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Impact of V2G Flexibility on Congestion Management in the German Transmission Grid

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Executive Summary

In this study, we investigate the effect of vehicle-to-grid (V2G) flexibility potential on solving transmission grid congestion in Germany using congestion management measures. We determine the flexibility provided for improving grid operation based on mobility behavior and findings on V2G user requirements from real-world EV users. The impact on transmission grid operation is analyzed using an optimal congestion management model with high temporal and spatial resolution. Using a scenario for the year 2030 with ambitious targets for European renewable generation development and electrification of private vehicles, our findings show that by enabling the available fleet of V2G vehicles to participate in congestion management, cost and amount can be reduced by up to 11 %. However, the required capacity is shown to be lower than installed capacities in ambitious future scenarios, implying that a limited amount of vehicles close to congestion centers will be utilized for transmission grid operation.

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

1 Introduction

The ongoing transformation towards a more sustainable energy system is driven by concerns about the impact of traditional energy sources on the environment and climate change. To mitigate these concerns, alternative sources of energy and ways to improve energy efficiency are necessary. One of the most promising options is electrification across different sectors in combination with increased electricity generation from renewable energy sources (RES), which are becoming increasingly cost-competitive. In the European electricity system, the share of renewable energy sources has been rising steadily in the last few years, and several countries have set ambitious targets to increase this share further. In addition to the increasing RES share in electricity systems, the electrification of different sectors, such as transportation, heating, and cooling, is also gaining momentum. In the private transportation sector, electric vehicles (EVs) are increasingly popular due to governmental subsidies, reduced carbon emissions, declining cost, and increasing range of the vehicles' battery package. The diffusion rate of EVs is expected to continue, with many governments setting targets for EV adoption. For example, the newly elected government has formulated a new medium-term target of 15 million EVs in Germany by the year 2030 [1]. However, the anticipated increasing electrification of privately owned vehicles presents new challenges for electricity grids, as uncontrolled charging of EVs can lead to synchronous charging behavior, resulting in significant electricity demand peaks and additional stress on the grid [2]. Vehicle-to-grid (V2G) technology has been proposed as a possible solution to this challenge. V2G technology provides a decentralized source of flexibility that can mitigate the increase of existing peaks in today's electricity patterns and perspectively improve RES integration potentials when used effectively in grid congestion management. In addition, V2G technology can partially substitute the role of redispatch power provision of thermal power plants and other storage technologies and lead to more economical and ecological congestion management.

In this study, we combine EV flexibility modeling and an optimal congestion management model from the German research projects *Bidirectional Charging Management* (BCM) and *New energy grid structures for the German Energiewende* (ENSURE) to investigate the potential impact of V2G technology on the German transmission grid. We take into account results from a study on user requirements for V2G performed in the project and present results for the impact of V2G technology on congestion management using a case study of the European electricity system in 2030.

2 Modeling of V2G in transmission grids

To assess the potential impact of large-scale use of V2G on the transmission grid, a model cascade was developed by combining project findings on user requirements and diffusion modeling of projected EV uptake. This approach allows for the estimation of time-dependent V2G flexibility potentials. To quantify the potential benefits of V2G technology, the flexibility shifting potential of charging operations was analyzed in the simulation of the transmission grid. This enabled the identification of the most congested grid areas, where V2G could be most effective in alleviating grid stress. The modeling framework used in this study is illustrated in Figure 1, which provides a schematic overview of the model cascade. The framework begins with a detailed analysis of V2G user requirements, which takes the individual preferences of EV owners into account. This information is then combined with diffusion modeling of EV uptake, predicting future EV adaption. The resulting time-dependent V2G flexibility potentials are then utilized to perform the simulation of the German transmission grid and evaluate the benefits of reducing congestion management measures in different scenarios.

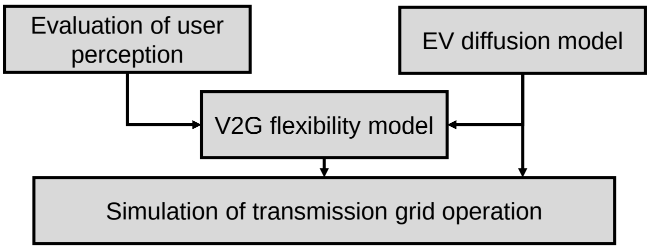

Figure 1: Model overview

2.1 User requirements

The bidirectional charging process directly involves the EV user, which makes the EV user one of the primary actors within a V2G system [3]. To enable a successful implementation of V2G technology, it is therefore important to actively engage the user while dismantling perceived barriers, such as a perceived loss of control over the charging process [4-6] or concerns of a shortened battery life due to V2G [5] One way to foster user acceptance is to account for charging requirements, which can be defined by the EV user. The minimum range is such a requirement. We define it as the minimum necessary range that EVs must always be able to cover in unpredictable cases, for example, an emergency case. [7]. It is also an essential parameter from an aggregator's point of view, as it defines the flexibility potential made available by the EV user.

In this study, we account for user requirements by integrating the results of the minimum range from a representative survey (N=1196) conducted in January 2021 to investigate i.e. the relevance of minimum range requirements in the context of a V2G charging tariff. As previous studies highlight the importance of EV experience to create informed decisions about issues in the realm of V2G [8,9], we addressed our survey to three stakeholder groups with different levels of EV experience (see [7] and asked respondents to provide their minimum range (SoC_{min}) requirements in an open-ended question. The question referred to a BMW i3 with a range of 270km. The results in Table 1 show that EV users indicated the lowest SoC_{min} values, which is equivalent to approximately 40% of the battery capacity of a BMW i3. Previous field studies with EV participants found similar values [10]). In this study, we report the average minimum range (SoCmin=110km) for the EV-owner group (n_{high}=264), as this group is the most experienced with EVs and therefore provides the most realistic values (see [7].

Table 1 EV-owners' minimum range requirements

Sample	[in km]							
	M	SD	SE	Min	Max	$q_{0,25}$	$q_{0,5}$	$q_{0,75}$
N=1196	119.01	98.37	2.84	0	500	50	100	150
N_{low}= 691	119.75	97.91	3.73	0	500	50	100	150
N_{med}= 241	126.05	104.78	6.75	15	500	50	100	150
N_{high}= 264	110.64	93.16	5.73	1	500	50	100	120

2.2 EV diffusion

The technology ramp-up of electric vehicles (EVs) in Germany was assessed using the Bass diffusion modeling approach, similar to [11]. The Bass diffusion model is a commonly used approach for assessing the adoption of new technologies[12]. The model is based on the assumption that the spread of new technologies often follows an S-curve pattern. The interplay between present and potential adopters, called innovators (q) and imitators (p), is central to the Bass diffusion model. The market potential is denoted by M, and t represents the index for the specific year being considered. The model forecasts fleet sizes for every year since the start year t_0, where the difference between the current year t and the start year t_0 is $t - t_0 = 0$. A formal description of the Bass diffusion model can be found in Equation (1), whereby $N(t)$ represents the number of cumulative adoptions up to a given time t.

$$N(t) = m \, \frac{1 - e^{-(p+q)(1-t_0)}}{1 + \frac{p}{q} e^{-(p+q)(1-t_0)}} \tag{1}$$

Considering the annual EV stock, assumptions about government EV registration targets, and the assumption that eventually, all internal combustion engine vehicles will be replaced by EVs, the equation parameters of the innovation and imitation coefficients are calculated. More precisely, a non-linear regression method using the Levenberg-Marquardt numerical optimization algorithm is employed to estimate the parameters of the Bass EV diffusion model.

2.2 EV flexibility

The V2G flexibility model is designed to generate representative, synthetic charging and flexibility profiles and thus estimate the V2G flexibility potential of EVs in Germany [13]. An overview of the methodological approach is illustrated in Fig. 2. In the first step, parking and mobility profiles are created based on data from the German Mobility Panel) [14]. The underlying data set contains plausibilized data from 1,850 households with a total of 3,074 persons and 70,252 trips. Subsequently, the charging behavior of the EV is simulated by the additional user-specific input data on EV and information on the charging infrastructure. Battery capacity, energy consumption, as well as the availability of charging points per location and associated charging power (selectable charging power of 3.7 kW, 11 kW, 22 kW and 55 kW) per charging point are set as parameters at the beginning of the simulation. The input parameters are assumed to be identical for all EVs and the time resolution is 10 minutes.

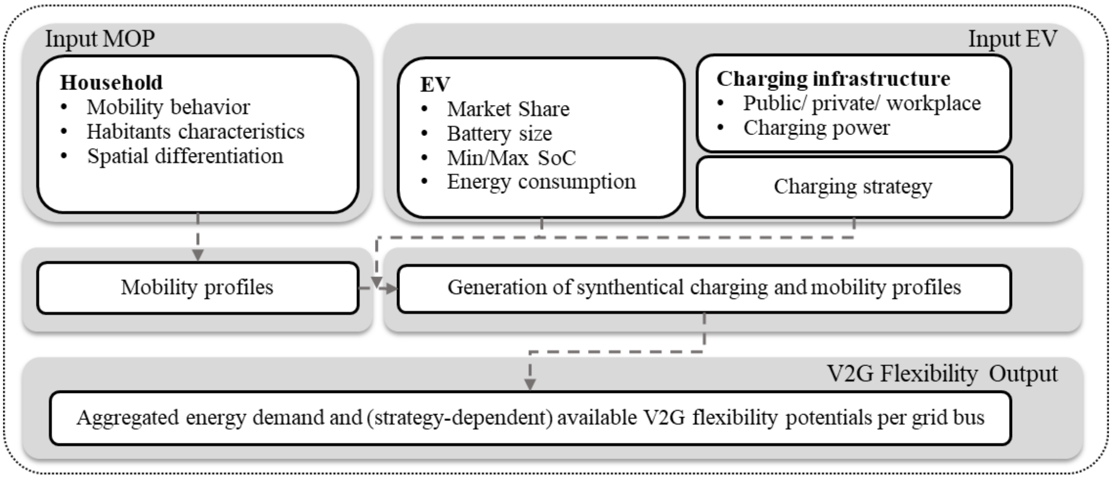

Figure 2: V2G flexibility model

In addition, different charging strategies are implemented. One charging strategy is the so-*called as soon as possible* (ASAP) strategy. Here, the vehicle is charged immediately with the maximum SoC-dependent charging power available at the charging location up to the maximum SoC level or until the departure time for the next trip. Another strategy is based on the assumption that EVs will start charging as late as possible during parking periods with charging opportunities while simultaneously considering user restrictions. The safety range (the range to which charging should take place as soon as possible after arrival at a charging station) and the target range (the range to which charging should take place as soon as possible before a journey until the start of the journey) are taken into account. After arrival at a charging station, charging takes place on the one hand as early as possible to a safety range and on the other hand as late as possible to a target range (target range >= safety range), which is to be reached at the time of departure.

The amounts of energy required for the journeys are determined based on the distances driven and the energy consumption. This results in the necessary energy demand for the charging processes. The maximum amount of energy that can be charged is then determined for each time step. This depends on the parking time, the charging status of the vehicle battery and the available charging infrastructure at the respective locations of the vehicles [13].

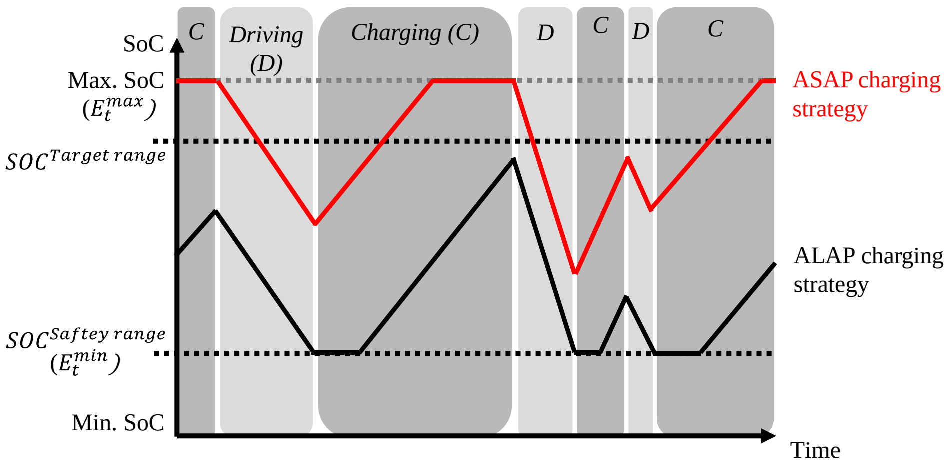

Figure 3: Schematic representation of the V2G flexibility potential and upper and lower bounds

Synthetic charging and mobility profiles are derived based on the mobility profiles and by simulating the charging behavior. These representative charging profiles can then be evaluated and interpreted regarding energy demand and V2G flexibility of the charging process. To integrate flexibility in the grid model, user requirements and the corresponding EV market ramp-up are considered in the flexibility model in the user-specific EV input data scope. Based on the user requirements and the EV market penetration, the model can be used to estimate the flexibility potential. The V2G flexibility potential can be estimated considering the implemented charging strategies. The ASAP charging strategy sets the upper limit for the allowed SOC. The second charging strategy sets the lower SoC limit. The area between the charging states of the two extreme SoC levels represents the permissible range for the SOC and, combined with the available charging power, describes the flexibility potential.

2.3 Transmission grid

Using a multi-objective optimization approach, we have developed a framework to investigate the optimal congestion management in the interconnected European transmission grid. The approach allows us to examine the role of EVs that need to be considered in the liberalized power market, such as congestion cost, additional carbon emissions, as well as deviations from market-based dispatch results, based on a formulation developed in [15,16]. The model is applied to the central European electricity market, with the grid simulation focusing on congestion management measures in Germany. We utilize highly spatially resolved time series of renewable generation and demand using data and methododlogy described in [17].

To model the interaction between the electricity market and congestion management, we use a two-step approach. In the first step, we determine the optimal dispatch of electricity generation in the interconnected market using linear programming. This approach considers various parameters such as fuel prices, generator capacities, and transmission constraints to identify the most cost-efficient solution for meeting electricity demand. The results of this step provide the minimal-cost, copperplate-based dispatch solution for the electricity market on a national level , with the objective function shown in Equation (2). For every timestep t, each of the systems elements are assigned a variable cost term C that is multiplied by the amount of generation p, with the set of thermal and hydraulic generation G, renewable generation source RES, decentral flexibility elements F and electricity demand D. In case of the last-mentioned, cost occur when load shedding LS is required.A more detailed description of the formulation can be found in [18].

$$min \sum_{g\in G,t\in T} C_g * p_{g,t} + \sum_{res\in RES,t\in T} C_{RES} * p_{res,t} + \sum_{f\in F,t\in T} C_F * p_{f,t} + \sum_{d\in D,t\in T} C_{LS} * p_{d,t} \quad \forall g \in G,\ res \in RES,\ f \in F,\ d \in D,\ t \in T \tag{2}$$

The linear formulation of a storage system can be modelled using the generalized formulation shown in Equation (3). The available energy $e_{s,t}$ of storage s in time step t is determined by the available energy in the previous time step $t-1$, charged power $p_{g,t}^{in}$ and discharged $p_{g,t}^{out}$ with their respective efficiency η and external energy inflows $\zeta_{s,t}^{in}$ and outflows $\zeta_{s,t}^{out}$.

$$e_{s,t} = e_{s,t-1} + p_{g,t}^{in} * \eta_{g,in} - p_{g,t}^{out}/\eta_{g,out} + \zeta_{s,t}^{in} - \zeta_{s,t}^{out} \ \forall s \in S, t \in T \tag{3}$$

When applying Equation (3) to V2G charging, the available energy is provided by the car battery, efficiency is determined by losses within the vehicle and in auxillary equipment such as the wallbox, while the mobility demand results in a irregular outflow. For single vehicles, charging and discharging power is zero during driving or when they are not plugged into a charger. Using the fleet flexibility potential aggregation of the V2G flexibility model shown in Figure 3, this can be expressed by Equations (4)-(7), where the bounds of the EV fleet storage state e_t , .charging and discharging capacity p_t are determined by the time-variant upper and lower bound depending on the composition of plugged-in and unavailable EVs. The external energy outflow $\zeta_{,t}^{out}$ is defined as the energy used at the time of plug in E_t^{mob} for mobility requirements since the previous plug-in. Using a fleet-wide aggregation of V2G flexibility can lead to the violation of individual storage state constraints, however, also implicates a large advantage in computational complexity compared to a discrete modeling approach.

$$E_t^{min} \leq e_t \leq E_t^{max} \ \forall \ t \in T \tag{4}$$

$$0 \leq p_t^{in} \leq P_t^{in,max} \; \forall \, t \in T \tag{5}$$

$$0 \leq p_t^{out} \leq P_t^{out,max} \; \forall \, t \in T \tag{6}$$

$$\zeta_t^{out} = E_t^{mob} \; \forall \, t \in T \tag{7}$$

In the second step, we determine the required dispatch adjustments using a linearized optimal power flow formulation as described in [19]. This step accounts for the V2G flexibility potential developed by implementing available capacities and bounds from the V2G flexibility model previously described. The calculation is performed for 8760 timesteps with consecutive weekly optimization horizons, formulating the objective of congestion management as minimization of the total amount of congestion measure volume in an analogous manner to [19]. Equations (3)-(7) can be applied in an analogous manner, with the nodal EV density being determined by the regionalization developed in [17]. Overall, this two-step approach provides a comprehensive framework for modeling the interaction between the electricity market and transmission grid operation.

3 Case study

Using the methodology presented previously, a case study was conducted to evaluate the possibility of deploying V2G to solve grid congestion. The study was carried out for the German high-voltage transmission grid in the year 2030 using a scenario developed in the project ENSURE [20].

To determine the scenario-dependent V2G flexibility potential, the input parameters shown in Table 2 are defined. Here, the minimum range and the safety range from Chapter 2.1 are taken into account. At the same time, two different market shares are included in the analyses, which result from the results of the bass diffusion model. Altogether, we investigate the impact of V2G in four scenarios, with three alternative parameter sets from the *Base* scenario : The scenario *Work* extends bidirectional charging availability from purely home-charging to workplace charging, which significantly reduces peak charging demand in case of immediate charging (ASAP) as can be seen in Figure 4. Furthermore, available flexibilities during working hours are increased for market and grid utilization.

Table 2 Scenario related input data

<table>
<tr><th>Scenario</th><th>BEV count</th><th>Charging location</th><th>Charging power</th><th>Battery capacity</th><th>Consumption</th><th>Efficiency</th><th>Availability market</th><th>Availablilty grid operation</th><th>Safety range</th><th>Target range</th></tr>
<tr><td>Base</td><td rowspan="2">15 mio.</td><td>Home-charging</td><td rowspan="4">11 kW</td><td rowspan="4">50 kWh</td><td rowspan="4">15 kWh/100 km</td><td rowspan="4">90 %</td><td rowspan="3">100 %</td><td rowspan="4">100 %</td><td rowspan="4">40 %</td><td rowspan="4">56.2 %</td></tr>
<tr><td>Work</td><td>Home- & workplace-charging</td></tr>
<tr><td>Reduced</td><td>10 mio.</td><td>Home-charging</td></tr>
<tr><td>Grid</td><td>15 mio</td><td>Home-charging</td><td>20 %</td></tr>
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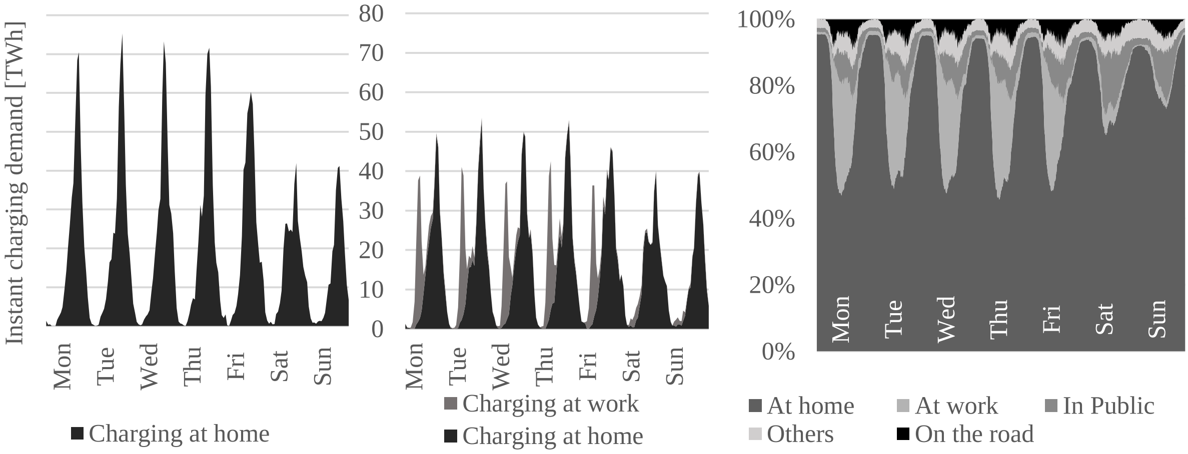

Figure 4: V2G charging demand in ASAP mode for scenario *Base* averaged over vehicle fleet, one week (left) and scenario *Work* (middle) and distribution of EV location over one week (right)

The available flexibility potential for the scenarios *Base* and *Work* is shown in Figure 5. In the home-charging scenario, available charging power decreases, with only half of the total capacity during midday on business days. On the EV fleet averaged level, available SoC upper bound levels remain consistently very high, as most of the charging unavailabilities are not connected to driving but parking at locations without charging equipment, which can be seen in the visualization of mobility behavior in Figure 4. Consequently, the relative change of total available charging power at midday is more significant than the change of the upper and lower SoC bounds for the scenario *Work*.

To estimate the innovation and imitation coefficient, a non-linear regression method was applied to both historical EV fleet data [21] and future EV fleet size targets [1]. Using these inputs, two EV ramp-up scenarios were developed. The first scenario *Base* aligns with the current government's objective of reaching 15 million EVs by 2030, while the second reduced transition speed scenario *Reduced*, was devised with the aim of achieving a number of 10 million EVs by 2030. Both variants assume that, eventually, all conventional vehicles will be replaced by EVs. EVs are expected to be the primary choice for meeting vehicle emission reduction targets, supported by increasing investments in charging infrastructure and major vehicle manufacturers' upcoming lineups of EVs. Additionally, the German vehicle fleet size is assumed to remain constant. However, trends such as autonomous driving and car sharing could lead to smaller vehicle fleets in the long term. As quantifying such effects is challenging and rapid changes in the individual mobility sector until 2030 seem unlikely,in the investigated scenarios, the fleet size is assumed to remain constant. Figure 6 displays the forecasted yearly EV fleet sizes for both scenarios.

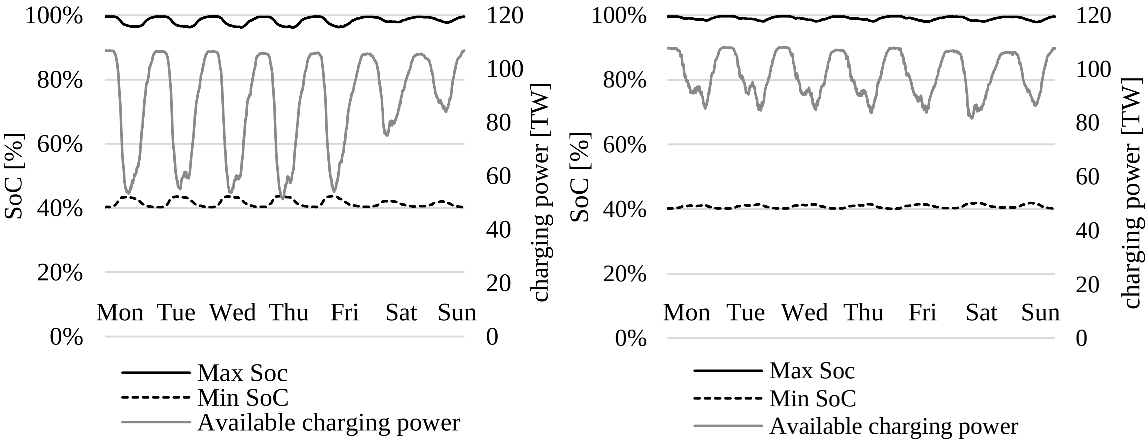

Figure 5: left: V2G flexibility potential for Base (fleet averaged, one week; charging availability at home), right: V2G flexibility potential (fleet averaged, one week; charging availability at home and at work)

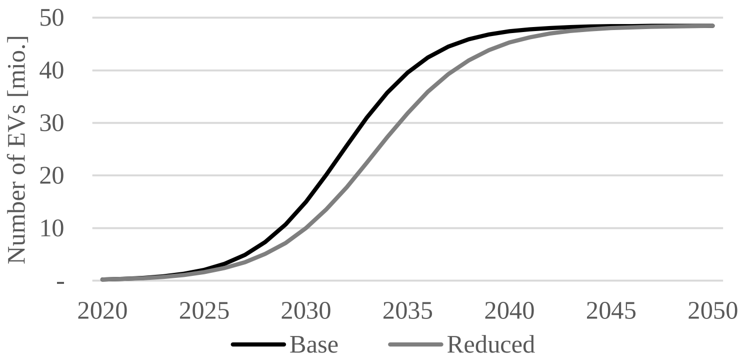

Figure 6: Development of EV adoption in Germany for scenarios Base and Reduced

Though the current diffusion of EVs is still in its early stages, the model predicts that the adoption rate will speed up, especially after the year 2025. The model also suggests that by the end of the 2030s, market saturation can be anticipated, leading to a reduction in the number of new EVs entering the market. Based on the two scenarios considered, nearly the entire German car fleet of over 48 million vehicles will be replaced by EVs between 2042 and 2045. Considering the predicted annual vehicle registrations of up to 5.5 million in the base scenario and up to 4.8 million annual EV registrations in the reduced scenario, the scenarios can be considered as an optimistic upper bound when compared to yearly historical passenger car registrations in Germany, which averaged at about 3.5 million annual vehicle registrations [22]. In the fourth scenario *Grid*, the participation rate of V2G vehicles in the electricity market is reduced to 20 % by limiting the available charging and discharging power uniformly. Charging and discharging power for transmission grid operation remains the same, thus assuming an option for the transmission grid operator to utilize available flexibility when it is needed due to transmission grid congestion, even if the user does not participate in the electricity market.

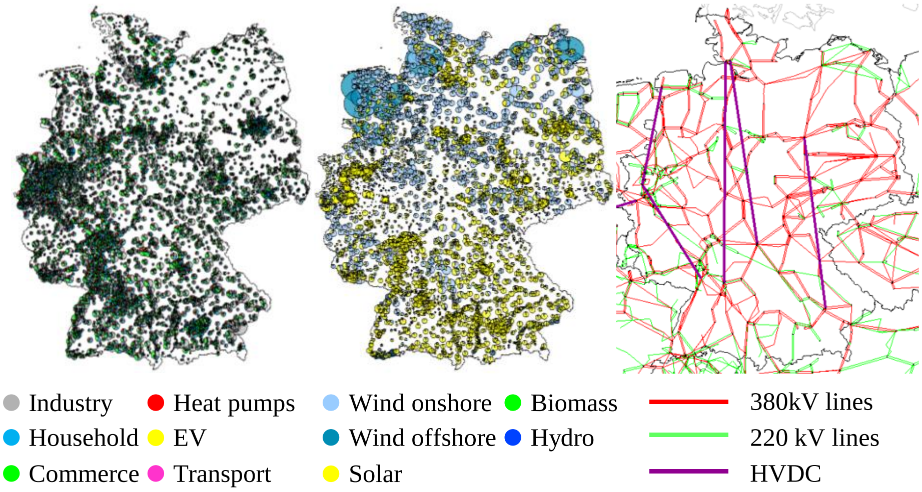

Figure 7: Demand allocation (left), RES allocation (center) on high voltage level and transmission grid model (right) of Germany

On the transmission grid level, a dataset for Germany, including overhead lines and cables above 200kV, AC and HVDC lines connected to busbars, and the present state of the grid with projected expansions until 2030, is used. The grid dataset is connected to the regionalized data on the high voltage level via transformers from extra high voltage levels to high voltage levels between 60 and 150kV using the methodology described in [18]. The data include the present state of the transmission grid as well as projected expansion measures in terms of deconstruction, replacement and construction of substations, busbars, lines and transformers until the year 2030, as detailed in the German network development plan. Technical data was derived from publicly available sources or approximated based on comparable equipment.

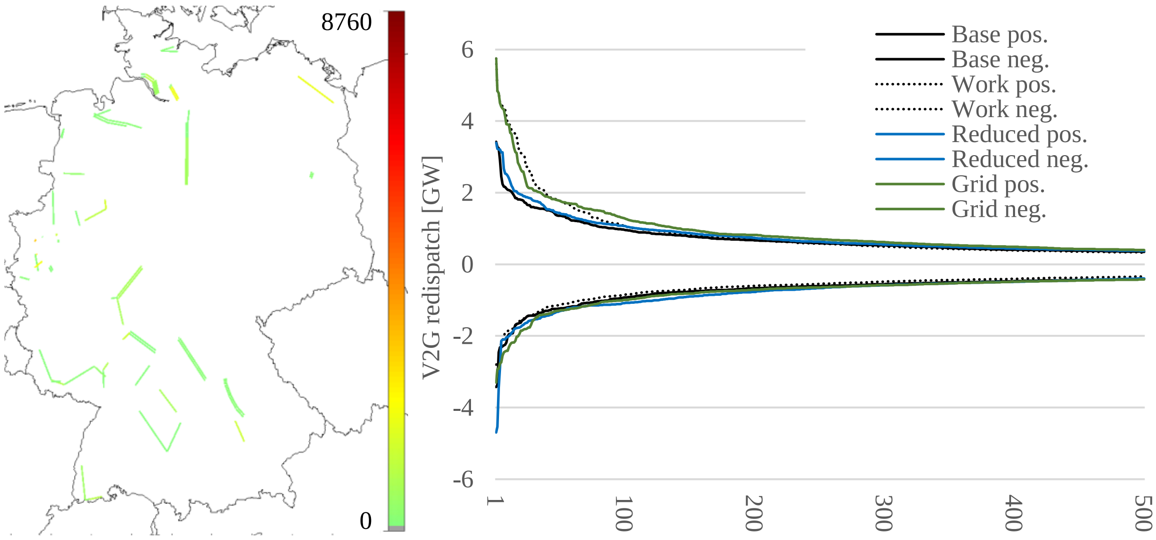

Figure 8: Congested transmission grid lines without V2G flexibility (left) and ordered hourly positive and negative V2G congestion management utilization for each scenario (right)

4 Results

The underlying assumptions in the energy scenario assumed in this case study lead to increased utilization of the German transmission grid, as the phase-out of coal generation and general reduction of available thermal generation capacities goes hand in hand with increased renewable generation, especially wind generation in Northern Germany. Subsequently, the increased interconnection capacities with neighbouring countries are used extensively, as spatial differences in renewable generation favor higher exchange volumes. The resulting required congestion management measures without V2G flexibility for grid operation are shown in Table 2. As adjustment of exchange flows is penalized, the main elements of congestion management in the scenario are positive thermal redispatch and curtailment of RES generation. This is due to wind onshore and offshore generation in Northern Germany being the main reason for the observed congestion. Figure 7 shows the spatial distribution of lines with active bounds in the optimization result, where congestion management measures have remediated line overloadings in the congestion-free solution. Here, the structural overloading of transmission lines in the North-South direction is observable. Negative thermal redispatch is the inferior solution when minimizing the volume of adjustments, as RES generation at the source of the congestion is more efficient in most hours. This result might differ when congestion alleviation costs are included in the objective function, as RES generation does not have variable costs, while the reduction of thermal generation units is economically beneficial. Maximum positive dispatch adjustment ranges from 3392 MW in the scenario *Work* to 5745 MW in the scenario *Reduced*, while minimum negative assignments range from -2797 MW in the same scenario to -4700 MW in scenario *Work*. The maximum simultaneous demand for congestion management is limited compared to the total available capacity from the entire EV fleet. A primary reason for this is that due to the wide distribution over the entire grid area, only limited capacities at suitable nodes are available.

The impact of including V2G as an additional source of flexibility in the model can be found in Figure 9. As expected, the volume of congestion management measures decreases for all scenarios. While the *Reduced* scenario results in the most considerable reduction, this scenario also reduces the EV electricity consumption

Table 3: Congestion management measures without V2G flexibility

[TWh]	Positive thermal redispatch	Negative thermal redispatch	Positive hydro redispatch	Negative hydro redispatch	RES curtailment	Exchange adjustment
Congestion management	16.10	0.20	0.35	0.38	16.02	0.21

and thus might lower congestion before flexibility usage. Both *Work* and *Base* scenarios lead to a comparable volume decrease. Both perform better than the *Grid* scenario with a lower participation factor when determining the national dispatch. This leads to the assumption that market-oriented dispatch of V2G is generally beneficial for reducing grid congestion, and additional measures are required when the initial V2G dispatch is lowered. The effect on CO_2 emissions and costs differs for the *Work* scenario on the one hand and the *Base* and *Grid* scenario on the other hand. While relative cost and CO_2 emission changes correlate very well for each scenario, both increase for the *Work* scenario while they decrease otherwise. This can be explained by the higher correlation between conventional electricity demand and the availability of charging at work, which is not beneficial for transmission grid operation in this scenario.

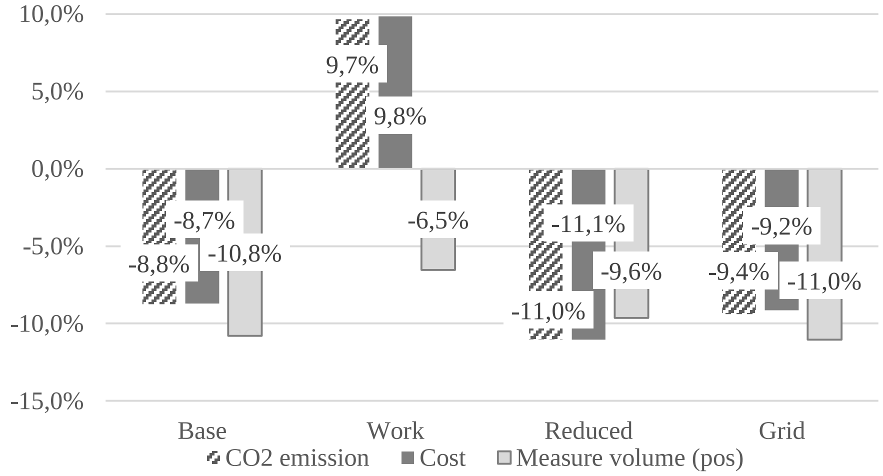

Figure 9: Congested transmission grid lines without V2G flexibility (left) and ordered hourly positive and negative V2G congestion management utilization for each scenario (right)

5 Conclusion

In this paper, we presented a model framework to investigate the impact of V2G flexibility on congestion management in the German transmission grid. We showed the impact of V2G for an ambitious scenario in the year 2030 derived from the research project ENSURE. The model cascade includes an analysis of V2G user requirements and diffusion modeling of projected EV uptake. This data has been used in the V2G flexibility modeling approach to derive time-dependent V2G flexibility potentials representing the input data and boundaries for the transmission grid optimization model. The simulation of the German transmission grid was conducted to identify the congested grid areas where V2G could be most effective in alleviating grid stress. The presented approach also accounts for the minimum range requirements of EV owners and assesses the adoption of EVs in Germany using the Bass diffusion modeling approach. The study shows that congestion management measures such as positive thermal redispatch and curtailment of RES generation are necessary to ensure the stability of the grid. However, the introduction of V2G as an additional source of flexibility can significantly reduce the volume of congestion management measures. The results suggest that market-oriented dispatch of V2G is generally beneficial for reducing grid congestion. Nonetheless, additional measures may be required when the initial V2G dispatch is lowered. The impact of V2G on CO2 emissions and costs varies depending on the scenario, with the Work scenario showing an increase in both, while the Base and Grid scenarios show a decrease. In future work, further decentralized flexibilities and interconnections between the European countries and their EV transition plans can be included to investigate the role of V2G for transmission grid operation.

Acknowledgments

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Presenter Biography

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