (EV) in general [3]. On technical level, there have been several reports [4], [5], [6] studying the possibility of bidirectional integration of EV into the low voltage grid. The technology for the necessary bidirectional charging/unloading poles [7] as well as the capacities of secondary batteries in EV [8] is advancing. At the same time, there is growing importance of Variable Renewable Energy resources (VRE), and some of them show a strongly intermittent generation profile (as solar PV - see [9]). This is continuously creating new challenges for operation, distribution and storage within electricity networks. It is therefore interesting to study in more detail the possible benefit of V2G as a national storage resource in scenarios that would lead to 100% RE supply in electricity. Modeling is presented for the German national electricity supply as there is already today a high contribution of VRE. Generally speaking, challenges due to more VRE generation within a distinct electrical network may be managed by change of consumption profiles, addition of new transmission lines or an increase in capacity. For the supply of a national grid there is always the possibility to exchange energy with neighbor states, which is actually currently contributing with some low percentage number of the national electricity supply. In this respect, one monetary dimension is introduced into the analysis as such trade with foreign countries generates payments for purchase of electricity as well as proceeds for sales of electricity of a nation's actual electricity stock. Often, even if the quantities of purchase and sales would be balanced during a given time period, losses are invoked for the national economy as purchase prices are typically higher compared to possible benefits from sales of electricity. It should be added that losses can be also be generated in case of sales of electricity at prices below actual generation cost, which might be necessary due to technical reasons. Such profits and losses arising from external trade are compared to predicted results when taking advantage of the V2G storage capacity and reducing the necessity to participate in external trade. Moreover, benefits with respect to climatic protection [10] can be studied when more storage capacity may reduce the necessity to operate fossil plants, but they are not explored within the scope of this work. The economic viability of the V2G approach for energy companies and for individuals participating in the V2G is estimated in this work for Germany following long term scenarios expanding existing data sets from 2017 until 2050.

2. Method

2.1. Basic Data Source

In fulfillment of a regulation of the European Commission [11] the national German regulatory authority ("Bundesnetzagentur"), has been prepared and published detailed data on generation and consumption of electricity in Germany in a program called SMARD. Information is provided on the internet [12] on a quarter-hourly time resolution base and has been accessed and conditioned for the preparation of this study. Based on data obtained for August 2016 through July 2017, the shares of the applicable power generation sources are adapted for future scenarios as described in the subsequent paragraphs. Actuals have been used for calculations, not synthetic plan data.

2.2. Modelling the Long Term Scenario

2.2.1. Development of EV and EV Battery

Considering the total number of EV within the market, a strong growth rate is postulated. An exponential learning curve is assumed leading from a number of 35.000 EV on the national German market in 2017 to 6 Mio EV in 2030 and 20 Mio EV in 2050. The graph Fig. 1 shows the cumulated number of EV and the associated total battery size used in this study. In 2028 it is assumed, that a new emerging technology is starting to be ready for use: Li-Air storage systems, that are already today promising highest capacities at low cost [13]. Our scenario assumes – apart from continuous improvement – an additional small accelerating step in 2040.

Table 1 shows properties of EV used for calculations. Only light electrical vehicles (LEV) are considered in this study as it cannot be assumed that EV-trucks or EV-buses will be available for participation in V2G. The terms LEV and EV are both used in parallel within this study to describe electrical vehicles of private persons or businesses that are not intended to transport primarily goods and are not part of mass transport systems like buses. It must be pointed out that all users of the EV's are granted to have a minimum reserve of 30% at any time in their battery system. This is necessary in order to satisfy under all circumstances minimum individual mobility needs. Users can at any time opt to participate in the V2G scheme or not. It is postulated, that in average 90% of the users shall participate in the V2G system. Moreover, typical user profiles are assumed, exempting certain hours of the day for V2G: this affects hours with anticipated high share of individual traffic, e.g. for commuting between home and job location during workdays.

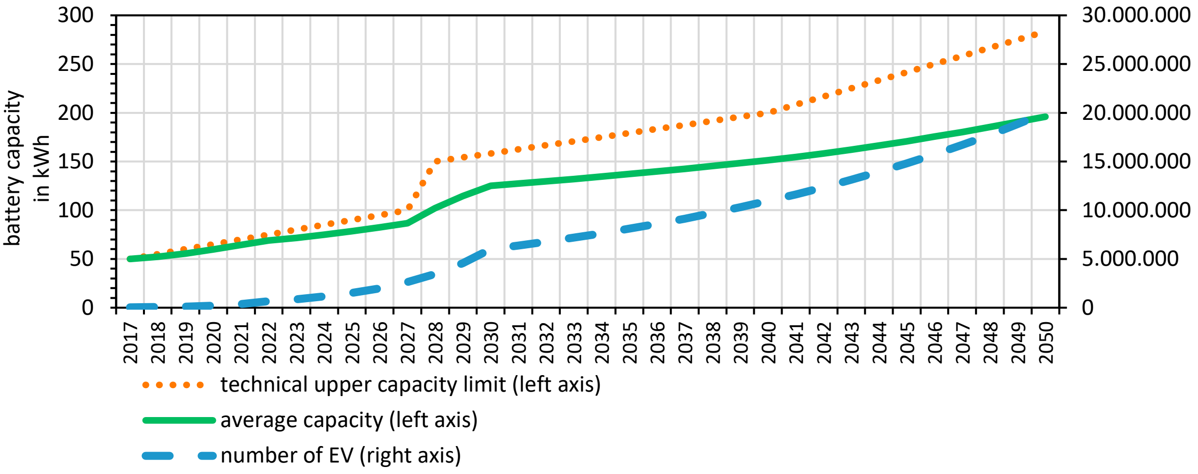

Fig. 1: assumed future development of battery capacity (right vertical axis) per EV (theoretical upper limit and projected average used for calculations) and number of EV in the national transport fleet (left vertical axis)

Table 1: Key parameters used for modelling

Parameter	Value	remark
Average battery capacity of EES within an EV 2017	40 kWh	start value 2017
Number of EV in Germany in 2017	35.000	start value 2017
Average battery capacity of EES within an EV 2050	196 kWh	target value in 2050
Number of EV in Germany in 2050	20 Mio.	target value in 2050
Efficiency during charging (parameter not changed in future)	0,98	constant value in future
Efficiency during discharge (parameter not changed in future)	0,98	constant value in future
Guaranteed minimum SOC (parameter not changed in future)	30 %	constant value in future
Average daily energy consumption of an (operated) EV	20 kWh	constant value in future
Average specific energy consumption of an EV	20 kWh/100 km	constant value in future

2.2.2. Future Energy Consumption and Power Generation

It has recently [14] been pointed out, that scenarios targeting an extreme (beyond 90%) coverage of the VRE wind and solar PV may lead to comparatively high necessities to install storage plus high CAPEX for VRE. In our scenario, we consider a fraction of only 81% for wind and solar in 2050.

There have been several approaches to model future electricity consumption and generation in Germany. Some authors are including the investigation of electrochemical energy storage EES in to their studies [15] , [16]. In order to estimate future changes in the electricity generation mix the climate-protection-goals of the federal administration of Germany can be used: share of RE in 2030 50% and in 2050 80%. Another stated boundary condition is to exit from nuclear energy by 2023. These are political statements. They are challenged and might in the future be adapted but today they serve as a realistic base for modelling and deriving conclusions.

When it comes to the prediction of future electricity consumption we share an approach formulated by others [17], namely to freeze today's energy consumption to 490 TWh p.a. for the future. Despite the fact that large efforts are made to enhance better energy efficiency of hardware, it cannot be taken for granted (yet) that this shall ultimately lower the energy demand. In this respect we are taking a rather conservative approach.

The boundary conditions of our model are shown in Fig. 2. The graph gives a breakdown per energy source.

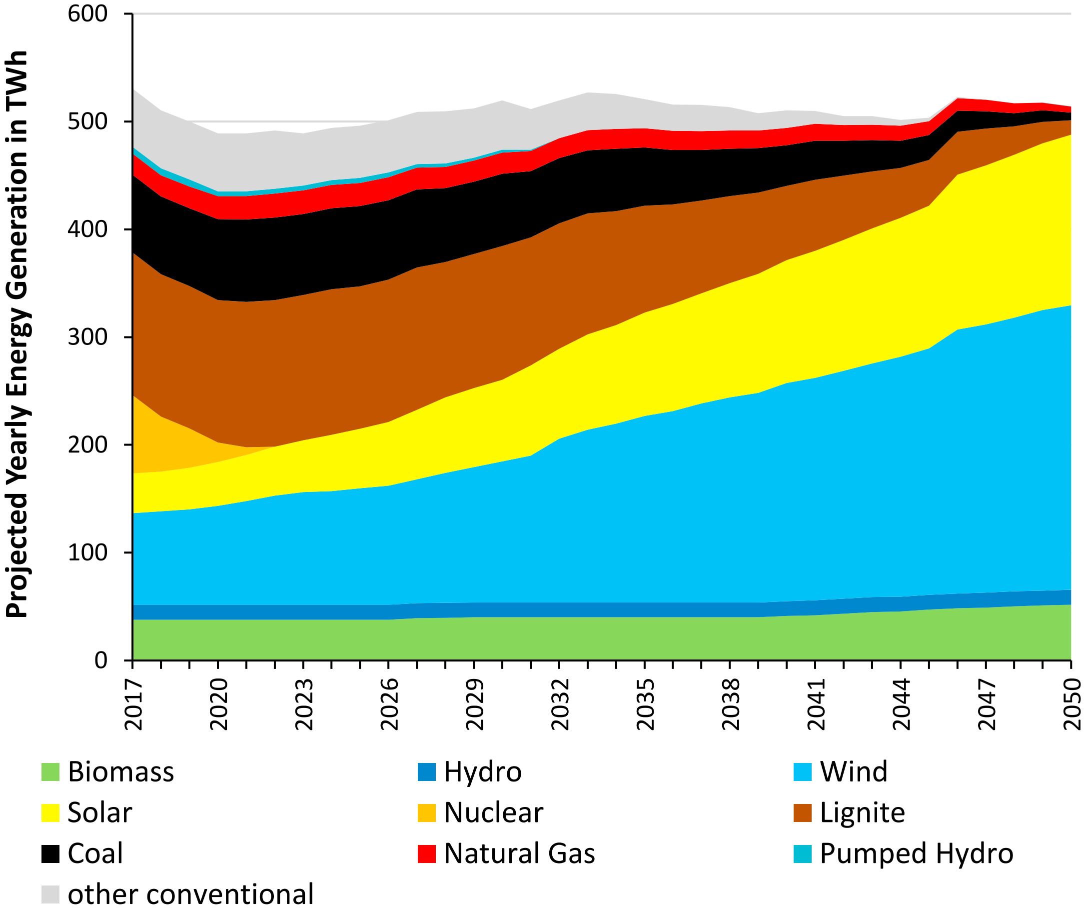

Fig. 2: projected future electric power generation profile used in this study. VRE wind and solar are assumed to provide 81% of the electric power in 2050

2.3. Model for National Electricity Supply and Export / Import

Surplus electricity and demand of electricity within a national grid are typically balanced by trade of electricity with neighbour countries. This report adds V2G as an additional and preferred storage. Surplus energy and electricity demand are with priority balanced by application of the bidirectional V2G interface and use of the accessible storage of the EV fleet. At any time, trade of electricity with foreign countries is only applied if the resources given by V2G are completely exploited.

A schematic model used for calculations in this report is given in Fig. 3: In case that the generation of electrical energy exceeds the actual demand this surplus energy shall be stored in EV batteries when accessible, unless those are already fully charged (SOC = 100%). In case all EV batteries are fully charged (SOC = 100%) all additional surplus energy must be exported. Another limitation for charging EV batteries is given by the maximum charging capacity of the (bidirectional) charging poles: energy that cannot be taken off by the capacity-limited charging infrastructure is exported to foreign countries and the maximum energy (according to the infrastructure capacity) is used for charging the EV batteries.

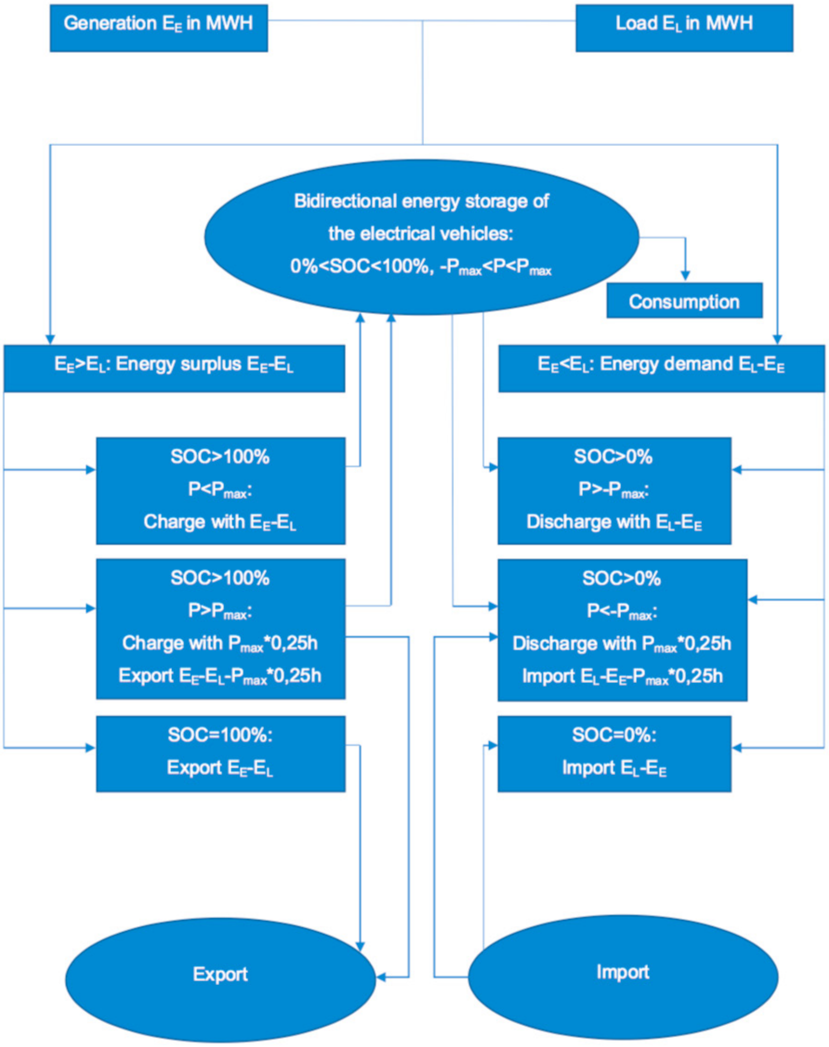

Fig. 3 : schematic view of the basic calculation model

An analogous approach is adopted in time periods where electricity demand is larger as generation: In case there is still enough energy in the EV battery fleet this energy is discharged to meet the demand. Import from foreign grid networks will only be performed when the EV battery cannot satisfy the demand. Likewise import from foreign countries' grids is necessary for those amounts of energy that would exceed the power limits of the bidirectional load/unload infrastructure. Further, the model implements a minimum SOC of 30% to guarantee that all users of EV's participating in the V2G scheme can be sure to have at any time a minimum degree of mobility without prior notice or preparation.

The described algorithm is applied for datasets on quarter-hourly resolution comprising generation and demand as described in the preceding paragraphs. The state of charge SOC of the EV fleet and the amount of electricity for foreign trade is calculated for every time step. The model is extrapolated until 2050 with changing composition of electricity generation resources as well as projected changes in storage technology – see paragraph 2.2.

In order to calculate a monetary benefit of V2G, the export price $p_{export,t}$ for electricity sold to foreign countries at time t countries is investigated. A negative correlation between $p_{export,t}$ and the surplus energy $E_{sur,t}$ at time t is observed. This negative correlation is modelled to reflect that high surplus energy $E_{sur,t}$ may be due to high generation of VRE wind and solar combined with less energy demand, e.g. during weekends. These boundary conditions are not unlikely to also extend to neighbor countries, reducing the willingness to take of the surplus energy and consequently reducing the price $p_{export,t}$.

A more detailed investigation revealed that this is even better reflected by introduction of interdependency factors, whereas two situations may occur as per eqn. (1):

$$p_{export,t} = \begin{cases} E_{\mathrm{sur},t} > E_{\mathrm{sur},avg}: & \left(1 - \frac{E_{\mathrm{sur},t}}{E_{\mathrm{sur},avg}} \cdot a_{bot,export}\right) \cdot p_{export,avg} \\ E_{\mathrm{sur},t} < E_{\mathrm{sur},avg}: & \left(1 - \frac{E_{\mathrm{sur},t}}{E_{\mathrm{sur},avg}} \cdot a_{top,export}\right) \cdot p_{export,avg} \end{cases} \tag{1}$$

The interdependency factors have been found to picture realistic results for the values of $p_{export,t}$ when chosen within the limits given in eqns. (2). In order to simulate a curtailment of electricity generation, parameters can be chosen close to the lower margin given in eqns. (2): For such smaller values chosen the simulation reveals less and less situations with a negative sales prices of electricity.

$$0{,}15 < a_{bot,export} < 0{,}21 \tag{2.1}$$

$$0{,}15 < a_{top,export} < 0{,}19 \tag{2.2}$$

Looking at the import price $p_{import,t}$ for lacking electric energy $E_{lack,t}$ to be imported another correlation with negative sign exists. In contrast to eqn. (1) this has been found to relate $p_{import,t}$ to the energy produced by the VRE sources wind and solar PV and not to general consumption or generation values. As this situation may occur at any time there is no influence of the current load or generation within the network and therefore $E_{VRE,t}$ is the best choice for parametrization. Again, it is assumed that similar boundary conditions are present in neighbor countries leading to the negative correlation. Additionally, an empirical factor of correlation k is introduced to model the the fact that similar weather conditions may prevail in neighbor countries.

$$p_{import,t} = \begin{cases} E_{VRE,t} > E_{VRE,avg}: & \left(1 - \frac{E_{VRE,t}}{E_{VRE,avg}}\right) \cdot a_{bot,import} \cdot p_{import,avg} \cdot k + p_{import,avg} \\ E_{VRE,t} < E_{VRE,avg}: & \left(1 - \frac{E_{VRE,t}}{E_{VRE,avg}}\right) \cdot a_{top,import} \cdot p_{import,avg} \cdot k + p_{import,avg} \end{cases} \tag{3}$$

For modelling purposes the following parameter choices revealed satisfying results:

$$0{,}35 < a_{bot,import} < 0{,}4 \tag{4.1}$$

$$0{,}28 < a_{top,import} < 0{,}34 \tag{4.2}$$

$$k = 0{,}7 \tag{4.3}$$

It should be noted that certain variability in the selection of the interdependency factors can be tolerated in the frame of this study since basically a relative comparison between an “as-is-scenario” and the V2G scenario is investigated. Parameters chosen have been fixed and maintained for both scenarios and variation of those within the limits of eqn. (2.1), (2.2), and (4.1) through (4.3) led to effects of secondary order, only.

2.4. Summary and Boundary Conditions for Charging and Discharging

Charging and discharging of EV batteries in the V2G concept is modelled with the following boundary conditions:

a) We are restricting the calculations to light electric vehicles LEV (LEV = passenger EV), only. Typically large time shares where vehicles are idle and not used for mobility are given for this type of cars, only [1], [2]. It is unclear or doubtable to which extend future electric vehicles used for transport of goods or mass commuting will be accessible for V2G.

b) The full theoretical discharge of EV batteries is not exploited by V2G. A stock of 30% SOC is reserved as a minimum to guarantee to the participant of the V2G model that a minimum individual mobility is always ensured.

c) Not all owners of LEV are both willing to participate in V2G and have access to the necessary technical infrastructure. It is assumed that 90% of all individuals with LEV will participate and it the total number of EV participating in V2G is denoted with n_{EV}. This is setting a theoretical top ceiling for the total battery capacity C_{max} available for V2G:

$$C_{max} = n_{EV} \cdot \bar{C} \tag{5}$$

, where $\bar{C}$ of eqn. (5) gives the average capacity of a single EV. Future evolution of $\bar{C}$ is expanded on a year-by-year level and discussed in section 2.2.1. and in Fig. 1.

d) Owners of LEV that are willing to participate in the V2G program will not provide battery capacity at any time. Certain time slots necessary for job commuting (morning / evening hours) are excluded from availability for V2G. The same holds for time slots during the weekend, where LEV are deemed to be reserved for leisure purpose. For each time interval t the total capacity available is modelled as a weighted average of several basic usage patterns. In the model weekdays Monday through Friday are treated equal whereas Saturday and Sunday are considered to have distinguished usage patterns. In summary, at each time step t a capacity factor c_t is calculated.

e) It is assumed that all EV participating in the V2G program are connected to a grid access point providing relevant bidirectional infrastructure for V2G (unless the time-restrictions of paragraph d) apply). The technical limit of this infrastructure is given by an average maximum nominal power $P_{bidir,max}$ for the individual bidirectional interface connection point. Obviously, cost of installation of such grid interface access points shall strongly differ with $P_{bidir,max}$ as higher charge/discharge power will set higher requirements and could also imply a transition from relatively economic Low Voltage (LV) installation to expensive Medium Voltage (MV) grid access solutions. Installations requiring MV access seem to be necessary for the sake of implementing fast charging for EV but may be not necessary for V2G. In this report all V2G infrastructure points are deemed to be of equal and negligible cost. Results as shown in section 3 justify this approach as it is found that a LV installation offers the most economic approach to V2G.

f) Another technical boundary condition is given by the maximum allowable charge and discharge power of the batteries $P_{bat,max}$ which is calculated using average quantities $\bar{C}$ and $\overline{\Delta t}_{charge,uncharge}$ only:

$$P_{bat,max} = \bar{C} / \overline{\Delta t}_{charge,uncharge} \tag{6}$$

Charge- and discharge power are treated equally, which is a valid assumption for Lithium-based batteries [13]. In conclusion, the technical limits as described in paragraphs e) and f) for the charge / discharge power P_t at a given time step t are limited by $P_{bidir,max}$ or $P_{bat,max}$ whichever is smaller:

$$P_t = \begin{cases} P_{bidir,max} > P_{bat,max}: & P_{bat,max} \\ P_{bidir,max} < P_{bat,max}: & P_{bidir,max} \end{cases} \tag{7}$$

g) When it comes to trade of electricity, energy and not power is the relevant quantity for calculation of prices. This is why losses during both charging as well as discharging must be considered. To this end efficiency factors of 0.98 are applied for each direction (charge / discharge) whereas the (short) V2G storage time within the battery is considered to have negligible losses, only.

3. Results

3.1. Global Results

In this study we exclusively base all economic considerations on the export and import of electricity (foreign trade) under time dependent prices $p_{export,t}$ and $p_{import,t}$ discussed in section 2.3., only. The quantities to be traded (if any) are calculated on the base of time series and the demand curve discussed in sections 2.2.2. Calculations are performed on a year-by-year base leading to the gains from foreign trade G_y in year y:

$$G_y = \sum_{t \text{ during year } y} \left[p_{export,t} \cdot E_{\text{sur},t} - p_{import,t} \cdot E_{lack,t} \right] \tag{8}$$

Eqn. (8) requires both $E_{\text{sur},t}$ and $E_{lack,t}$ to be normalized to the length of a time interval Δt. Moreover gains from foreign trade G_y are considered under different scenarios that are defined and summarized in Tab. 2.

Finally, the advantage A_{V2G} of the V2G concept is defined considering the maximum spread of the scenarios studied as

$$A_{y,V2G} = G_{y,V2G,consumption} - G_{y,no\ V2G,no\ consumption} \tag{9}$$

Fig. 4 shows results for years $y = 2017 \dots 2050$ for $A_{y,V2G}$, $G_{y,V2G,consumption}$, $G_{y,V2G,no\ consumption}$, and $G_{y,no\ V2G,no\ consumption}$, related to the number of EV. $A_{y,V2G}$ (solid line) is always positive, reflecting the fact that it is always more economic to use internal storage (here: the V2G storage) than buying and selling electricity externally (foreign trade).

In this scenario the maximum advantage of implementing V2G will be reached in 2044: the record advantage of more than 11 bn EUR will be reached by reducing losses due to external trade from 17 bn EUR to roughly 6 bn EUR. These said losses in external trade are expected both due to the necessity to purchase electricity at high prices in times of low national generation and the non-advantageous sales of surplus energy during times of high (volatile) generation.

Table 2: Definitions of Gains from Foreign Trade in Different Scenarios

Quantity	Scenario
G_y	basic definition as given in eqn. (8)
$G_{y,V2G,consumption}$	V2G is applied and EV are supplied from the energy stored by V2G
$G_{y,V2G,no\ consumption}$	V2G is applied and EV are supplied from public grid as additional load
$G_{y,no\ V2G,no\ consumption}$	No V2G, but EV are supplied from public grid as additional load

Whereas the absolute benefit is projected to peak in 2044, the relative benefit per EV participating in V2G would have its maximum in 2023, i.e. one year after the projected exit of nuclear power. At this time period comparatively low export is expected to meet high import rates. Again, this is a situation where V2G will add beneficial storage capacity. Since the number of EV is still expected to be modest in 2023, the specific benefit of each EV participating in V2G will be high and subsequently peak in 2023 with the given boundary conditions.

It can be observed in Fig. 4 that starting from 2038 the inclusion of loading the EV ($\mathrm{i.e.:}\ G_{y,V2G,consumption}$) is allowing ever higher benefits compared to non-including the loading of EV (which means: $G_{y,V2G,no\ consumption}$). The reason is the increased contribution of VRE solar PV and wind, both of them leading to a frequent SOC = 100% during daytime (when consumption during transport would typically occur at most). This scenario yields estimated sales prices that are such unattractive that it is better much better for the utility to provide the energy for purposes of EV loading (consumption).

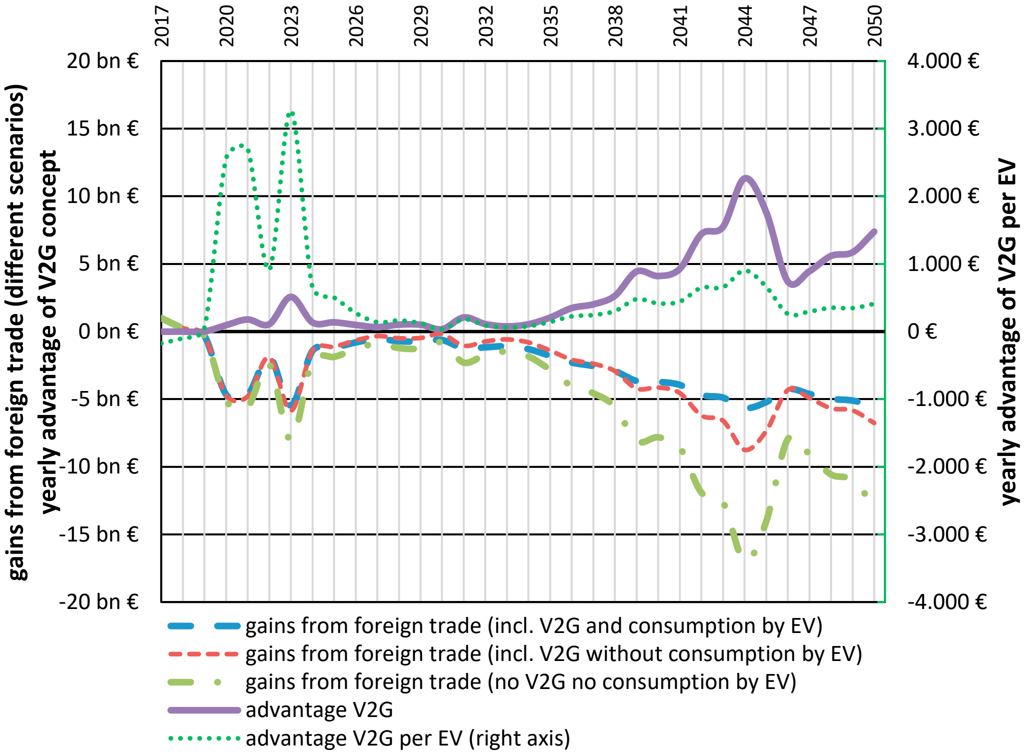

Fig. 4 gains from foreign trade and advantage of V2G. Definitions given in tab. 2 and eqn. (9).

The fact that it may be more advantageous for the utility to offer electricity during high surplus situations to the V2G participant can be expanded further. Typically, already the generation cost for electricity is higher than $p_{export,avg}$. According to eqn. (1) it is likely that when generating a lot of surplus electricity the achievable sales price will be even lower or become negative. If the utility can provide the participating EV during this time with electricity at prices below standard tariffs but e.g. higher than $p_{export,avg}$, the benefit is shared between EV customer (who has bought energy and thus mobility at better conditions compared to standard tariffs) and the utility (which avoids poor sales prices in foreign trade). The exact share of benefit and modality must be agreed upon between utility and EV customer. The advantage for the customer should in principle be added to the total advantage $A_{y,V2G}$ to map the full advantage for the economy. We have modelled some approaches and found that a substantial boost can be tagged to such approaches. However, this invokes much more complex modelling including in depth assumptions about the driving habits of EV users. We refrain from presenting such results in this report as we do not want to distract the reader from the core results. However, it can be stated, that $A_{y,V2G}$ serves as a minimum estimate for the total benefit for the national economy, only.

The general increase of A_{V2G} over time (as shown in Fig. 4) partly relates to a decrease in the necessity to trade electricity with foreign markets. Fig. 5 shows the comparison between the V2G concept realized (solid line) and scenario without V2G (dashed line). The total installed storage capacity is an important prerequisite for the growth of A_{V2G}, but it is not the only one as can be seen by comparison with Fig. 4: Prices are varying over time and the match of the storage size in combination with the mix of energy sources plays as a major role as will be discussed in the following paragraph.

The benefit of exploiting V2G is of course linked to a well-balanced ratio between the storage size of the available battery capacity in relation to the balance between energy to-be-stored (surplus energy) and the storage size. A strong dependency of this ratio has been demonstrated earlier for the case of autarky in residential PV systems comprising battery storage [18]. For our current work this has been confirmed for the exemplary predictive calculation of the year 2022. If the surplus energy is varied from 8% (share of the entire energy generation) to 2%, the number of hours with SOC = 100% (V2G batteries fully charged) can be substantially reduced from 3500 h to 1800 h. From a profitability point-of-view it is the better option to operate less frequent at SOC=100% since this allows to take better advantage of the entire battery capacity. The signature of this effect is comparably large in 2022 as the number of EV available will still be modest.

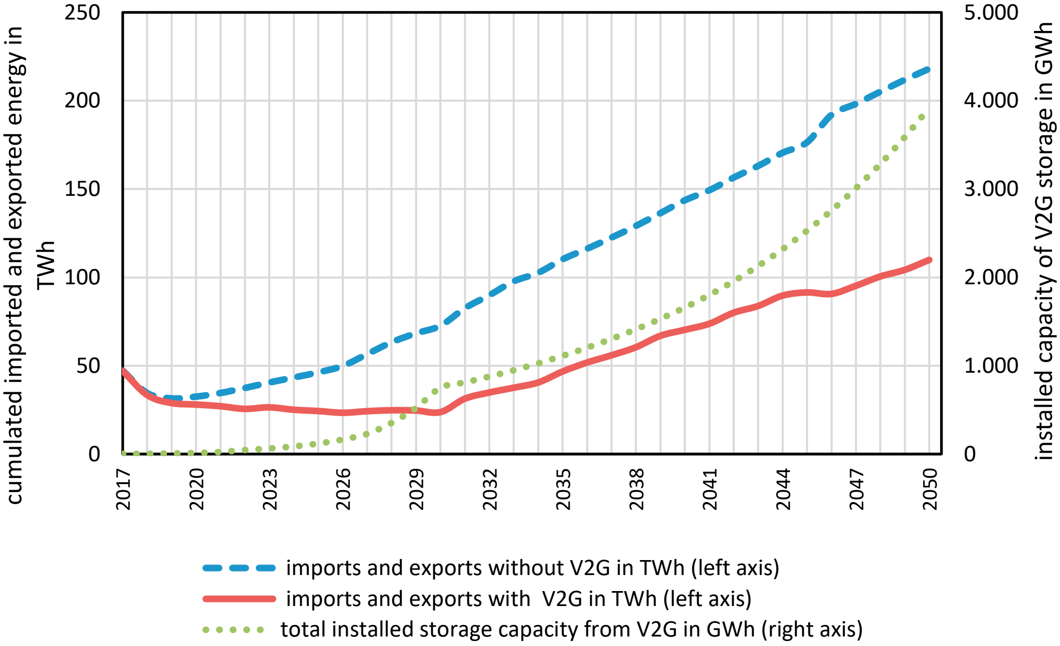

Fig. 5: cumulated imported and exported energy for V2G scenario and default (no V2G). As additional information the total installed storage capacity in the V2G concept is given (dotted line).

3.2. Impact of RE Volatility, Infrastructure Nominal Power, and Storage Size

It is instructive to investigate the impact of volatility of RE production. A hypothetical scenario is calculated for the year 2036 with a projected share larger than 60% RE. Further simulation parameters assumed for 2036 are an average battery capacity of 135 kWh of 7.6 Mio EV participating and an infrastructure capable to handle in average $P_{bidir,max}$= 7 kW. The volatility of RE sources can vary between very intermittent (PV solar), medium intermittent (wind) and not intermittent (biomass and hydro). The impact of the type of intermittency on $A_{y,V2G}$ is given in Fig. 6a and 6b.

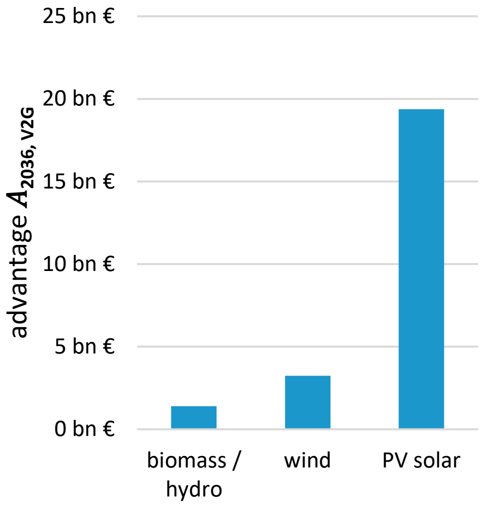

Fig. 6a: total advantage $A_{2036,V2G}$ under assumption that the 60% share would be supplied from RE sources of different intermittency / stability

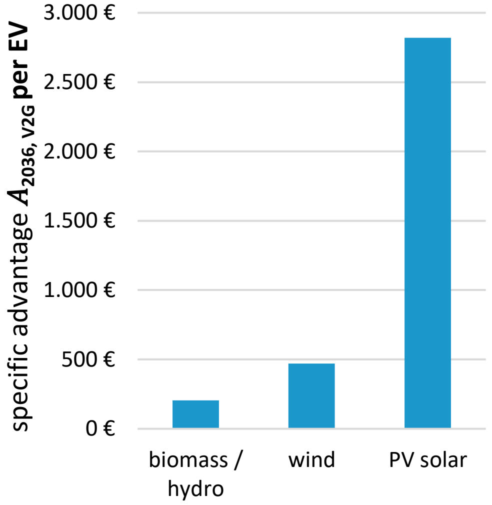

Fig. 6b: specific advantage $A_{2036,V2G}$ per EV under assumption that the 60% share would be supplied from RE sources of different intermittency / stability

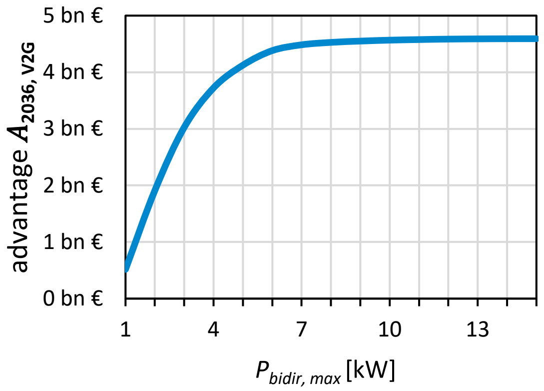

Fig. 7a: total advantage $A_{2036,V2G}$ with variation of the nominal maximum power of the infrastructure $P_{bidir,max}$. Battery capacity of $\bar{C}$ is set to 135 kWh.

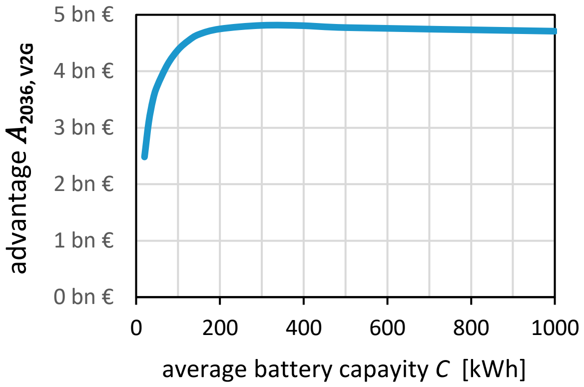

Fig. 7b: total advantage $A_{2036,V2G}$ with variation of the battery capacity $\bar{C}$. The maximum power of the infrastructure $P_{bidir,max}$ is set to 15kW.

As interim result it may be stated that the V2G advantage will deliver maximum results if the energy supply is highly intermittent (i.e. demand for storage) and at the same time surplus energy is comparatively small (storage can be exploited best when operated not too often close to SOC=100%).

Starting on the preceding investigations another parameter variation is of interest: The parameters “battery size” $\bar{C}$ and “power rating of the bidirectional infrastructure” $P_{bidir,max}$ for charge and discharge are varied. The scenario builds again on a prediction for the year 2036 with a projected share of beyond 60% RE and of 7.6 Mio EV participating in V2G. First, the infrastructure’s nominal power $P_{bidir,max}$ is varied with a projected average battery capacity of $\bar{C}$ =135 kWh. Calculations are impacted through eqns. (5) and (7). Results are shown in Fig. 7a. As infrastructure’s nominal power $P_{bidir,max}$ does level off, a value of $P_{bidir,max} = 15\text{kW}$ was chosen to study the impact of average battery size $\bar{C}$ as shown in Fig. 7b.

The results shown in Figs. 7a and 7b are provide guidance is given for the practical design of the hardware associated with V2G: The infrastructure does not need to provide power ratings beyond 7 kW, a requirement that can be realized at comparable low cost by connecting to the LV mains. At the same time a development target of 200 kWh per EV storage capacity seems sufficient to satisfy V2G requirements in the future.

4. Conclusions

V2G offers additional storage distributed in the electrical grid. The advantage of this very large storage for the national electricity supply is of course the possibility to level out peaks and valleys in generation or – to be more general – in the timely mismatch between generation and demand. Typically, these load-demand-mismatch situations can be balanced through import/export with neighbour countries. From an economic point-of-view, V2G is less cost intense (compared to import/export) and creates profit. Even when the profit is shared between the utility and all participating V2G providing individuals, there is yearly Bn. EUR gross profits possible. It must be noted, that in certain cases this approach might encounter limits e.g. when a high portion of renewable energy is due for export, the prices might be poor as similar meteorological could be present in neighbour states. However, these effects cannot be fully quantified today. Other factors, as possible savings due to avoidable cost for transmission line expansion have not investigated, but it is obvious that V2G will be beneficial due to its distributed nature and the possibility of load levelling / peak shaving.

The study shows that V2G can contribute to manage the challenges from future more volatile energy generation (PV, wind). V2G promises a considerable financial benefit for both energy generating / distributing companies and private users. In this respect it is important to emphasize that the optimum for the bidirectional V2G pole has been found to be as low as 7 kW, meaning that this is not targeting to “fast charging” technology. Comparatively slow charge and discharge processes (manageable with comparably cheap standard LV technology comparable to so called “wall box” system) are the adapted time frame. Under this assumption the investment cost for the bidirectional poles will be not unreasonably high, as they are expected to be related to ICT as smart-grid devices, only.

Often, EV infrastructure is associated with fast charging facilities, which is an expensive choice due to the usually required connection to the MV grid. Moreover, only little possibility for price digression for such MV connections is expected [19]. In turn, V2G puts only negligible emphasis on the time-to-charge, since the addressed target participant uses the EV with a high share of idle time. In this respect the V2G concept contributes to change the paradigm of EV charging. V2G entails no longer the concept of queuing at a gas station to fill the tank of a combustible engine. V2G reflects rather the concept known from consumer electronics permanently connected to the grid: Charging is then no longer an activity deliberately looked after by the user, but it happens permanently in the background – and provides at the same time ancillary services (load/generation levelling, provision of EES) to the public grid.

It should be added that despite the fact that this work is presented within the framework of a highly developed country like Germany, the results are considered transferable to other countries (including less developed countries) . The example of India shows, that a strong growth potential for EV and in consequence for V2G may be assumed. As has been stated, the integration into the LV distribution grid is a comparatively low financial barrier.

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