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

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Abstract: 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 extend existing work on effects of V2G on transmission grid congestion by determining the flexibility provided for improving grid operation based on mobility behavior and findings on V2G user requirements from real-world electric vehicle users. Furthermore, 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 number of vehicles close to congestion centers will be utilized for transmission grid operation. Our results further suggest that high numbers of vehicles with low availability of V2G for grid operation purposes can lead to an increase in congestion management measures, while V2G proves beneficial for congestion management emissions and cost in all scenarios.

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

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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 (RESs), 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 the RES share in electricity systems, the electrification of different sectors, such as transportation, heating and cooling, is 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 in existing peaks in today's electricity patterns and accordingly improve RES integration potential 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 [3] and lead to more economical and ecological congestion management. In previous studies on V2G technology, many aspects of the impact on the energy system have been investigated. While the majority of these works focused on electricity market integration and balancing markets, the impact on ultra-high voltage and high voltage grid expansion requirements has been studied in [4]. Refs. [5,6] have investigated the potential of EVs for congestion management in Germany and Austria, each using an aggregated model of the transmission grid. Furthermore, EV flexibility has been previously investigated as an element of aggregated decentralized flexibility potential for transmission grid operation [7].

In this study, we investigate transmission grid effects as well as detailed EV flexibility potential by combining approaches of EV flexibility modeling and an optimal congestion management model. We use the model cascade to investigate the potential impact of V2G technology on the German transmission grid for a future energy scenario. 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 potential. To quantify the potential benefits of V2G technology, the flexibility shifting potential of charging operations was analyzed in the simulation of the transmission grid. In this last step, all previously generated input data are utilized in an optimal power flow formulation using a minimal congestion management formulation. The results allow for the identification of the most congested grid areas, where V2G could be most effective in alleviating grid stress.

2.1. Model Overview

To investigate transmission grid congestion management actions, first, a detailed modeling of generation, consumption and flexibility behavior is required on a nodal level. Using these data, the grid operation and utilization of connected flexibility options are often analyzed using optimal power flow formulations. In this work we present an approach that includes V2G flexibility in an optimal congestion management formulation based on the basic optimal power flow. To generate the necessary data for EV charging behavior and flexibility potential for V2G operation, three submodels are used. The resulting modeling framework and the information flow 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 adoption. The resulting time-dependent V2G flexibility potential is then utilized to perform the simulation of the German transmission grid and evaluate the benefits of reducing congestion management measures in different scenarios.

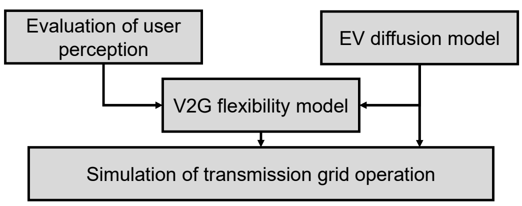

Figure 1. Schematic representation of the different model parts and input/output flow.

2.2. 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 [8]. 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 [9–11] or concerns of a shortened battery life due to V2G [10]. 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 [12]. 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 users' willingness to pay (WTP) and minimum range requirements in the context of a V2G charging tariff. Specifically, by building a mediation model, the study evaluates the importance of three charging strategies on users' WTP and minimum range requirements. The study reveals EV owners' preference for a climate-neutral charging strategy, leading to a higher readiness to accept lower minimum ranges and lower monetary savings [12]. As previous studies highlight the importance of EV experience to create informed decisions about issues in the realm of V2G [13,14], we addressed our survey to three stakeholder groups with different levels of EV experience (see [12]) 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 270 km.

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 [15]. In this study, we report the average minimum range (SoC_{min} = 40%) 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 [12]).

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

2.3. EV Diffusion

The technology ramp-up of electric vehicles in Germany was assessed using the Bass diffusion modeling approach, similar to [16]. The Bass diffusion model is a commonly used approach for assessing the adoption of new technologies [17]. 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.

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

The innovation coefficient q and imitation coefficient p of the model are estimated by fitting the S-curve derived from the Bass diffusion model to historic annual EV stock data [18] in Germany and planned registration targets for the year 2030. The delta between the S-curve and the input data is minimized by using a non-linear regression method. More precisely, a Levenberg–Marquardt numerical optimization algorithm was employed in the OriginPro Solver to estimate the parameters of the Bass EV diffusion model.

2.4. EV Flexibility

The V2G flexibility model was designed to generate representative, synthetic charging and flexibility profiles and thus estimate the V2G flexibility potential of EVs in Germany [19]. An overview of the methodological approach is illustrated in Figure 2. In the first step, parking and mobility profiles were created based on data from the German Mobility Panel [20]. The underlying dataset contains plausible data from 1850 households with a total of 3074 persons and 70,252 trips. Subsequently, the charging behavior of the EV was 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 were set as parameters at the beginning of the simulation. The input parameters were assumed to be identical for all EVs and the time resolution is 10 min.

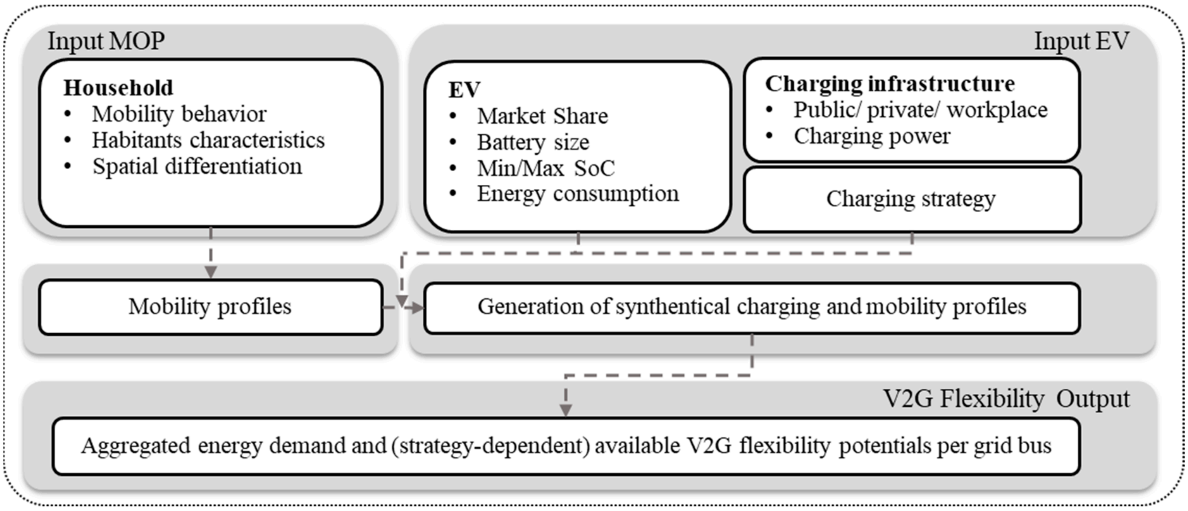

Figure 2. V2G flexibility model.

In addition, different charging strategies were implemented and shown in Figure 3. 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. We accounted for user restrictions by including the minimum range from Section 2.1, which is henceforth called the security range. 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) were 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 $\geq$ safety range), which is to be reached at the time of departure.

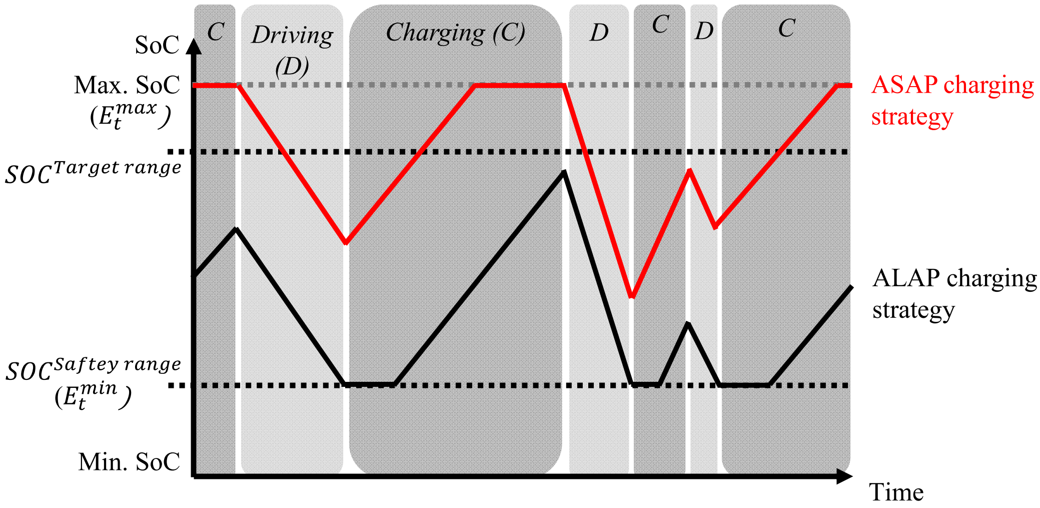

Figure 3. Schematic representation of the V2G flexibility potential and upper and lower bounds.

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 [19].

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.

2.5. 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 [21,22]. The model is applied to the central European electricity market, with the grid simulation focusing on congestion management measures in Germany. We utilized highly spatially resolved time series of renewable generation and demand using data and methodology described in [23].

To model the interaction between the electricity market and congestion management, we used a two-step approach. In the first step, we determined the optimal dispatch of electricity generation in the interconnected market using linear programming. This widely used and described economic dispatch approach [24] 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 system's 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 the case of the last-mentioned, cost occurs when load shedding LS is required. A more detailed description of the formulation can be found in [22].

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

The linear formulation of a storage system can be modeled 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 $p^{in}_{g,t}$ and discharged $p^{out}_{g,t}$ with their respective efficiency η and external energy inflows $\zeta^{in}_{s,t}$ and outflows $\zeta^{out}_{s,t}$.

$$e_{s,t} = e_{s,t-1} + p^{in}_{g,t} \times \eta_{g,in} - p^{out}_{g,t} / \eta_{g,out} + \zeta^{in}_{s,t} - \zeta^{out}_{s,t}\ \forall s \in S,\ t \in T \tag{3}$$

When applying Equation (3) to V2G charging, the available energy is provided by the car battery, and efficiency is determined by losses within the vehicle and in auxiliary equipment such as the wallbox, while the mobility demand results in an 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 and charging and discharging capacity p_t are determined by the time-variant upper and lower bounds depending on the composition of plugged-in and unavailable EVs. The external energy outflow $\zeta^{out}_{,t}$ is defined as the energy used at the time of plug in E^{mob}_t 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 but also implicates a large advantage in computational complexity compared to a discrete modeling approach.

$$E^{min}_t \le e_t \le E^{max}_t\ \forall\ t \in T \tag{4}$$

$$0 \le p^{in}_t \le P^{in,max}_t\ \forall\ t \in T \tag{5}$$

$$0 \le p^{out}_t \le P^{out,max}_t\ \forall\ t \in T \tag{6}$$

$$\zeta^{out}_t = E^{mob}_t\ \forall\ t \in T \tag{7}$$

In the second step, we determine the required dispatch adjustments using a linearized optimal power flow formulation. This step accounts for the V2G flexibility potential developed by implementing available capacities and bounds from the V2G flexibility model previously described. In the linearized optimal power flow formulation, the nonlinear branch flow equations are simplified by an approximation which assumes a lossless system with constant voltage levels [25]. The resulting linearized power flow equation is shown in Equation (8), with the active power flow $P_{i,j}$ between nodes i and j dependent on the respective bus voltage angles φ.

$$P_{i,j} = b_{i,k}(\varphi_k - \varphi_i) \tag{8}$$

To determine the optimal congestion management measures, we formulated the objective function as a minimization of the total amount of congestion measure volume in an analogous manner to [22], as shown in Equation (9). While all variables have an additional bus index in the following due to the additional spatial dimension, the index is omitted for the sake of simplicity. Each congestion management action consists of the deviation from the market result, denoted by Δp. As both positive and negative measures are contributing in a uniform manner to the objective, the objective function consists of the absolute value of change. This is not required for load adjustment, where reduction in load always results in a positive contribution, which is additionally penalized by the load shedding penalty factor $C_{LS,grid}$. The corresponding bounds are shown in Equations (10)–(13). The available potential for reduction or increase in generation for conventional, renewable and flexibility generation is subject to the technical minimum and maximum limits P_{min}. and P_{max} as well as the market dispatch P_t which results from Equation (2). It should be noted that for volatile RES generation from solar and wind, no generation increase potential remains, as $P_{res,max}$ equals $P_{res,t}$.

$$min \sum_{g \in G, t \in T} \left| \Delta p_{g,t} \right| + \sum_{res \in RES, t \in T} \left| \Delta p_{res,t} \right| + \sum_{f \in F, t \in T} \left| \Delta p_{f,t} \right| + \sum_{d \in D, t \in T} C_{LS,grid} \times \Delta p_{d,t} \quad \forall g \in G, \ res \in RES, \ f \in F, \ d \in D, \ t \in T \tag{9}$$

$$P_{g,t} - P_{g,min} \leq \Delta p_{g,t} \leq P_{g,max} - P_{g,t} \ \forall \ t \in T, \ g \in G \tag{10}$$

$$P_{res,t} - P_{res,min} \leq \Delta p_{res,t} \leq P_{res,max} - P_{res,t} \ \forall \ t \in T, \ res \in RES \tag{11}$$

$$P_{f,t} - P_{f,min} \leq \Delta p_{f,t} \leq P_{f,max} - P_{f,t} \ \forall \ t \in T, \ f \in F \tag{12}$$

$$0 \leq \Delta p_{d,t} \leq P_{d,t} \ \forall \ t \in T, \ d \in D \tag{13}$$

To include V2G flexibility, Equations (3)–(7) can be applied in an analogous manner by adding a spatial component on a nodal basis, with the nodal EV density being determined by the regionalization developed in [23]. The calculation is performed for 8760 timesteps with consecutive weekly optimization horizons, ensuring an optimization time-horizon long enough to allow the activation of available flexibility from individual mobility demand patterns. 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 [26]. The scenario "Storyline B" assumes an ambitious path towards decarbonization of the electricity sector, with high growth for RES generation until 2030. The generation capacities are shown in Figure 4. While both onshore and offshore wind generation, as well as solar generation, increase compared to today's state, power generation from hard coal and lignite has been phased out by 2030 under the assumptions. The corresponding transmission grid scenario for the future date and the corresponding spatial distribution of generation and demand is shown in Figure 5. A very detailed description of the scenario and its regionalization, as well as the extension of the future energy scenarios to 2050, can be found in [26].

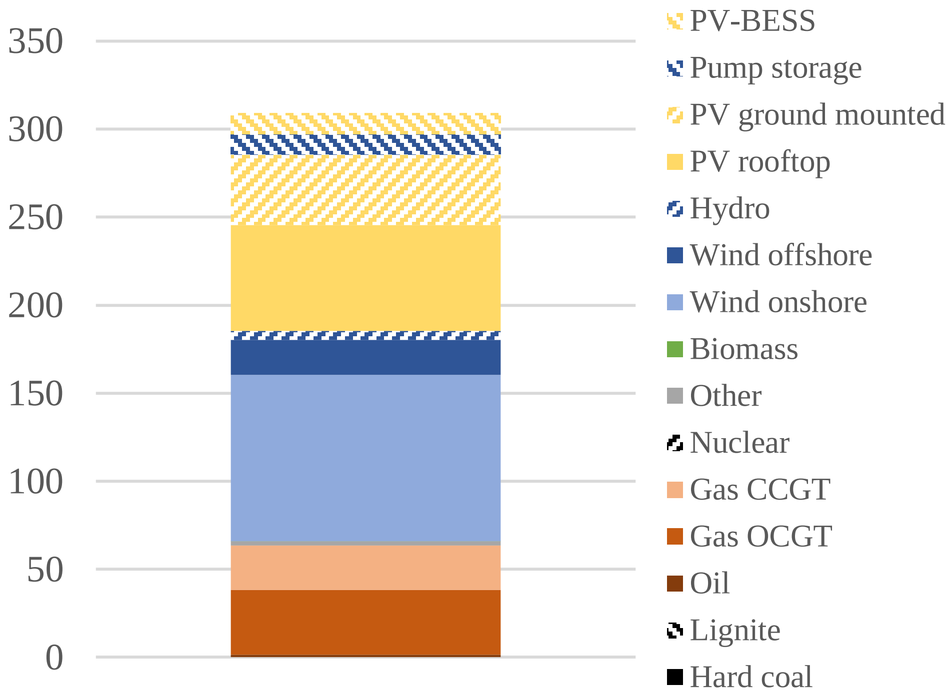

Figure 4. Generation capacities in Germany from central and decentralized sources in the case study for the year 2030 [20].

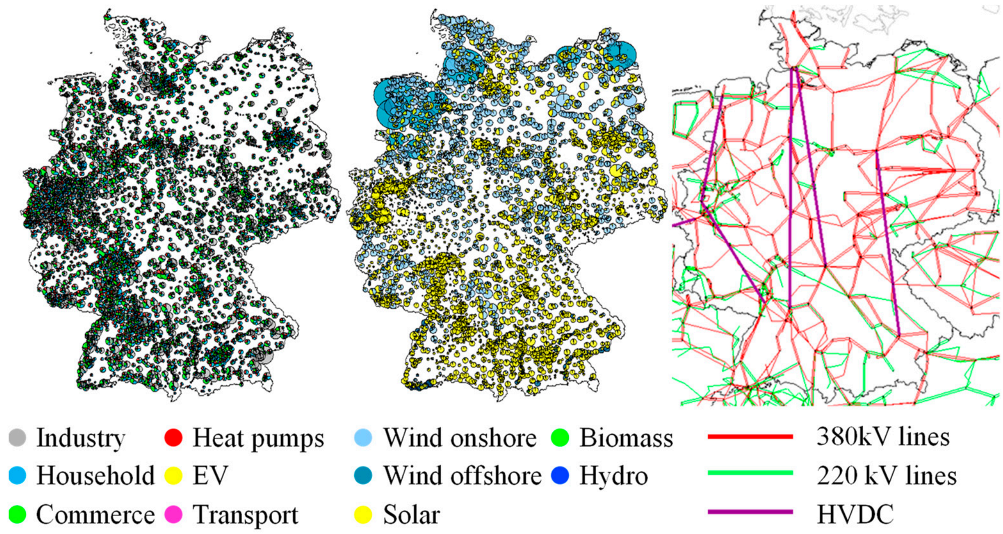

Figure 5. Demand allocation (**left**), RES allocation (**center**) on high voltage level and transmission grid model (**right**) of Germany.

To determine the scenario-dependent V2G flexibility potential, the input parameters shown in Table 2 are defined. Here, the minimum range from Section 2.1 is 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 5. Furthermore, available flexibilities during working hours are increased for market and grid utilization.

Table 2. Scenario-related input data.

Scenario	BEV Count	Charging Location	Charging Power	Battery Capacity	Consumption	Efficiency	Availability Market	Availability Grid Operation	Safety Range	Target Range
Base	15 million	Home charging	11 kW	50 kWh	15 kWh/100 km	90%	100%	100%	40%	56.2%
Work		Home- and workplace charging								
Reduced	10 million	Home charging								
Grid	15 million	Home charging					20%			

The available flexibility potential for the scenarios Base and Work is shown in Figure 6. 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 6. Consequently, the relative change in total available charging power at midday is more significant than the change in the upper and lower SoC bounds for the scenario Work as shown in Figure 7.

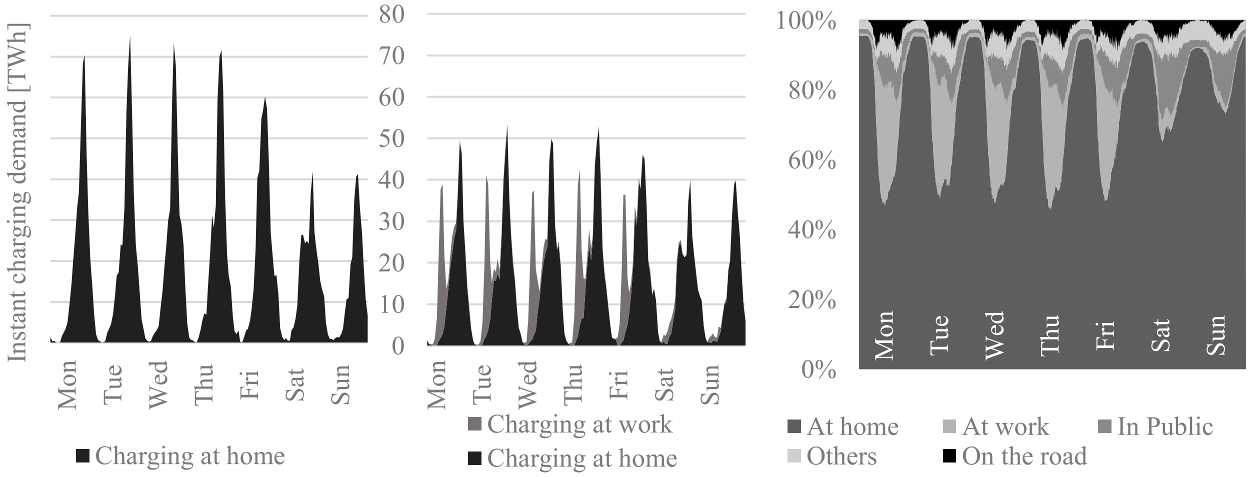

Figure 6. V2G charging demand in ASAP mode for scenario Base averaged over the vehicle fleet, one week (**left**) and scenario Work (**middle**) and distribution of EV location over one week (**right**).

To estimate the innovation and imitation coefficient, a non-linear regression method was applied to both historical EV fleet data of the German Ministry of Transport [18] and future EV fleet size targets of the German government [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 8 displays the forecasted yearly EV fleet sizes for both scenarios.

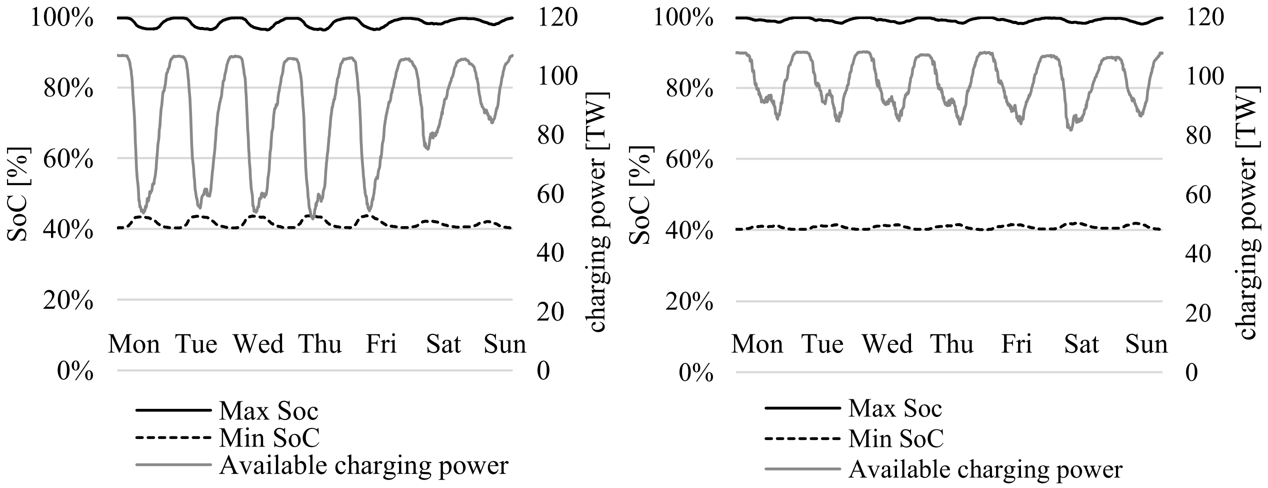

Figure 7. (**left**): V2G flexibility potential for Base (fleet-averaged, one week; charging availability at home), (**right**): V2G flexibility potential (fleet-averaged, one week; charging availability at home and at work).

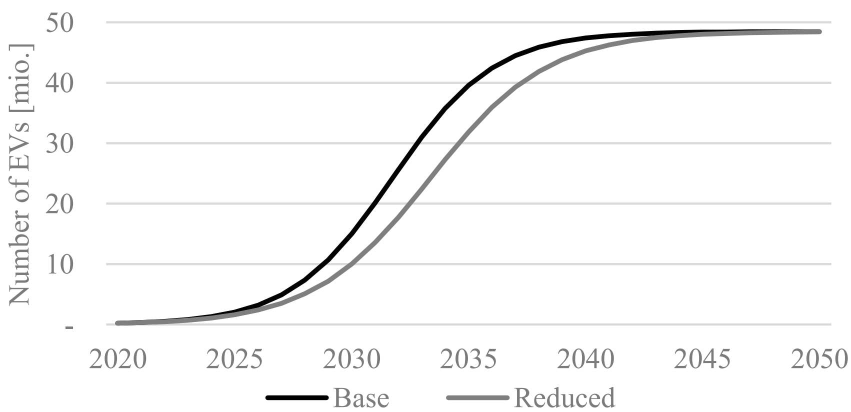

Figure 8. Development of EV adoption in Germany for scenarios Base and Reduced.

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 results also suggest 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 [27]. 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.

On the transmission grid level, a dataset for Germany, including overhead lines and cables above 200 kV, 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 150 kV using the methodology described in [23]. 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 were derived from publicly available sources or approximated based on comparable equipment.

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 in available thermal generation capacities go hand-in-hand with increased renewable generation, especially wind generation in Northern Germany. Subsequently, the increased interconnection capacities with neighboring 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 3. 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. The left part of Figure 9 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 in 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 hourly ordered distribution of dispatch adjustments can be found in the right part of Figure 9. 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.

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

The impact of including V2G as an additional source of flexibility in the model can be found in Figure 10. 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 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.

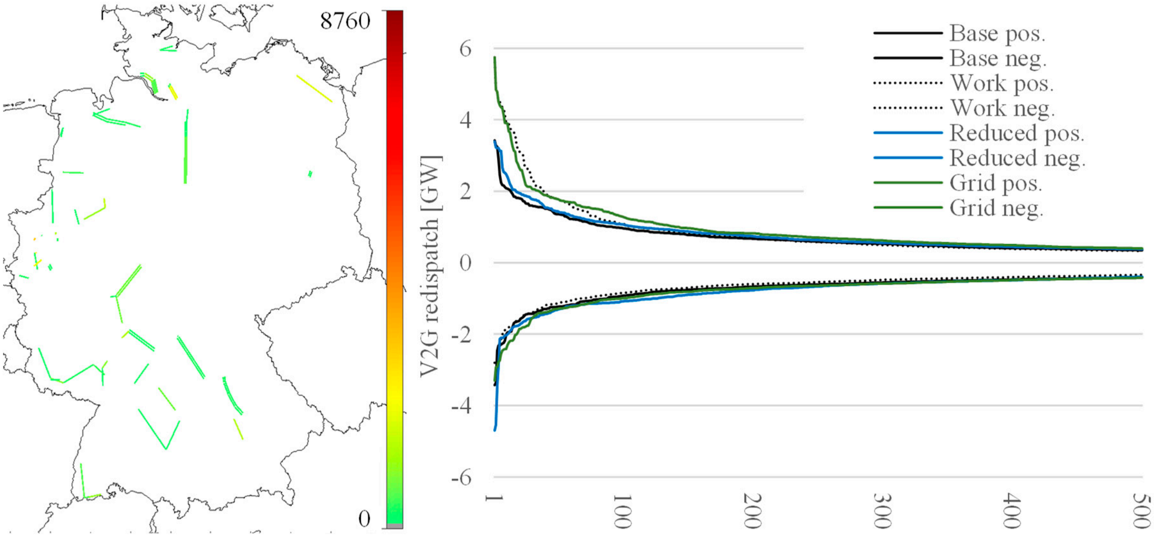

Figure 9. Congested transmission grid lines without V2G flexibility (**left**) and ordered hourly positive and negative V2G congestion management utilization for each scenario (**right**).

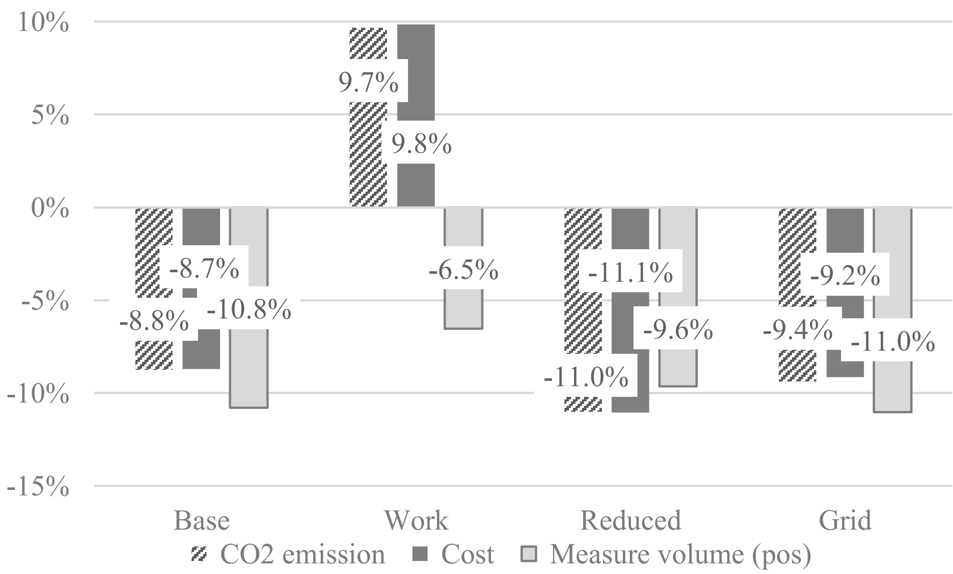

Figure 10. Results of V2G flexibility scenarios in comparison to reference case.

The model results for the sensitivity of the V2G share, as shown in Figure 11, allow a more detailed interpretation of how transmission grid congestion varies depending on the V2G adaptation rate. In the Grid scenario, the V2G share on the market side was reduced to 20%. Here, however, the V2G share of the total EV fleet has been varied synchronously. The 0% and 100% cases are represented by the Reference and Base scenarios, respectively. It is observed that a proportional reduction in V2G share leads to an increased requirement for congestion management measures. This can be explained by the fact that market actions are based on national capacities, while grid measures require spatial alignment to address overloads. However, this effect is not observed in terms of emissions and costs, where increasing V2G shares lead to reduced outcomes for both. As expected, the greatest reduction in congestion management measures is observed in the Base scenario.

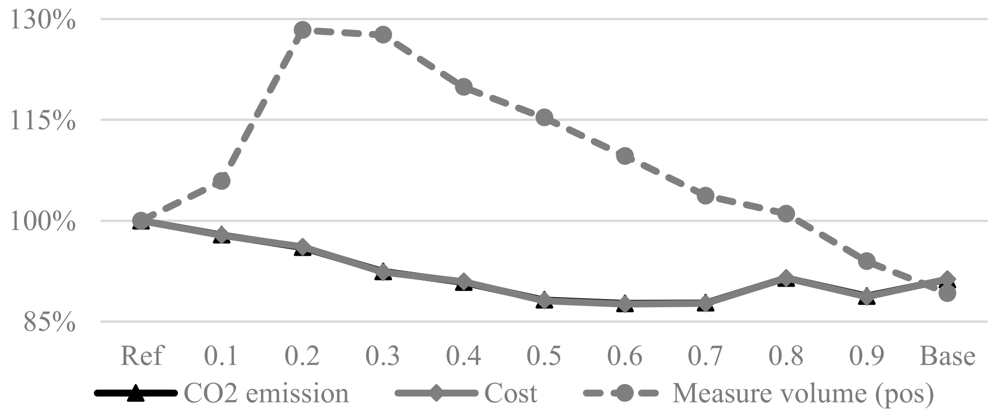

Figure 11. Sensitivity of the congestion management results to the V2G share of total EVs.

5. Conclusions

In this paper, we presented a model framework to investigate the impact of V2G flexibility on congestion management in the German transmission grid. Our approach extends the existing literature by including user requirements for V2G as well as a highly spatially disaggregated flexibility modeling allowing a combination with a detailed future transmission grid model. We showed the effect of V2G for an ambitious scenario in the year 2030. The model cascade includes an analysis of V2G user requirements and diffusion modeling of projected EV uptake. These data have been used in the V2G flexibility modeling approach to derive time-dependent V2G flexibility potential 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 results show that including V2G in congestion management can reduce the required number of redispatch measures by more than 10%. This is a conservative estimation compared to the results for eight million EVs in [5] but can be explained by the more detailed spatial modeling in this approach, leading to fewer EVs being able to effectively contribute to eliminating transmission grid congestions. The results are also in the same range compared to the study on redispatch in Austria [6]. However, we cannot observe a strong negative effect of EV flexibility participating in the electricity market previously for the German case. 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 grid's stability. 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 CO_2 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. Especially, interdependence with other battery storage applications could be helpful, if a high technical and spatial level of modeling detail can be sustained. While the role of individual EV users has been included in this work, the high importance of spatial alignment of flexibility requirements and V2G usage points to a need for research on flexibility potential on an individual level, determining the type and location of future V2G potential needed, as not every EV can contribute to congestion relief equally.

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