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Effects of Charging Strategies and Policies on Electric Vehicles and Infrastructure From a Microscopic Perspective

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Abstract. The growing number of battery electric vehicles (BEV) implies changes in urban infrastructure. Large amounts of charging stations are to be built within few years to supply energy for a mostly electric vehicle fleet. In parallel the power grid has to be adpated to the growing energy demand. However charging behaviour depends on mobility patterns and which type of charging stations can be accessed. For example, charging at work is mostly restricted to employees and happens during working hours. Public charging stations cater any BEV user but take precious public space. In this work several charging station configurations for a city are studied on a microscopic level together with different BEV shares and charging strategies and policies. 24 hour working day SUMO microsopic traffic demand travels along trip chains and charges their electric vehicle battery when needed. Parking and charging infrastructure is limited to reasonable capacity for a medium sized German city. Then the configurations are evaluated with respect to charging station usage and the expected energy demand/supply of BEV for balanced and time-shift charging strategies as well as vehicle-to-home/vehicle-to-grid policies. Applying these strategies and policies on a large scale can lower the energy peak demand visibly.

Keywords: Electric Vehicle, Charging Stations, Traffic Simulation

1. Introduction

Reducing greenhouse gas emissions is a major task in many domains to mitigate the effects of climate change. In the transport sector, European emission standards have paved the way for locally emission-free vehicles like battery-electric ones (BEV). The BEV share of the vehicle fleet is expected to increase steadily since the European Parliament voted to end registering new internal combustion engine vehicles in 2035 [1]. This means BEV passenger cars may become the norm independently of whether users can charge on their property within the next two decades. In order to actually achieve emission reductions, renewable energy sources have to be used at large scale. This may lead to much more demand for electric energy whereas the energy supply will vary more during the course of the day and between seasons. In parallel a growing number of home owners installs stationary storage systems together with photovoltaic systems as pointed out by [2].

Assuming that human mobility will remain car-centered in the short run and drivers accept small detours or delayed departures due to charging, the needed infrastructure and energy demand can be estimated. Many studies like Windt and Arnhold [3] deliver a macroscopic view on charging infrastructure, defining expected amounts of certain charging station types for German administrative areas a within the next decade. Hardinghaus et al. [4] derive charging demand from microscopic traffic demand using a small decision model. Few works actually consider how charging stations can be operated on a microscopic level given a charging demand: Mostly charging stations are installed on already existing parkings, limiting the amount of charging points in densely built areas. The main categories of charging stations with reference to accessibility and location are listed in table 1.

Table 1. *Different categories of charging station locations.*

Category	Accessibility	Property
Residential	Private	Private
Commercial / Work place	Private	Private
Retail	Semi-public	Private
Public	Public	Public

Current European guidelines and German legislation enforce charging stations at major existing commercial and retail properties as well as at newly constructed residential blocks [5] [6]. Surveys about BEV usage show that (potential) users prefer to charge the vehicle while they conduct some other activity like staying home, education, working and shopping [7]. The main German mobility survey "Mobilität in Deutschland" (*MiD*) [8] collects time lines of peoples' activities across the day suitable for validating a synthetic traffic demand. Märtz et al. [9] have found that charging the BEV once returned home at around 18:00 is a frequent pattern with BEV users, contributing to the peak energy demand. This leads to the question which charging station locations shall be preferably developed to meet sustainability goals. Windt and Arnhold [3] define multiple extreme scenarios regarding charging station development: Whether fast chargers will dominate, whether charging points with restricted access will be especially developed or particularly disregarded. Given people get multiple occasions along their daily trip chain to charge their BEV, extreme scenarios would induce major changes when and where charging happens. In general the energy offer needs to be adapted along with the charging station setup.

Many authors worked on optimising charging station locations (see meta study [10]). Others optimised charging station utilisation through various operational approaches (e.g. [11] [12]). Both research topics are of major use where few (public) charging stations compete for customers. With a growing number of BEV and charging infrastructure the connection between energy supply and traffic becomes more important.

That's where charging strategies step in. Whenever BEV do not need to be charged as fast as possible, the charging process can be shifted in time or the power can be lowered. This way peak energy demand can be redistributed to less busy hours, reducing the risk of overloading the power grid. Although authors (see [13] [14]) name their strategies differently, some basic common ones can be identified: "reduced"/"balanced" charging, where the power is lowered such that the whole parking duration has to be used to charge. Then there is “residual load”/“market-oriented” charging which shifts the charging process to more advantageous times for the power grid. Similarly, bidirectional charging also known as vehicle-to-home (V2H) / vehicle-to-grid (V2G) can help balancing energy demand and supply: According to Müller et al. [15], BEV users can either make more use of self-owned photovoltaic systems (V2H), optimise charging times by tariff or contribute to shave peak loads in the power grid (both V2G).

Said relations between energy supply and traffic lead to simulating both topics together. Frequently studies focus on one part and model the other in a more coarse way. For example, Gemassmer et al. [14] generate synthetic trajectories from *MiD* trip characteristics as input for their charging strategy model. Gauglitz et al. [16] construct a charging point distribution model on household level to better investigate local effects on the power grid using demographic and mobility data. On the other side, traffic simulation is used for questions regarding charging station locations and optimal usage from a user or transport system perspective. Widmann et al. [17] use MATSim to minimise waiting time of BEV in a long distance scenario.

Gharbaoui et al. [18] were among the first to simulate charging stations within SUMO [19]. They emulated charging station operation in an Italian city using the Traffic Control Interface (TraCI) before charging stations got integrated into the microscopic simulation in 2013 [20]. Frendo et al. [21] assess the effects of charging strategies on a corporate vehicle fleet using SUMO. Some authors model the population of an entire city to create charging station demand ([22], [23]). While Schönberg et al. [22] focus on how individuals can integrate charging stops in their daily trips, Klingert and Lee [23] deduce load of the power grid on a local level. Although the latter work respects *MiD* trip characteristics, trips are not chained and origins and destinations are uniformly distributed across the city. Further applications in SUMO include commercial EV fleet route planning [24] and modeling public charging stations using open data of the German Federal Network Agency [25].

1.1 Research questions

Windt and Arnhold [3] provide extreme scenarios and a reference scenario how charging infrastructure in Germany might develop. The amount of needed charging stations per category from the table 1 cannot be determined independently: BEV users may substitute charging at home with charging at work or vice versa. The effects on the energy system can only be assessed once the overall charging times and locations are known.

This leads to microscopic traffic simulation as a tool to evaluate different charging station configurations of whole cities. SUMO can be used to test which charging station usage patterns can be seen for different charging station configurations and BEV shares. Then the energy demand coming from BEV can be derived and effects of charging strategies can be quantified. Concrete questions in this context would be which share of charging events charging stations in public space should cater and which measures should be used to keep the peak energy demand as low as possible.

2. Methodology

Developing a microscopic traffic simulation centered on BEV charging requires several building blocks. Besides preparing the road network and the traffic demand SUMO has been extended to include a device for charging station search. Then the scenarios are built using parameters for parking and charging infrastructure.

2.1 Charging station specific vehicle behaviour

Within this research the **stationfinder** device of SUMO has been extended and applied to redirect BEV to charging stations when their state of charge (SoC) drops below an indivual threshold value. The device allows vehicle-driver units to search for suited charging stations nearby their route and carry out the charging process on their own. Optionally, the vehicle can break down when running out of energy.

Every vehicle equipped with the device can be constrained in its charging station search. Further on the main idea of the **stationfinder** device and the set conditions are explained with help of figure 1. By default the device is active during the whole trip of an equipped vehicle and monitors the SoC every second. Imagine vehicle *V1* travels from origin *O* to destination *D* as its SoC drops below a threshold (default 40%) and the remaining route is deemed unfeasible with the remaining charge. Thus it starts at its current location searching for a charging station. Three candidates named *C0* to *2* are present in the network but *C0* is located outside the maximum accepted air-line distance *R*. Additionally, a charging station can be ignored when causing a too long detour in terms of travel time. The preferred charging station is chosen taking into account how much the vehicle-driver unit values indicators like detour, expected charging duration and waiting time due to preceding vehicles like vehicle *V0*. Moreover, charging stops can be aligned with other planned stops. If a charging station is found, the vehicle will head there immediately before serving other planned stops. In case no free charging point can be found or the selected one is occupied the search is repeated later on. So the main thresholds to set for a charging station search are:

- Detour: Only consider charging stations adding at most this expected additional travel time
- Air-line distance: Only consider charging stations within a spatial search radius

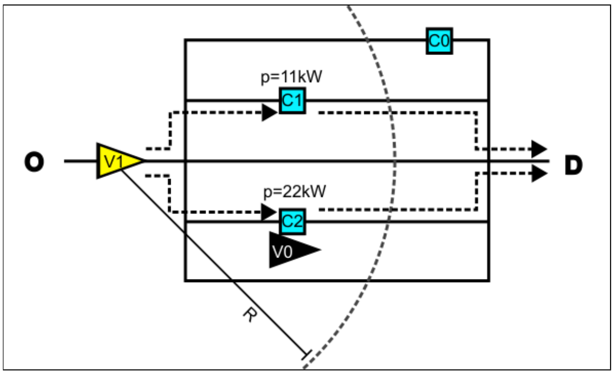


Figure 1. *stationfinder device routing principle.*

In contrast, **stationfinder** instances do not optimise the stop order with regard to charging (yet) but choose to stop at a charging station first. Vehicle-driver units do not learn from previous searches except for remembering the last n already occupied charging stations.

The BEV fleet is built out of three base vehicle types representing small (Renault Zoé), medium (Volkswagen ID.3) and big (Tesla S) passenger cars in equal shares. Corresponding battery and vehicle characteristics have been configured in SUMO. When simulating the BEV fleet of a whole city one needs to set the inital states of the vehicles carefully. They influence largely the charging events in a city because the battery range of recent BEV outnumbers the expected daily trip lengths by far. Moreover simulating a random working day implies vehicles do not start all with the same SoC. Accordingly, every BEV vehicle-driver unit draws initial SoC and **station-finder** device thresholds from distributions. Here three normal distributions (means 10%, 30%, 50%) are used for SoC in equal shares. Drivers start looking for a charging station when the SoC drops below a value drawn from $\mathcal{N}(0.4,\, 0.1)$. Said distributions are not backed by empirical data but are necessary to spread charging events in time and location.

2.2 Scenarios

Firstly, the microscopic traffic simulation has to be prepared to apply a specific charging station configuration in a second step. Whereas the road network, the base traffic demand and parking infrastructure are shared among the scenarios, charging station locations and the number of charging points are sampled using the SUMO tool **distributeChargingStations.py** separately for each scenario.

Some assumptions have been made for assigning vehicles to parking spaces or charging points: Parkings and charging stations are grouped, creating at most a public and a private one of each type per edge. Splitting them even more does not seem convenient due to the lack of supporting data and how this worsens parking search in SUMO. Trip chains are concatenated into single trips in SUMO with intermediate destinations becoming stops. The vehicle gets assigned a private (personal) parking site on the origin and destination edge of the concatenated trip (if still available). This way parking at home at a personal parking site is modeled. Vehicles are inserted into the simulation before their actual departure from the origin and remain at their final stop for some time to represent parking/charging "at home". In this work vehicle-driver units prefer to replace already planned stops with stops at close charging stations. If successful they park/charge at the charging station as long as for the original stop. This way charging while executing an activity nearby is modeled.

Currently V2H and V2G have not been integrated into the simulation. Their effects are estimated in post-processing like for the other charging strategies. V2H/V2H-enabled Vehicles and charging stations are selected randomly. As long as a vehicle stops longer than needed at a charging station, the resulting flexible time is used for the charging strategy or V2G/V2H operation.

2.2.1 Traffic demand and road network

Studying charging station related questions for a whole city requires a substantial amount of microscopic traffic demand. Charging may take hours depending on the SoC and the power of the charging station. Therefore users prefer to integrate it into the daily trip chain by charging nearby places they execute some other activity. A macroscopic traffic demand (origin-destination matrix) could not provide a consistent SoC throughout several trips of the same car. In contrast, microscopic traffic demand contains trips of persons which can be concatenated to a trip chain. Assuming everybody uses a personal car (no car sharing), the final SoC of the previous trip is assumed to be the initial SoC of the current one. Evaluating aggregated measures regarding charging station occupancy and the resulting energy demand requires a realistically spatially and temporally distributed traffic demand to clearly see the effects of certain charging station configurations.

In this work we use the SUMO Braunschweig scenario available at [26] based on OpenStreetMap data [27] together with a separate microscopic traffic demand. The latter was generated with help of a traffic demand model in a previous project. It con-

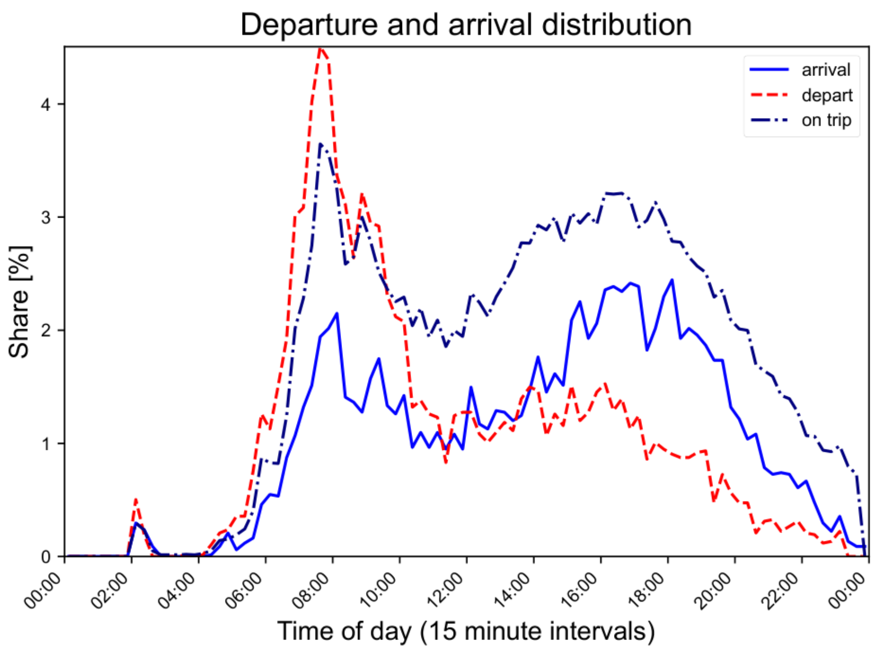


Figure 2. *Model-based 24 hours traffic demand of motorised inner-city car traffic in Braunschweig, Germany.*

sists of the internal car traffic in the city during 24 hours, totaling 645k trips or 134k trip chains. By consequence it misses several kinds of trips with oder modes as well as commercial transport, incoming, outgoing and through traffic. As simulating parking events increases the number of vehicles within the simulation, the total number of simulated vehicles had to be cut for performance reasons. Finally, only electric vehicles are simulated because they are essential for the research questions – potentially underestimating the parking search and traffic flow effects on energy consumption.

The line graph in figure 2 visualises the share of car drivers leaving their origins and those arriving at their destinations over the course of the day. It represents the basic pattern of working day traffic with clearly visible peaks for departures and arrivals. The derived amount of traveling people can be compared roughly to traffic volume time variation curves like in [28]. There the more pronounced morning peak and the more diluted afternoon peak can be recognised. Nobody leaves around midnight although this may be partially due to the time limits of the scenario.

The small peak at around 02:00 is caused by initalising issues of the simulation. Vehicles are inserted into the simulation before their actual departure time to allow for nightly charging close to their origin location. However SUMO vehicles are inserted on the road instead of being placed directly on a parking. Some of the vehicles may travel to a charging station directly. This means traveling up to $300m$ to a parking or a charging station does not yet count as departure in figure 2. Most travel times needed to reach the nightly charging station have been removed from the evaluation using heuristics but failed in a few cases: If the "artificial" trip leg to the actual parking or charging location is too far away from the origin the insertion time is kept as departure time. Note that the complete count of vehicles from the microscopic traffic demand could not be simulated in SUMO: Keeping all vehicles in the simulation during the simulated day to keep parking sites occupied and rerouting many BEV increased the computation time way too much. Still the simulation of the BEV and few other vehicles needs around 1.5 days to terminate for some of the scenarios in 2.2.3.

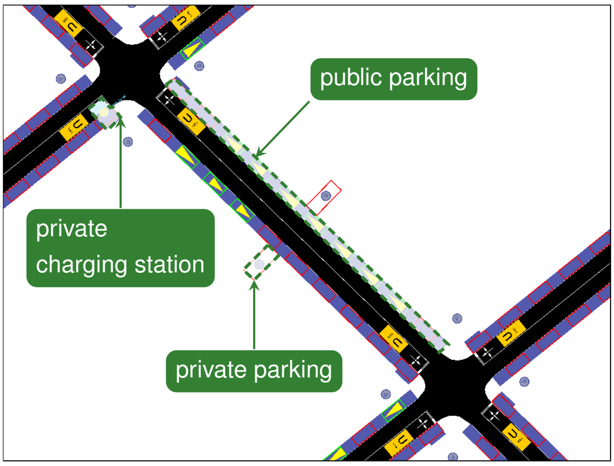


Figure 3. *Annotated SUMO visualisation of the parking and charging infrastructure.*

2.2.2 Parking and charging infrastructure

Generally speaking, charging stations can be installed in various sites. House owners may install a wallbox on their private parking site. Retailers and big companies can enhance their parking facilities with charging stations. Finally, public administration can allow to build charging stations next to parking sites in public space. In some cases service stations may dedicate space for charging stations. This means the parking space already exists in most cases but may not be accessible for everyone: Only residents are allowed to use parking spaces next to their home and usually only employees can make use of charging stations on sites of their company. On the opposite charging stations on public space (roadside parking) can be accessed without restrictions.

Essentially charging points are modeled on top of existing parking spaces. In order to model future charging infrastructure the existing parking capacity and its access restrictions have to be known. Unfortunately existing information about parking sites on OpenStreetMap [27] is incomplete and private parking sites are exempted anyways. For this reason the amount of road side parking spaces and parking spaces on private property per SUMO edge have been estimated from Braunschweig aerial photos: The built environment has been subdivided into different land use areas and rates of parking spaces per road length for different land use types have been calculated (see table 2). "Low density" residential refers to detached houses and row housing, "medium density" to apartment blocks with some dedicated parking and "high density" to inner

Table 2. *Estimated parking space rates in parking spaces per meter of (unidirectional) road depending on the land use type, based on empirical samples from Braunschweig, Germany.*

Land use type	Road side parking space $\left[\frac{space}{m}\right]$	Parking space on private property $\left[\frac{space}{m}\right]$
Low density residential	0.07	0.50
Medium density residential	0.10	0.50
High density residential	0.13	0.15
Commercial	0.14	1.00
Retail	0.14	1.50
Mixed use	0.10	0.10

city housing. The main purpose was to vary the relation of public to private parking spaces depending on the land use type. High density residential areas typically offer less options for parking a car on the property than low density residential areas.

For each road a public road side parking area and a private parking area are generated using the road lengths from the SUMO network. The charging station setup is part of the scenario definition (see 2.2.3) and defined similarly to the parkings. For every combination of land use and property type (public/private), the following numbers are defined:

- The probability of a road to have a charging station
- The share of parking spaces along the road to be converted into charging points

In a second step, the roads are drawn randomly where charging stations are to be split from existing parking areas. In order to differentiate between public and private parking areas in SUMO, the parking access system has been developed in this work: Every parking can define a set of codes from which vehicles need at least one defined on their side to get granted access. Public parking areas can be accessed by any vehicle whereas only vehicles which start or end their trip chain on a certain road get access to the local private parking.

2.2.3 Scenario characteristics

Three scenarios are defined as displayed in table 3. The *base* scenario represents the current state in the city of Braunschweig with a BEV share below 10 % and no V2H/V2H in place (although some house owners may already use V2H on a small scale). In the *near future* scenario the BEV fleet increases by a small extent and more charging stations are opened. The number of public charging points is extrapolated from current development in Braunschweig. Already installed charging points from a licence granted by the city administration are scaled with their target number of charging points by 2030. Finally the *V2H/V2G* scenario assumes V2G/V2H is available on the market for both the vehicle and the infrastructure side.

2.3 Calibration and post-processing

Calibration and validation measures which actually fit the research questions described in 1.1 are difficult to define. Several traffic simulation studies use measures such as section counts, delay or speed to calibrate the simulation. Instead this study focuses on replicating charging behaviour of BEV users concerning time and location. Small changes in energy consumption due to delays should not change the overall user behaviour. Main wanted characteristics are

Table 3. *Scenario key characteristics.*

Scenario name	BEV share $[\%]$	V2G/V2H share $[\%]$	Share of public charging points $[\%]$
Base	5	0	2
Near future	10	0	9
V2H/V2H	10	$[10; 20]$	9

- nightly charging and
- massive charging events around 18:00 corresponding to [9].

As the aggregated simulation results are derived from several thousands of trip chains, it is not deemed necessary to conduct several repetitions of the simulation. After the simulation a post-processing step is necessary to actually implement nightly charging and to compute the evaluation indicator values. As only one day of traffic has been simulated, charging station search (see 2.1) cannot integrate trips of the day to come and the day before. Moreover, the **stationfinder** device promotes charging shortly after departure because it reroutes the vehicle immediately. The post-processing logic shifts departures and arrivals as well as charging times to emulate nightly charging. Several heuristic conditions are set to ensure only vehicles with charging events in the early morning or late evening are modified.

3. Results

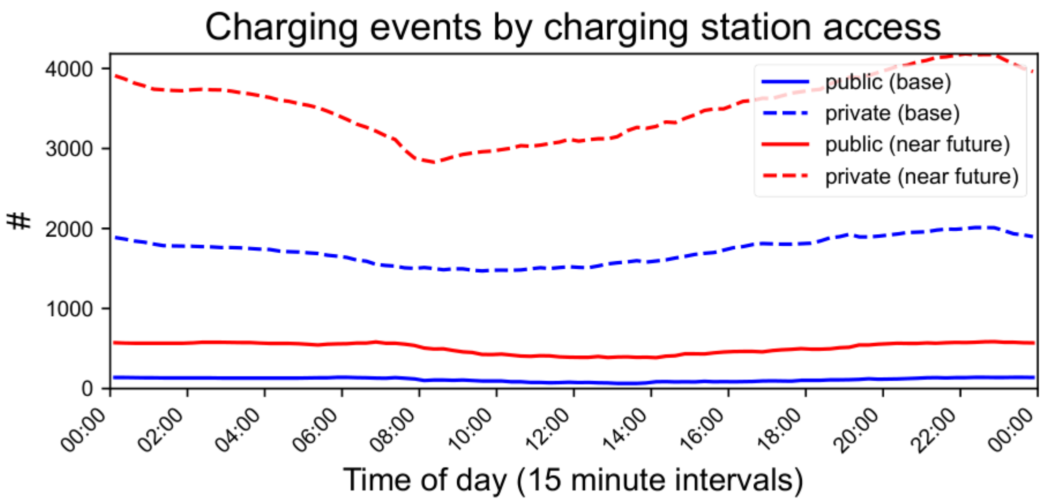
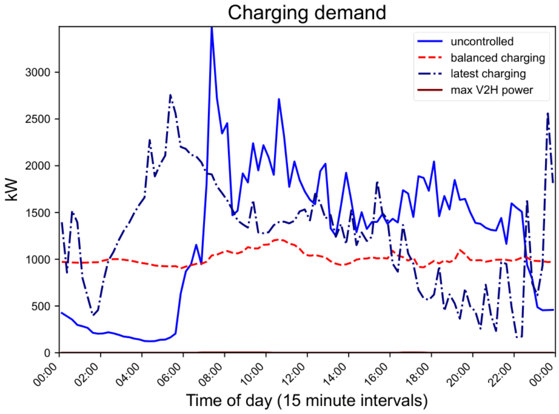


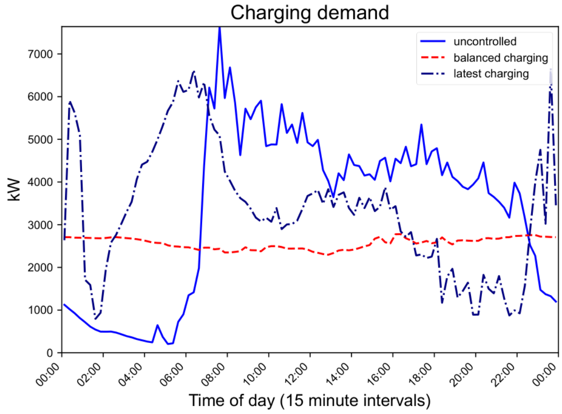
Figure 4. *Charging events at publicly and privately accessed charging stations over the time of day per scenario.*

Here some preliminary insights are presented regarding the research questions. It is conceivable that the immense number of rerouting operations and teleports happening in the scenarios has influenced the results. Especially vehicles looking for a free parking site can remain blocked easily for several minutes delaying their arrival at charging stations. The figure 4 plots the number of vehicles connected to charging stations across the day. Charging stations are categorised into the ones accessible to everyone (public) and those with access restrictions. Clearly the post-processing has added nightly charging with more vehicles connected during night times. This is in line with [9] who noted large numbers of vehicles plugged in in the late afternoon and plugged out in the morning. The relation of public to private charging stations in both scenarios amounts to around 10%. Given that only internal city traffic is simulated and many assumptions have been made when preparing the simulation, this seems to be a reasonable number.

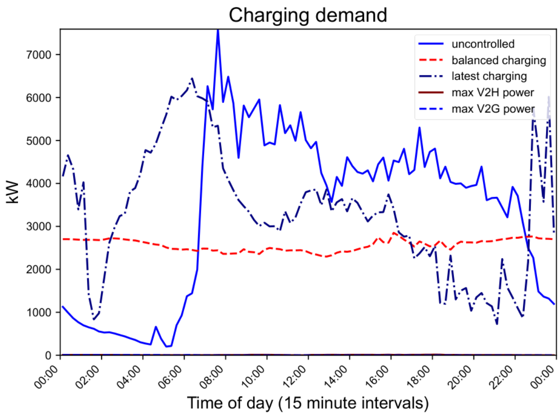
The figure 5 shows the energy demand of charging BEV over the time of day labelled as "uncontrolled". Effects of charging strategies on energy demand have been added in the post-simulation processing, assuming the parking duration of the vehicle is known in advance and communicated to the energy provider. The "balanced" charg-



(a) *Base scenario*



(b) *Near future scenario*



(c) *V2H/V2G scenario*

Figure 5. *Estimated charging demand across the day using different charging strategies for the investigated scenarios.*

ing strategy lowers the charging power to the minimum needed to charge the vehicle in time, whereas the "latest" charging strategy shifts the charging begin to the latest point in time to complete with maximum charging power. The figure 5c adds the power V2H and V2G-equipped charging stations can provide to the power grid. It can be seen that adapting the charging power like with the "balanced" strategy clearly reduces the peak energy demand. At this level V2H and V2G contribution remains small but may still be useful for short and local balancing of the power grid.

4. Conclusion

This work had to use many assumptions which cannot be validated easily to build the simulation scenarios. For example, empirical parking and charging infrastructure data is only partially available and charging behaviour is influenced by more factors than have been included here. Charging strategies were assumed to be applied to all charging BEV. So there is still a long way to make the simulation predict charging station usage reliably and be more efficient in computing resources. Nevertheless basic features like nightly charging and predominant use of private charging stations could be replicated. The "balanced" charging strategy seems promising to lower the energy peak demand. On a macroscopic scale, a 10% share of BEV users participating in V2G does not contribute much to relieving the power grid. However this could change if the V2G option would be integrated into the charging station search and not applied randomly in post-processing.

Data availability statement

The data is not publicly available (yet).

Underlying and related material

Some of the input and used scripts are publicly available. The SUMO network used in this work can be accessed at [26]. The **stationfinder** device and the script **distributeChargingStations.py** to distribute charging stations on previously defined parking areas have been integrated into the official SUMO 1.22 release [29].

Author contributions

The work has been done exclusively by the main author.

Competing interests

The authors declare that they have no competing interests.

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