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Sector Coupling through Vehicle to Grid: A Case Study for Electric Vehicles and Households in Berlin, Germany

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Abstract: A key factor in limiting global warming is the conversion of conventional electricity generation to renewable energy sources. However, a major obstacle is that renewable energy generation and energy demand often do not coincide in time, and energy must therefore be stored temporarily. Vehicle to grid (V2G) can be used to store excess renewable energy in battery electric vehicles (BEVs) and feed it back into the electric grid when needed. For effective V2G operation, the grid may have to be expanded, as the energy needs to be transported to BEVs. However, the grid should only be strengthened where renewable energy demand exceeds current grid capacity due to high grid expansion costs. This requires a method that determines the spatial distribution of V2G potential at a high resolution. Since such a method has not yet been reported in the existing literature, and so is developed in this paper. The method is demonstrated for the city of Berlin and its 448 sub-districts. For each sub-district, the method allows determining the percentage of residential and BEV energy demand that can be met by renewables if V2G is deployed, and answers the question of whether a full renewable supply is possible. The results show that BEVs can be effectively used as intermediate storage for renewable energy. If 30% of the BEVs participate in V2G, more than 99% of the energy demand of households and BEVs in Berlin can be covered by renewables on certain days. On the other hand, V2G deployment increases the average peak load in the districts by up to 100% and results in a nearly double load on vehicle batteries. High shares of renewable energy can be observed in districts with a high degree of motorization, which are predominantly found in the outskirts of the city.

Keywords: electric vehicle; renewable energy; vehicle to grid; sector coupling; spatial resolution

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1. Introduction

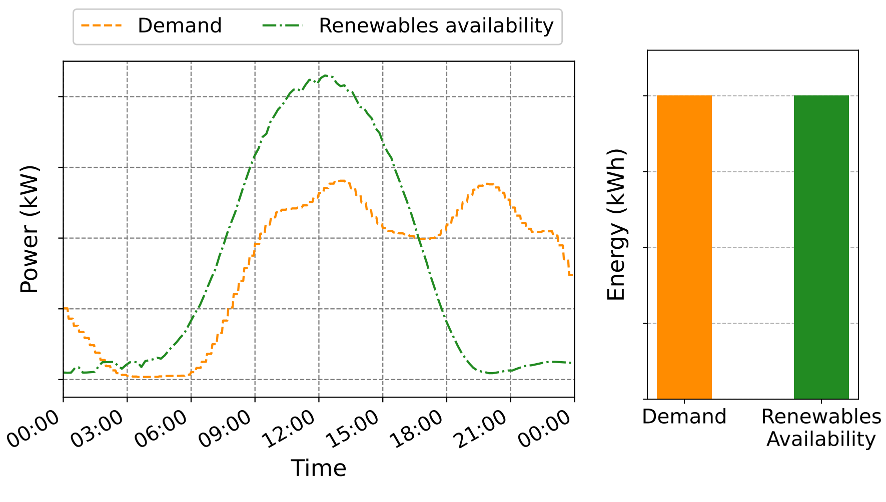
The worldwide reduction in greenhouse gas emissions is the main factor limiting the global temperature increase to 2 °C above pre-industrial levels, as agreed in the 2015 Paris Agreement [1]. To meet this goal, the European Commission has agreed on the "European Green Deal" which stipulates net zero greenhouse gas emissions for the entire European Union by 2050 [2]. In accordance with these guidelines, Germany plans to reduce greenhouse gas emissions by 50% by 2030 with respect to 1990 [3].

The decarbonization of the transport sector is one of the most important levers to achieve this result. Therefore, private vehicles with internal combustion engines (ICEVs) are increasingly being replaced worldwide by vehicles with decarbonized drive systems, especially battery electric vehicles (BEVs) [4]. According to the German Federal Motor Transport Authority (KBA), around 356,000 BEVs were registered in Germany in 2021, 5.6 times as many as in 2019 [5].

In addition to decarbonizing the transportation sector, replacing electricity generation by fossil fuels with renewable energy sources such as solar and wind energy is an important component to reduce emissions. Tröndle et al. [6] have shown that all European countries can cover their entire energy consumption with renewable energies if their infrastructure is expanded accordingly. However, a major limitation of renewable energies is their volatile generation. Power generation and demand do not always coincide in time [7–9]. To reduce this discrepancy, load shifting strategies can be employed to charge BEVs whenever a surplus of energy is available [7,8,10–12].

Load shifting cannot be fully exploited in times when the demand exceeds the power generation. This problem can be addressed by coupling the energy and transportation sectors through vehicle to grid (V2G). Sector coupling is the connection, interaction and joint optimisation of energy sectors. The aim is to consider all sectors (e.g., electricity, transport and industry) holistically and to create synergy effects instead of developing solutions tailored to individual sectors [13–15]. One possibility for sector coupling is V2G, in which surplus renewable energy is stored in battery electric vehicles (BEVs) and fed back into the electric grid as needed. This allows other consumers, such as households, to increase their share of renewable energy in their total energy demand [16–18]. However, the grid may have to be expanded for effective V2G operation, as the energy needs to be transported to the BEVs unless it is generated locally.

The need to strengthen the grid is evident from Figure 1, which shows the energy demand of an example region and the renewable energy provided to meet that demand. The energy demand in the region is equal to the energy supply from renewable sources. However, because renewable energy is available primarily at midday (e.g., solar energy), more energy must be supplied to the region at midday than is needed. The excess energy is temporarily stored in the BEV batteries to meet the region's demand in the evening and morning. This significantly increases the peak load in the example region. If the grid is not dimensioned for this new peak power demand, it must be reinforced.



(a) (b)

Figure 1. Peak power increase due to V2G. (**a**) Power demand and availability. (**b**) Energy demand and availability.

In addition to the integration of renewable energies, BEVs can also be used for other services when connected to the grid. For example, for voltage regulation [19], frequency regulation [20–22] or as reactive power support operation [23].

The application of V2G for renewable energy integration has been the object of extensive research both in the case of microgrids [9,24–26] and in large geographic areas with thousands of BEVs [27–31].

For a reference area in northern Italy containing 200,000 BEVs, Fattori et al. [27] studied the usage of V2G to reduce the peak power demand. Assuming a photovoltaic peak power of 620 MW, they showed that a 35% reduction in the peak power demand is possible.

For four interconnected islands in Croatia, Pfeifer et al. [28] investigated what share of the total energy demand could be covered by renewable energies if 7700 BEVs were used for V2G. They showed that, for three of the four islands, a share of at least 80% can be achieved with a photovoltaic capacity of 62 MW and additional stationary batteries with a capacity of 179 MWh.

For the Croatian island of Korčula, Dorotić et al. [29] showed that the entire energy consumption can be covered by renewable energies by 2030 if 40 MW of wind and 6 MW of solar capacity were installed and V2G deployed.

Forrest et al. [30] predicted that California can meet 80% of its total energy demand by using renewables in 2050 if 80% of light-duty vehicles are BEVs and V2G is deployed. No additional energy storage systems are required for this.

Again for 2050, Nunes et al. [31] showed that, with an installed photovoltaic capacity of 16,669 MW and an electric vehicle fleet of 4.176 million, 95% of Portugal's energy demand can be met by renewable energies if V2G is deployed.

The studies discussed do not consider spatial variance in the degree of motorization, the BEV driving behaviour, and the distribution of vehicle size classes. As a result, spatial variance in available battery capacity, and consequently in energy storage, are not represented. Therefore, these results provide a good overview of a geographic area's V2G potential, but cannot be used by grid planners to adapt infrastructure for effective V2G operation. For this, the V2G potential of an area must be known with high spatial resolution, as the grid should only be strengthened where renewable energy demand exceeds current grid capacity due to high grid expansion costs.

To overcome the aforementioned limitations and fill this research gap, we develop a method to determine the V2G potential of an entire geographic area with high spatial resolution. To ensure the ability to trace and reproduce this method, only open data were used. The method is demonstrated for the urban area of Berlin, Germany and its 448 sub-districts called "Lebensweltlich-orientierte Räume" (Eng.: neighbourhood-oriented districts, abbr.: LORs). The LOR classification is an official classification of the Berlin administration. Within each LOR, the structure of the included buildings and the socio-economic status of the inhabitants are similar. The LORs are usually separated from each other by major roads, rivers or rails [32,33]. For each of the 448 sub-districts, the method is able to determine the percentage of residential and BEV energy demand that can be met by renewables if V2G is deployed and answer the question of whether a full renewable supply is possible.

The percentage of power demand that can be met by renewable energies if V2G is applied is highly dependent on the number of BEV owners who provide their vehicles for V2G services. Therefore, we examine a total of ten scenarios ranging from 0 to 75% participation in V2G services. The availability of renewable energies during the course of the day depends on the season. We, therefore, distinguish between a summer and a winter case.

V2G requires communication between the vehicle owner and the V2G control centre, in which the vehicle owner specifies, for example, their planned parking time. The V2G control centre collects the information and processes it. Appropriate communication between the V2G control centre and the vehicle owner is assumed in this work. An overview of the current communication standards can be found in [17,34].

The rest of this paper is structured as follows: in Section 2, the methodology is introduced. The results are presented and analysed in Section 3. The main conclusions of this paper are derived in Section 4.

2. Methodology

This section is divided into three parts. In Section 2.1, the driving and charging behaviour of the BEVs is described. In Section 2.2, the availability of renewable energy sources depending on the time of day is discussed. Section 2.3 presents the method we used to determine the share of residential and BEV power demand that can be met by renewables if V2G is applied.

2.1. Driving and Charging Behaviour

In order to determine the V2G potential of a geographic area with high spatial resolution, the spatial distribution of BEVs in the area must be determined. In addition, to know when BEVs are available for V2G services, the daily driving behaviour of each BEV must be known, including parking times, parking locations, and parking duration.

A method for determining these input parameters is described in [35] and is demonstrated for the urban area of Berlin, Germany. In the first step of this method, the spatial distribution of conventional passenger cars (1,045,000 in Berlin in 2018 [36]) is determined using statistics on population density, motorization rate, and household income. Then, assuming full electrification of the conventional fleet, the vehicles are replaced by electric reference vehicles. The vehicle type, battery capacity, and WLTP consumption of all reference vehicles are listed in the Appendix A (Table A1). Finally, on the basis of a travel survey, a full-day travel schedule for an average work day (Monday–Thursday) is generated for each BEV. As can be seen in Figure 2, each schedule consists of a sequence of activities and trips between these activities and describes the driving behaviour of the BEVs.

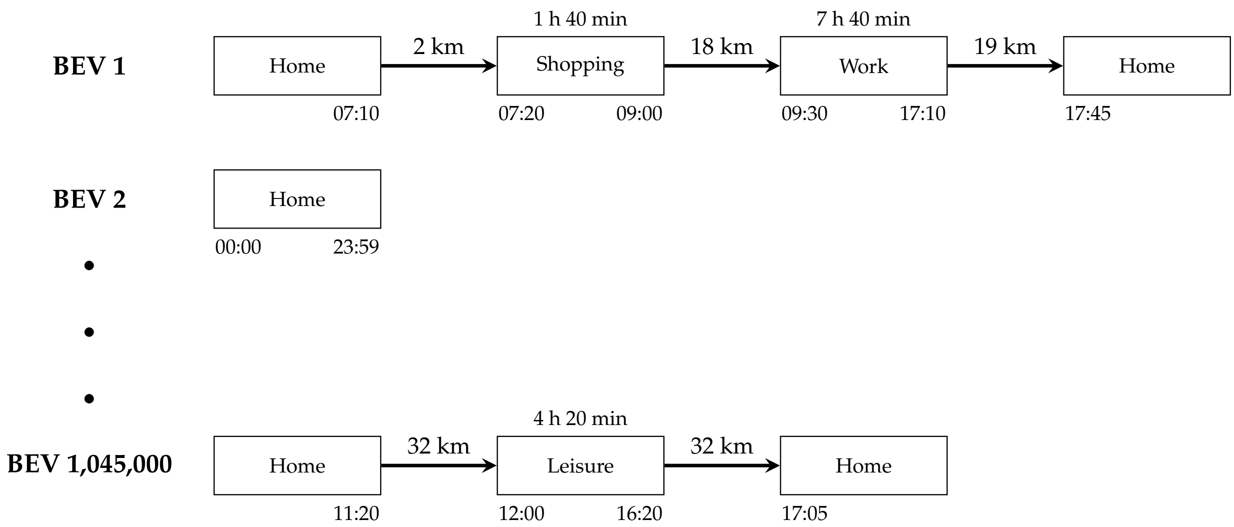


Figure 2. Full-day travel schedules of BEVs [37].

Based on the known driving behaviour, the charging behaviour of BEVs can be simulated by applying charging scenarios. Two different charging scenarios are applied in this paper depending on whether the owner of the BEVs has decided to participate in V2G.

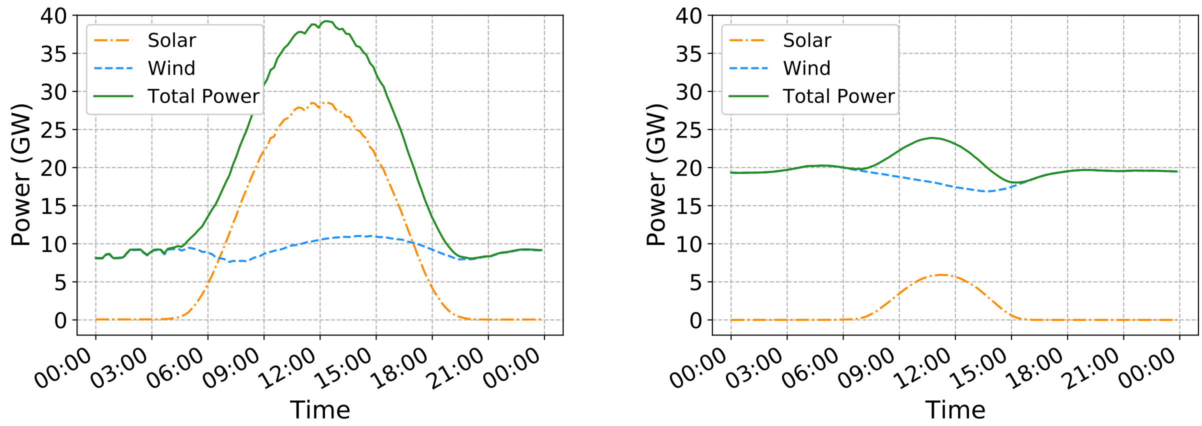
Charging scenario 1: BEVs whose owners have decided to participate in V2G services are charged exclusively at the owner's place of residence, as we assume that an energy contract has been negotiated with the grid operator. This is advantageous for the grid operator since in Berlin 45% of private cars are parked all day at their owners' places of residence. The vehicles used are parked on average 18.3 h per day at their owners' places of residence [35,38]. Such an agreement is also worthwhile for vehicle owners, as the contract includes benefits such as a lower electricity price in comparison with other locations, such as charging stations at their workplace or at public parking spots [39,40]. The grid connection time of a BEV for scenario 1 corresponds to its parking time.

Charging scenario 2: the charging behaviour of BEVs whose owners have decided not to participate in V2G services is derived from the operational data measured for 41 private BEVs in Beijing, China in [41]. This charging scenario is described in detail in Section 4.2 in [37]. According to this scenario, BEVs are charged at locations with long parking times, namely private residences, workplaces, and shopping locations. The probability of BEV charging at these locations is determined based on the rechargeable SOC difference of the vehicles during their parking times. The higher the rechargeable SOC difference, the higher the probability of charging. The rechargeable SOC difference describes how much SOC can be recharged at a specific location during the parking time (a SOC of 20% before charging and a rechargeable SOC difference of 40% would, for example, result in a SOC of 60% after charging). When charging, the maximum available charging power is always used. The grid connection time of a BEV for scenario 2 corresponds to its charging time.

The maximum charging power available at the charging stations is set to 11 kW at the residences. For charging at work, the maximum power is set to 22 kW in accordance with real-world applications [42,43]. For opportunity charging while shopping, the maximum power is set to 50 kW, which is in accordance with real-world applications [44–46] as well. The maximum charging power that can be used by the BEVs is SOC-dependent and is described by charging curves. For both previously described charging scenarios 1 and 2, the charging curves of the reference vehicles are shown in the Appendix A (Figure A1). The charging curves were determined by experimental measurements [47,48].

2.2. Energy Availability from Renewable Sources

In contrast to other renewable energy sources such as biomass or geothermal energy, the availability of wind and solar power is weather- and time-dependent. Since energy generation often does not match demand, temporary storage of surplus energy is desirable. Therefore, for intermediate energy storage in car batteries, only wind and solar energy are considered in this paper. In Figure 3, the daily profiles of average power generation from renewable energies (RE) in Germany are depicted. It is assumed that these profiles are also valid in Berlin. The profiles are derived from reference [49], which lists historical data on energy generation in Germany.



(**a**) (**b**)

Figure 3. Average energy generation from renewables in Germany, determined from data for two weeks in summer and winter 2021 [49]. (**a**) Average summer day. (**b**) Average winter day.

To compensate for fluctuations in power generation (e.g., summer day with zero hours of sunshine), the average values from two weeks are used to generate the profiles. Accordingly, the results that will be derived show the V2G potential for such an average day. On a particular day, the amount of renewable energy that can be integrated into the electricity mix depends on the actual daily profile.

Since the availability of solar and wind energy is highly dependent on the season, a distinction is made between a day in summer and a day in winter. The comparison between Figure 3a,b shows that power generation from renewable sources is dominated by solar energy in summer, while it is dominated by wind energy in winter. The peak power in summer is 64% higher than in winter. However, the electrical energy generated is almost the same in summer and winter. 4% less energy is available on the summer day than on the winter day.

2.3. Vehicle to Grid Approach

The iterative V2G approach developed in this paper is schematically shown in Figure 4 and is applied to each LOR in Berlin individually. The goal is to determine for each LOR whether V2G can be used to store and release renewable energy in such a way that the residential and BEV power demand is met exclusively with RE sources. To reach this goal, BEVs are employed to store energy when the available RE exceeds the demand (surplus) and to release it back to the electric grid when the demand exceeds the available RE (deficit). The availability of renewable energy in the LORs is described by the RE profiles defined in Section 2.2. It is assumed that the required amount of renewable energy in the LOR can be provided. To avoid RE losses, the amount of RE available is adjusted by fitting the RE profile to each LOR. In districts where energy demand cannot be met with renewable energy without loss, the method determines how much additional energy is needed from non-renewable sources.

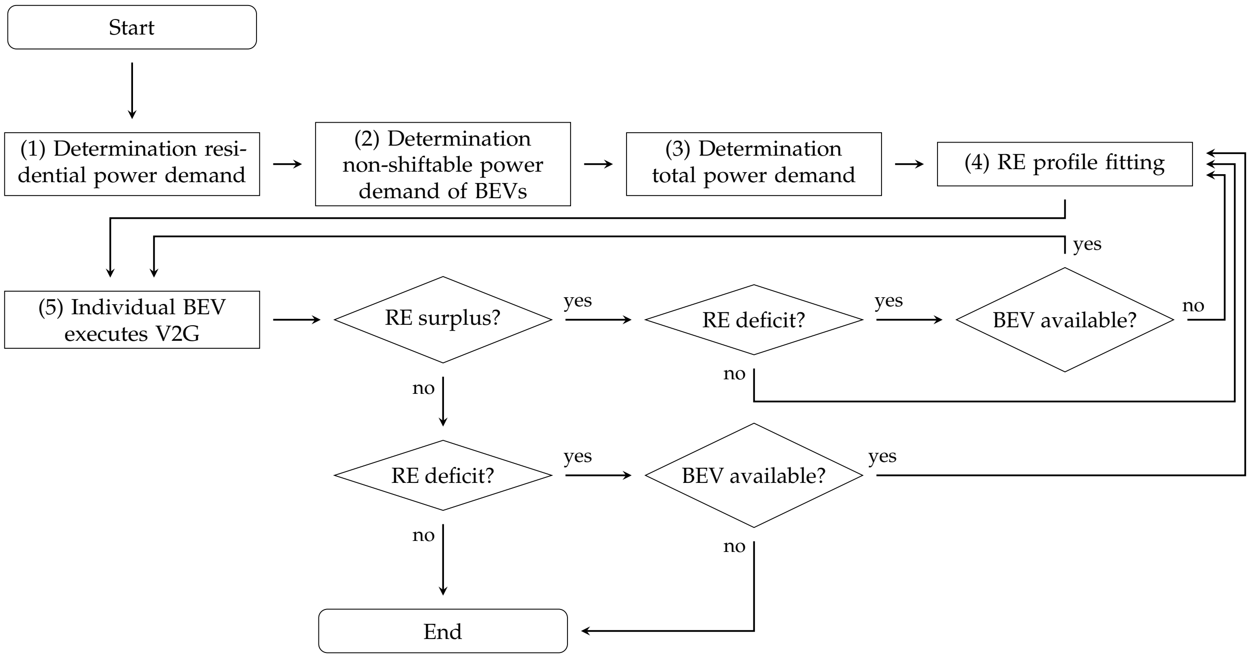
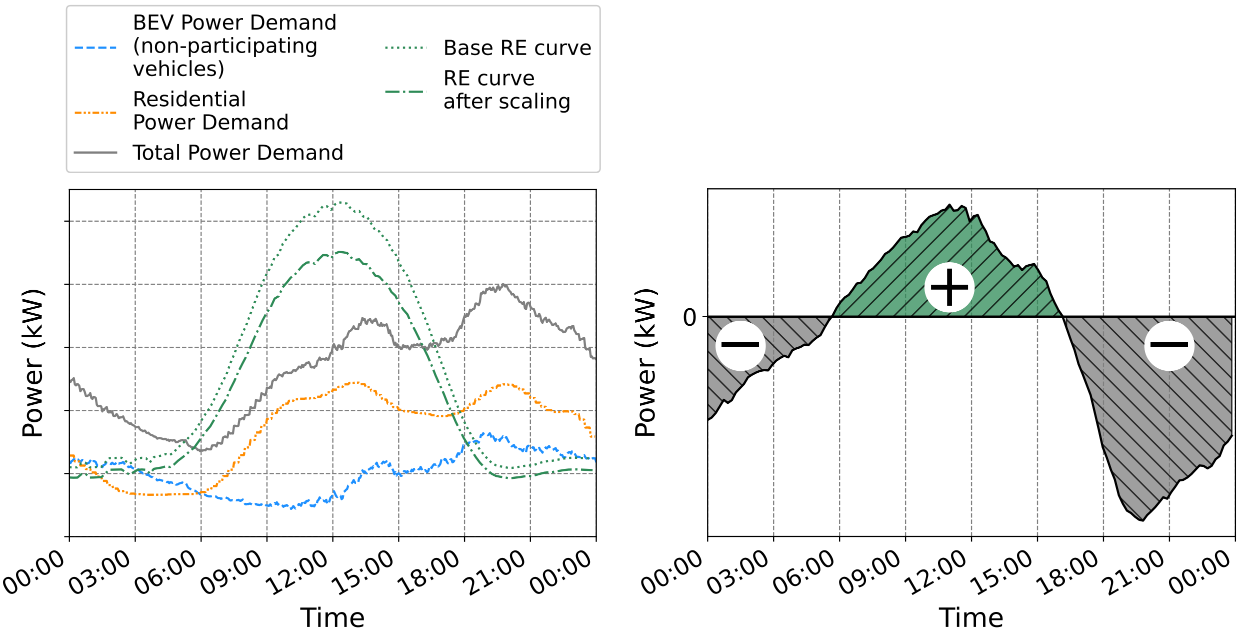


Figure 4. Method for determining the share of residential and BEV power demand coverable by renewables if V2G is deployed.

In step (1), the residential power demand of the LOR is determined by scaling the standard load profile for Berlin households. This is performed based on the household numbers and sizes in the LOR. The scaling process is described in detail in Section 3.5 in [35]. In step (2) the non-shiftable power demand (at the residences) of the BEVs whose owners have decided not to participate in V2G is determined (see charging scenario 2 in Section 2.1). The charging efficiency (grid to battery) is considered with a constant factor of 0.88 according to [50]. In step (3) the total, non-shiftable power demand of the LOR is determined as the sum of the residential power demand and the non-shiftable BEV power demand, as can be seen in Figure 5a. Then in step (4) the base RE profile is fitted to the energy demand of the LOR. This is performed by fitting the RE profile defined in Section 2.2 in such a way that the amount of renewable energy available is equal to the energy demand in the LOR. The base RE curve is depicted for the summer case as a green dotted line in Figure 5a as well. Subtracting the total power demand from this base RE curve yields the initial curve for the V2G process. This initial curve is depicted in Figure 5b. During the day, there is both a surplus (+area in Figure 5b) and a deficit (−area) of RE power, which is to be balanced by applying V2G.



(**a**) (**b**)

Figure 5. Exemplary power demand and RE profile for a LOR and resulting initial curve for V2G.(**a**) Power demand and RE profile for a LOR. (**b**) Initial curve for V2G.

The V2G process is a combination of peak-shaving and valley-filling and is performed in step (5) for one BEV at a time. Peak-shaving is used for charging the vehicle. This means that the vehicle is charged at times when the surplus of renewable energy is greatest.

Valley-filling is used for discharging the vehicle. This means that the vehicles feed energy back into the grid when the renewable energy deficit is greatest. Thus, the combination of peak shaving and valley filling reduces both the surplus and deficit of renewable energy. All parking events at the BEV owner's residence are considered grid connection events. Therefore, the vehicle can only participate in V2G at home and can only be discharged at home. While the vehicle is connected to the electric grid, it is allowed to charge and discharge several times.

The charging and discharging efficiencies are both considered to be 88% according to [50]. The factors are similar, but slightly more conservative compared to [51,52], which consider a charging and discharging efficiency of 90%.

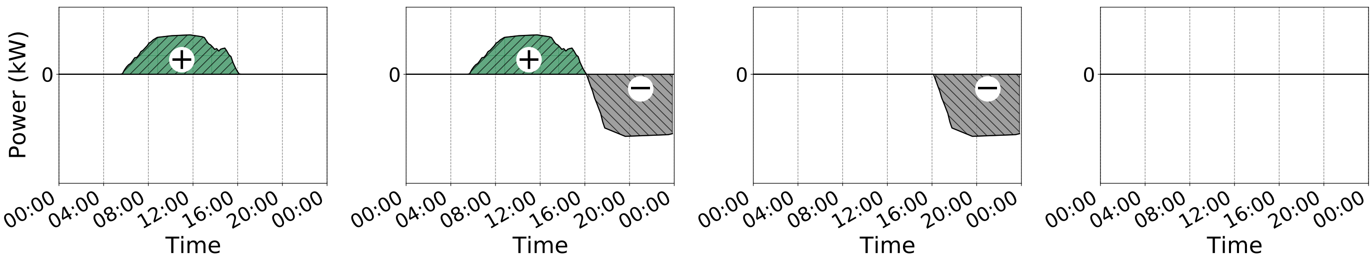
High discharge rates lead to accelerated battery ageing [53,54]. Therefore, discharge during V2G is limited to a SOC of 20%, which is consistent with literature data and real V2G applications [55,56]. The charge target value is set to a SOC of 90% in accordance with [56] and must be reached before the vehicle leaves for its next trip.

If the vehicle requires more than 90% capacity for its trips between two grid connection times, the charge target value is adjusted accordingly. This is necessary to ensure that the vehicle has sufficient energy to complete the trip.

After V2G is executed for the individual BEV in step (5), the following conditions are checked, and the iterative process continues accordingly:

- If there remains a RE surplus but no RE deficit (see Figure 6a), the process continues with step (4) and the RE profile is scaled down, which is exemplarily shown in Figure 5a. This is necessary to prevent RE losses in the LOR.
- If both, a RE surplus and a RE deficit remain (see Figure 6b) and another BEV is available for V2G, step (5) is executed again for the next BEV. If no other BEV is available, the process continues with step (4) and the RE profile is scaled down to prevent RE losses.

- If no RE surplus but a RE deficit remains (see Figure 6c) and another BEV is available for V2G, the RE profile is scaled up in step (4) to try to further reduce the RE deficit. If no other BEV is available, the process is terminated and the additional energy which is required from non-renewable sources is determined for the LOR.
- If neither a RE surplus nor a RE deficit remain (surplus deficit balance achieved, see Figure 6d), the process is terminated. Residential and BEV energy demand is met exclusively with RE sources.



(**a**) (**b**) (**c**) (**d**)

Figure 6. Distribution possibilities of renewable energy surplus and deficit after V2G application. (**a**) RE surplus. (**b**) RE surplus and deficit. (**c**) RE deficit. (**d**) Surplus deficit balance.

3. Results and Discussion

This section is organized as follows: Section 3.1 presents the power demand and supply for an example LOR as a function of time. Section 3.2 discusses the share of renewable energy in the total energy demand that can be provided through V2G application. Section 3.3 analyses the increase in peak power demand in the Berlin LORs due to V2G application. In Section 3.4, the battery load increase due to V2G is investigated. The results are discussed in Section 3.5.

3.1. Power Demand and Supply Over the Course of the Day

This section presents the results of applying the method described in Section 2.3 to the LOR "Invalidenstraße", which is located in the centre of Berlin. The LOR has 17,950 inhabitants and a motorization rate of 173 vehicles/1000 inhabitants. Figure 7 shows the power demand and supply over the course of the day in the LOR "Invalidenstraße" for the summer and winter case and different V2G participation scenarios.

For the summer case and 0% vehicle participation in V2G, Figure 7a shows that significant non-renewable energy must be provided to meet energy demand, especially in the evening hours (peaking between 6:00 PM and 9:00 PM). This is due to (i) the high residential demand in the evening hours, (ii) the high BEV charging energy demand in the evening (vehicles start charging immediately when they arrive home), and (iii) the low availability of renewable energy in the evening compared to midday hours. In total, 52.4% of the total energy demand is covered by renewables. If the share of vehicles participating in V2G is increased to 20% in summer (participating vehicles are randomly selected), the share of renewable energy in the total energy demand can be increased to 89.9%, as shown in Figure 7b. This is because BEVs store renewable energy during midday hours and feed it back into the grid during evening hours.

As shown in Figure 7d, with a V2G share of 20%, 100% of the districts' energy demand can be met by renewables in winter, although residential energy demand is significantly higher than in summer. This is due to the fact that renewable energy is available more evenly throughout the day in winter compared to summer (see Section 2.2). In particular, availability during midday is not significantly higher than at other times in winter. Midday is generally the time when the least amount of renewable energy can be temporarily stored by BEVs, as this is the time when the fewest vehicles are parked at their homes.

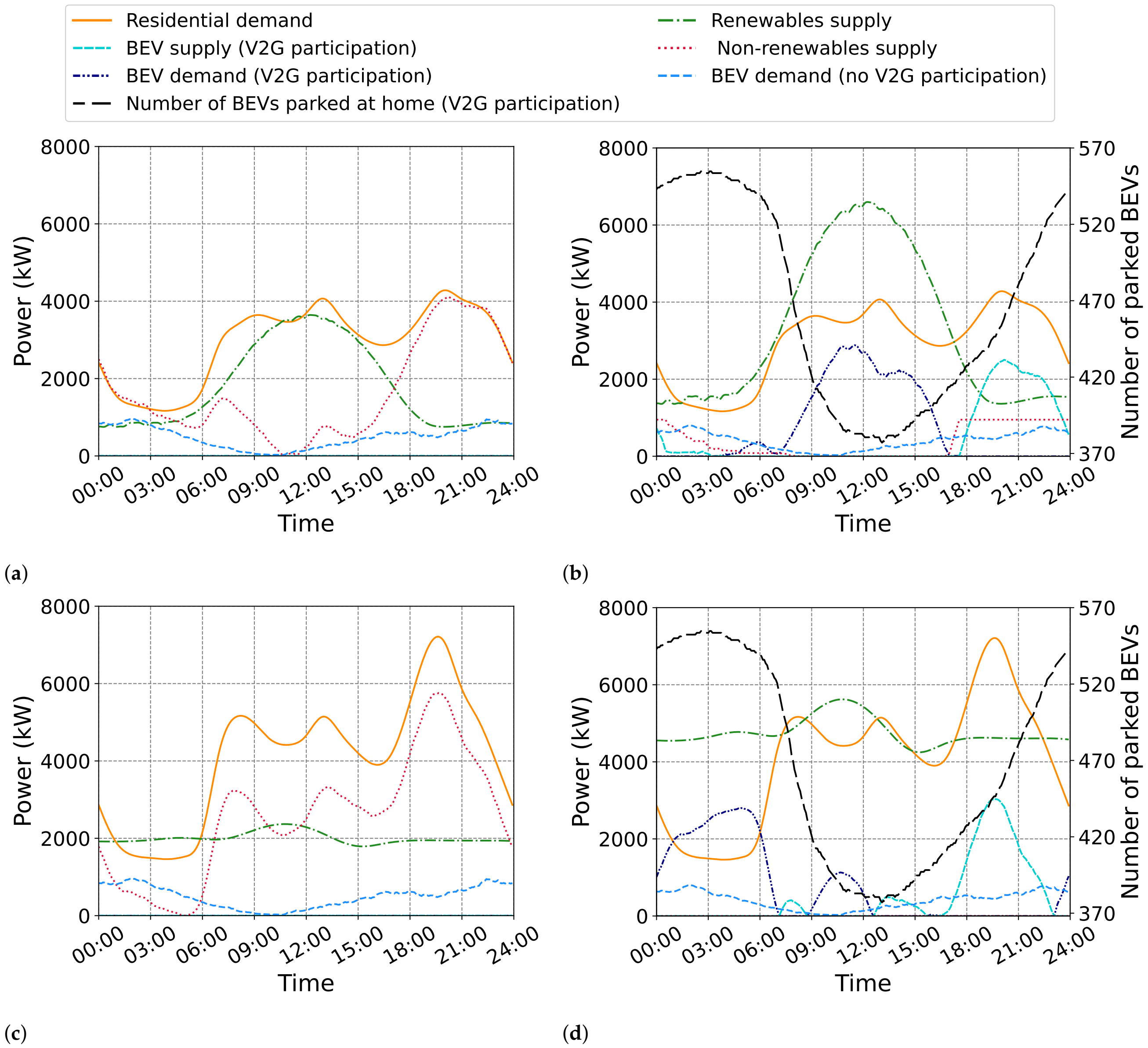


Figure 7. Power demand and supply for the LOR "Invalidenstraße" as a function of time.(**a**) Summer case. 0% vehicle participation in V2G. (**b**) Summer case. 20% vehicle participation in V2G. (**c**) Winter case. 0% vehicle participation in V2G. (**d**) Winter case. 20% vehicle participation in V2G.

3.2. Share of Renewable Energies in the LORs

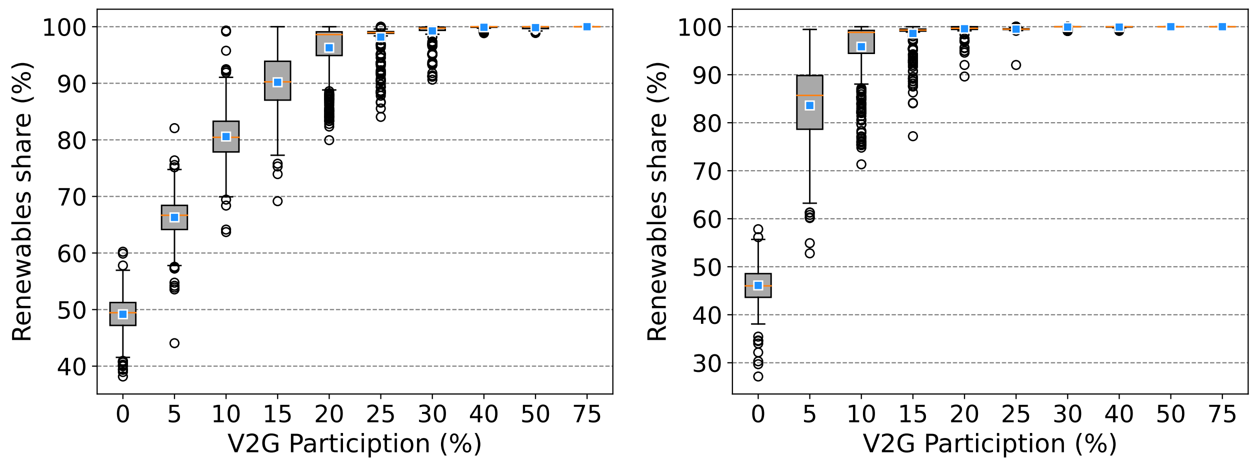
Table 1 shows, for the ten V2G participation scenarios studied, the number of LORs whose energy demand can be met entirely by renewable energy if V2G is deployed. It can be seen that in winter, already at a V2G share of 15% (participating vehicles are randomly selected for each LOR individually), more than 50% of the LORs can fully cover their energy demand with renewables, compared to only 6.7% in summer. The reason that more LORs are able to cover their energy demand entirely from renewables in the winter than in the summer is due to the near-constant availability of renewables throughout the day in the winter. Therefore, as described in Section 3.1, more renewable energy can be temporarily stored by BEVs than in summer. With 75% vehicle participation in V2G, the energy demand of Berlin's households and BEVs can be met entirely by renewable energy in winter and summer. Table 1 also shows the share of renewables in total energy demand (i.e., household and BEV demand) in Berlin for the ten participation scenarios. With 10% vehicle participation in V2G, 80.4% of the energy demand in summer and 95.2%

in winter can be covered by renewable energies. From a V2G share of 30%, more than 99% of the energy demand of Berlin's households and BEVs can be covered by renewable energy.

Table 1. Number of LORs whose energy demand is met entirely by renewables and share of renewable energy in Berlin for the ten V2G participation scenarios investigated.

	Case	V2G Participation Scenario									
		0%	**5%**	**10%**	**15%**	**20%**	**25%**	**30%**	**40%**	**50%**	**75%**
LORs that use 100% RE (x/448)	Summer	0	0	2	30	213	383	408	445	446	448
	Winter	0	4	113	260	430	445	446	446	448	448
Renewables share in Berlin (%)	Summer	49.5	66.2	80.4	90.0	96.1	98.0	99.1	99.93	99.98	100
	Winter	46.3	83.0	95.2	98.4	99.5	99.8	99.95	99.99	100	100

The share of renewable energy in the total energy demand of each LOR is shown in Figure 8 as boxplots. The blue square indicates the mean error. The outliers are shown as circles.



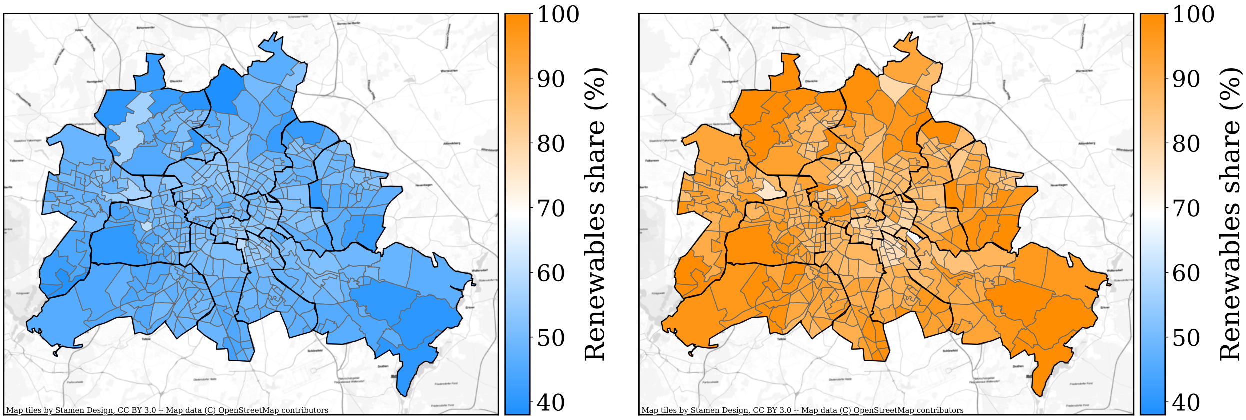
(**a**) (**b**)

Figure 8. Share of renewables in the Berlin LORs with V2G application. (**a**) Summer case. (**b**) Winter case.

It can be seen that the average share in the LORs is very similar to the average share in Berlin shown in Table 1. In summer, the average share is 49.2% at 0% vehicle participation in V2G and then increases to 66.3% at 5% participation. With a V2G participation of 25%, the average renewable energy share in the LORs is 98.2%. Therefore, the renewables share has almost doubled compared to the 0% V2G participation scenario.

In winter, this doubling is already achieved with a V2G share of 10%. At 0% vehicle participation in V2G, the average renewable energy share in the LORs is 46.1%, and at 10% participation, it is 95.8%. The reason why doubling the renewables share in winter is possible with lower V2G participation is that renewables are available more evenly throughout the day in winter compared to summer.

Figure 9 shows the spatial distribution of the share of energy demand that can be met by renewables in summer, both at 0 and 15% vehicle participation in V2G. With 0% vehicle participation in V2G, higher shares are achieved in the inner-city LORs. This is due to the fact that inner-city LORs have low levels of motorization, correspondingly few BEVs, and thus a low BEV charging energy demand. The share of renewable energy in the residential area and BEV energy demand is therefore the highest.



(**a**) (**b**)

Figure 9. Spatial distribution of the share of energy demand met by renewables in Berlin LORs. Summer case. (**a**) 0% vehicle participation in V2G. (**b**) 15% vehicle participation in V2G.

In contrast, as the number of BEVs participating in V2G increases, high shares of renewables are observed, especially in outer-city LORs. Due to the high level of motorization and the resulting higher number of BEVs, more renewable energy can be temporarily stored during the midday hours (and fed back into the grid in the evening) than in the inner-city districts. Accordingly, the share of renewable energy in the energy demand of households and BEVs is higher.

3.3. Peak Power Demand Increase in the LORs

This section examines the increase in peak load in the LORs resulting from the application of V2G. The peak power demand increase *PDI* always refers to the residential peak load and is calculated as follows:

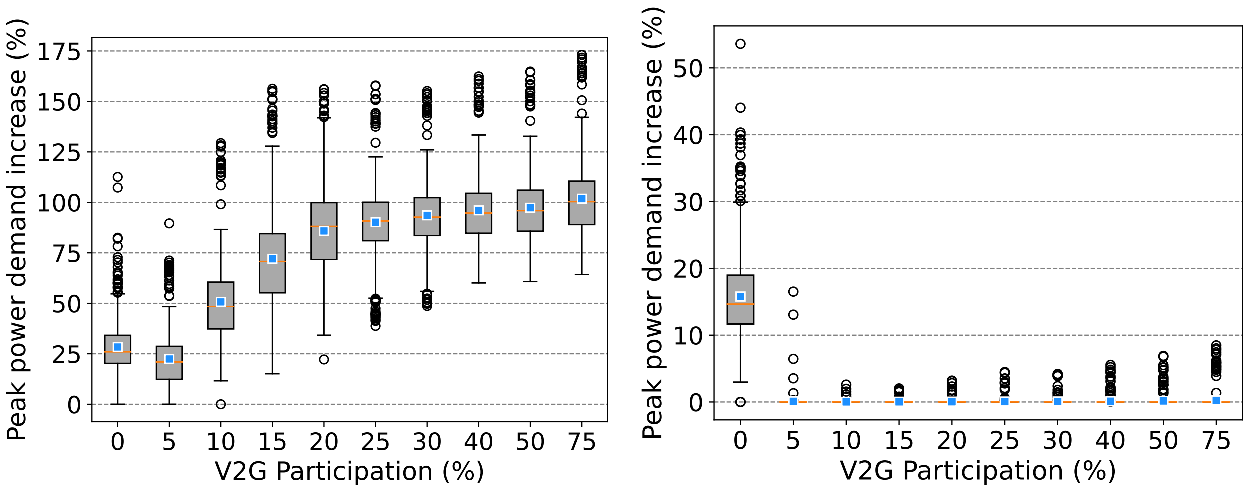
$$PDI = \frac{max(LOR\ demand) - max(Residential\ demand)}{max(Residential\ demand)} \quad (1)$$

where *LOR demand* is obtained by adding the curves of renewable energy supply, non-renewable energy supply, and BEV supply (see Figure 7).

The distribution of the peak power demand increase in the LORs can be seen in Figure 10 as boxplots. The blue square depicts the average increase in the LORs. The outliers are shown as circles.

For the summer case shown in Figure 10a, it can be seen that the average increase is 28% when no BEVs are participating in V2G and therefore uncontrolled charging occurs. This increase is due to the fact that the residential peak power demand in the evening coincides with the BEV peak charging demand (as shown in Figure 7a). With 5% vehicle participation in V2G (participating vehicles are randomly selected for each LOR individually), the increase in peak power demand decreases to 22% because 5% of BEVs are charged in a controlled manner and therefore BEV power demand is reduced in the evening hours.

From a V2G participation of 10%, the peak power demand increases sharply compared to the 0% V2G participation scenario; at a participation of 20%, the average increase in peak power demand is 86%. At 75% participation, the average increase is 102%. This increase is due to the fact that, as V2G participation increases, more renewable energy can be temporarily stored and the renewable energy curve rises accordingly (see Figure 7a,b). As can be seen in Figure 7b, the renewable peak load then exceeds the residential peak load. Accordingly, the peak load in the LOR increases.

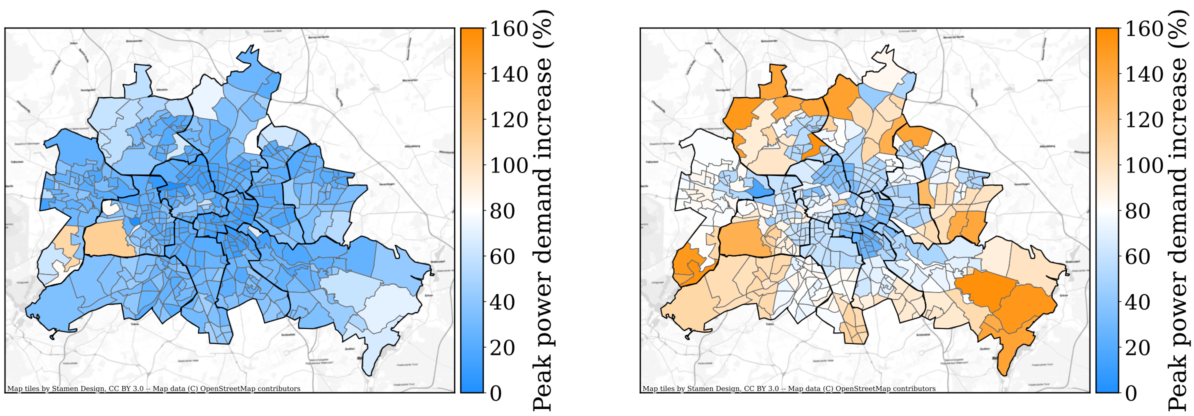


(**a**) (**b**)

Figure 10. Peak power demand increase in the Berlin LORs with V2G application. (**a**) Summer case. (**b**) Winter case.

Other findings can be observed for the winter case in Figure 10b. With 0% vehicle participation in V2G, the average peak power demand increase is 16%, which is lower than in summer. The lower increase is due to the fact that the residential peak power demand is significantly higher in winter (see Figure 7). From 5% participation, the average peak power demand increase is close to 0%. This is due to the fact that, in contrast to summer, renewable energy is available more evenly throughout the day and the residential peak power demand is higher. As a result, the renewable energy peak load is lower than the residential peak load (see Figure 7d). Accordingly, the peak power demand in the LOR does not increase.

Figure 11 shows the spatial distribution of the peak power demand increase in Berlin LORs in summer, both at 0 and 15% vehicle participation in V2G. As explained above, it can be seen that as the number of BEVs participating in V2G increases, the peak power demand in the LORs increases. In addition, it can be seen that the increase in peak power demand is higher in the outer-city LORs than in the inner-city LORs. This is due to the fact that, with a higher level of motorization and a correspondingly higher number of BEVs in the LOR, more renewable energy can be temporarily stored. As discussed in the previous paragraph, the renewable peak load then exceeds the residential peak load. Accordingly, the peak power demand in the LOR increases.



(**a**) (**b**)

Figure 11. Spatial distribution of the peak power demand increase in Berlin LORs. Summer case. (**a**) 0% vehicle participation in V2G. (**b**) 15% vehicle participation in V2G.

3.4. Battery Load Increase Due to Vehicle to Grid

This section examines the increase in battery load due to V2G. The battery load increase (BLI) is calculated for each LOR as follows:

$$BLI = \frac{E_c - E_d}{E_d} \tag{2}$$

where E_c is the amount of energy charged by the vehicles which participate in V2G and E_d is the amount of energy consumed by the participating vehicles during their trips.

The distribution of the battery load increase in the LORs is shown in Figure 12 as boxplots. The blue square depicts the average battery load increase in the LORs.

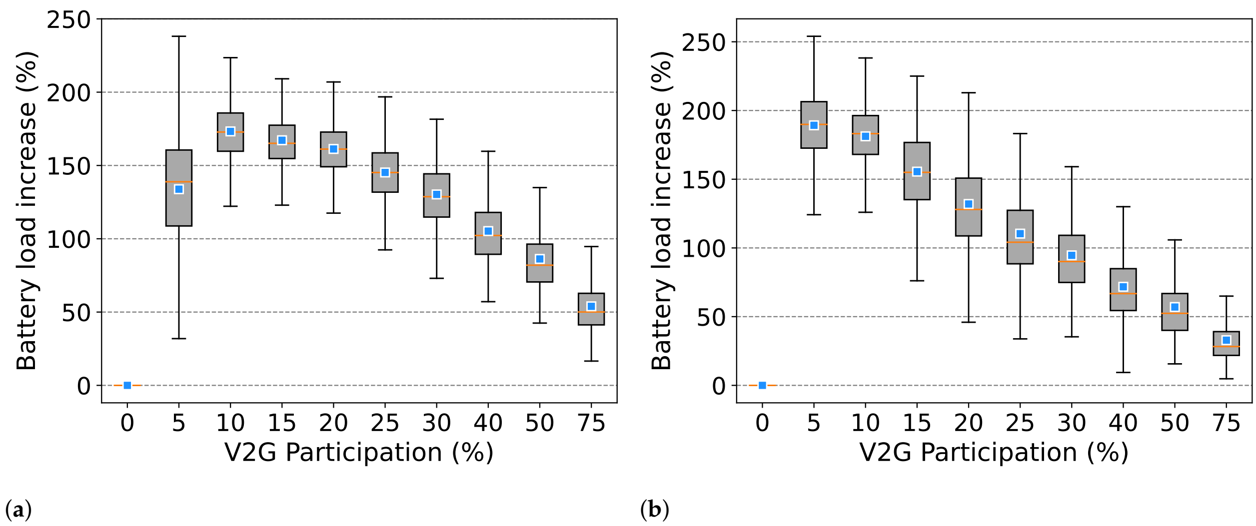


Figure 12. Battery load increase in the Berlin LORs due to V2G application. (**a**) Summer case. (**b**) Winter case.

In the summer case shown in Figure 12a, the average increase in battery load in the LORs is 134% at 5% vehicle participation in V2G and 173% at 10% vehicle participation. At higher participation rates, the average battery load continues to decrease and is 54% at 75% vehicle participation in V2G. The reason for this decrease is the increasing number of LORs whose energy demand is fully met by renewable energy. The amount of energy charged therefore remains almost constant, while the number of vehicles to which this amount of energy is distributed increases. Accordingly, the battery load decreases.

The reason that the average increase in battery load is lower when 5% of vehicles participate in V2G than when 10% participate is because, when 5% of vehicles participate, the absolute number of participating vehicles is very small in some LORs (<10 vehicles). Due to the small number of vehicles, it is possible that all vehicles are on the road during the midday hours. In summer, however, midday is the time when renewable energy is mainly available. From 10% participation, it becomes increasingly unlikely that all vehicles are on the road during midday due to the larger absolute number of participating vehicles. Therefore, more renewable energy can be temporarily stored and the average battery load increases.

For the winter case shown in Figure 12b, this effect cannot be observed because renewable energy is more evenly available throughout the day. The highest average increase in battery load is observed for 5% vehicle participation in V2G and is 189%. As explained previously, the average battery load decreases at higher participation rates and is 33% at 75% vehicle participation in V2G. The reason that the average battery load is lower in winter than in summer when 75% of vehicles participate in V2G, is due to the nearly constant availability of renewable energy. As a result, more renewable energy can be used directly and does not have to be stored temporarily in the BEVs.

3.5. Discussion

The results show that, already at 10% vehicle participation in V2G, a significant share of the energy demand of households and BEVs in Berlin can be covered by renewable energy (80.4% in summer and 95.2% in winter). High shares of renewables are observed mainly in the outer-city LORs, as the motorization rate is higher than in the inner-city. With 30% vehicle participation in V2G, more than 99% of household and BEV energy demand can be met by renewables in summer and winter. A renewables share of 100% can be obtained with 75% vehicle participation in V2G.

Uncontrolled charging (0% V2G participation) increases the average peak power demand in summer by 28% compared to residential power demand. V2G deployment increases the average peak power demand in the LORs by up to 102% in summer compared to residential power demand. In winter, peak power demand in the LORs hardly increases due to V2G (close to 0% increase) and can even be reduced compared to uncontrolled charging.

V2G deployment leads to an additional load on the vehicle batteries. The average battery load increase is up to 189% in winter and 173% in summer.

Concerning these results and the proposed approach, a couple of aspects should be discussed:

- In this work, the V2G potential in Berlin was determined for two specific days, one in summer and one in winter. An average profile for available renewable energy was used for each of these two days. However, the availability of renewable energy fluctuates and can deviate significantly from this average. Accordingly, the generated results indicate the V2G potential in Berlin. On a particular day, the amount of renewable energy that can be integrated into the electricity mix depends on the actual daily profile (see Outlook).
- The vehicles participating in V2G are randomly selected in the LORs for each V2G participation scenario. Depending on the selected vehicles, the results may vary from the calculated value, which has not been investigated. However, due to the large number of vehicles in Berlin (1,045,000), we expect a rather small fluctuation.
- The power grid was not modelled. Therefore, network congestion as well as losses of transmission and distribution of electric power were disregarded. If grid conditions are also considered in the model, a lower V2G potential is expected. A possibility of modelling grid conditions is described in [57].
- V2G requires communication between the vehicle owner and the V2G control centre, in which the vehicle owner specifies, for example, their planned parking time. The V2G control centre collects the information and processes it. Appropriate communication between the V2G control centre and the vehicle owner was assumed in this work. An overview of the current communication standards can be found in [17,34].
- Battery ageing is not considered for the V2G investigations. However, due to the increase in battery load battery life is expected to be shortened. The V2G investigations should therefore be extended by a battery ageing model with the aim to find a good trade-off between renewable energy integration and battery degradation. In addition, BEV owners should receive financial compensation for the loss in value of their vehicle due to battery ageing.
- In our case study, we assume that the driving and parking behaviour of all considered vehicles is known in advance. In reality, however, these factors are subject to considerable uncertainty. Therefore, our study clearly shows the potential benefits of V2G integration but the results must be seen as an upper bound and further work is necessary to include uncertainty in our model. One possibility is to use stochastic approaches, as shown in [58].
- With 30% vehicle participation in V2G, more than 99% of the residential energy demand and BEV charging demand in Berlin can be met by renewable energy. Accordingly, there is further untapped V2G potential that could be used to increase the share of renewable energy in commercial or industrial energy consumption.

- In addition to passenger cars, other vehicles such as commercial vehicles or buses are currently being electrified. These vehicles can contribute significantly to the integration of renewable energies into the electricity mix through V2G, as shown in [59]. For a holistic view, these vehicles should therefore be included in our model.

4. Conclusions and Outlook

In this paper, a method is developed that determines the V2G potential of BEVs in a considered area with high spatial resolution. The method is applied to the urban area of Berlin and its 448 sub-districts, assuming full electrification of the 1,045,000 private cars in Berlin. For each sub-district, the method allows determining the percentage of residential and BEV energy demand that can be met by renewables if V2G is deployed, and answers the question of whether a full renewable supply is possible. We investigated the V2G potential for each district considering ten V2G participation scenarios (0–75% participation). Since the availability of renewable energy during the day depends on the season, we distinguish between a summer and a winter case. For each case, the availability of renewable energy is described by an availability profile. The profiles correspond to the average availability of renewable energy in Germany for two weeks each in the summer and winter of 2021. Accordingly, the results obtained refer to a single day in summer or winter with the two-week-average renewable power availability.

The results show that with 5% vehicle participation in V2G, more than 60% of the energy demand of households and BEVs in Berlin can be met by renewable energy in summer and more than 80% in winter. High shares of renewables are mainly observed in the outer-city districts, as they have a higher motorization rate than the inner-city districts. With 30% vehicle participation in V2G, more than 99% of household and BEV energy demand in summer and winter can be met with renewable energy. A share of 100% renewable energy can be achieved with 75% vehicle participation in V2G.

However, V2G deployment increases the average peak power demand in the LORs by up to 100% in summer compared to residential power load. This may require reinforcement of the electric grid. In winter, peak load in the LORs hardly increases due to V2G (close to 0% increase). In addition, the deployment of V2G leads to an additional load on the vehicle batteries. The average battery load increase is up to 190% in winter and 170% in summer. This increase in battery load leads to increased battery ageing. BEV owners must therefore receive financial compensation for the loss in value of their vehicle.

Based on the proposed methodology, we plan to conduct further research in the future:

It was assumed that vehicles only participate in V2G if they are parked at their owner's residence. The method also allows for investigation of the V2G potential for other parking locations such as workplaces.

In this work, full electrification of Berlin's private vehicles was assumed. Since the developed method operates at the vehicle level, it can also be used to determine V2G potential in the districts for lower levels of electrification (e.g., 50%).

An average profile for available renewable energy was used for one day in summer and one day in winter. To account for the fluctuation of renewables, simulations should be conducted on a daily basis with the actual daily availability profile over several weeks and across different seasons. In addition, the local resolution of renewable energy availability should be increased by using the profile of the geographic region around Berlin instead of the profile of Germany.

Furthermore, it is desirable to consider the modelling of the power grid in order to account for the effects of network congestion as well as losses of transmission and the distribution of electric power.

Finally, the electricity demand side has to be expanded beyond private households by including commercial and industrial electricity demand.

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Abbreviations

The following abbreviations are used in this manuscript:

BEV	Battery electric vehicle
ICEV	Internal combustion engine vehicle
LOR	Lebensweltlich-orientierter Raum (neighbourhood-oriented district)
RE	Renewable energy
SOC	State of charge
V2G	Vehicle to grid
WLTP	Worldwide harmonized light vehicles test procedure

Appendix A. Electric Reference Vehicles and Charging Curves

Table A1. Electric reference vehicles. The vehicle data are obtained from databases of the ADAC (Allgemeiner Deutscher Automobil Club), a German motoring association [60].

Class	Model	Battery Capacity (kWh)	WLTP Consumption (kWh/100 km)
Mini compact	Mitsubishi i-MiEV	14.5	13.5 *
	Renault Zoe	52.0	17.7
	VW e-Up!	16.0	14.3
Compact	BMW i3	37.9	15.3
	Hyundai Kona E	64.0	14.7
	VW e-Golf	32.0	15.8
Medium	Kia e-Niro	64.0	15.9
	Nissan Leaf	60.0	18.5
	Tesla Model 3	53.0	14.3
Large	Audi e-tron	83.6	23.0
	Mercedes EQC	80.0	22.6
	Tesla Model S	85.8	18.9

* New European Driving Cycle (NEDC) consumption. WLTP consumption is not available.

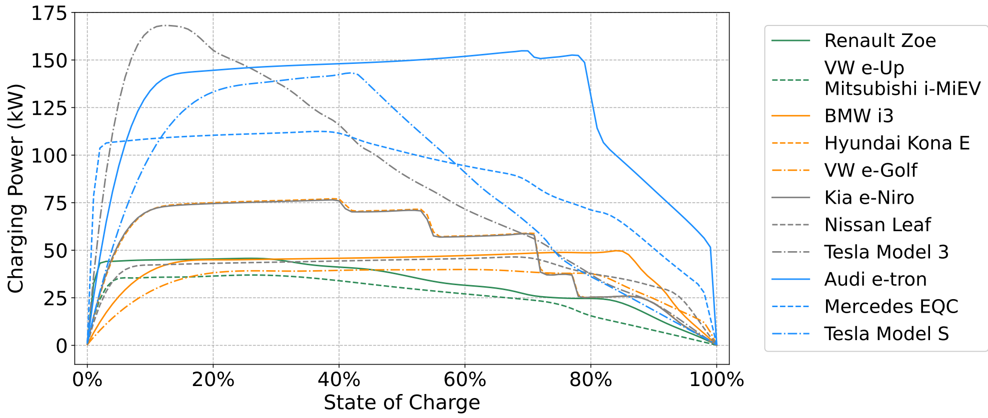

Figure A1. Charging curves of the reference vehicles [47,48].

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