



Article

Finding Attractive Electric-Vehicle-Charging Locations with Photovoltaic System Integration

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Abstract: The rise of electric mobility poses a challenge and an opportunity for the housing industry to provide charging infrastructure. The housing industry can take advantage of its large roof areas to install photovoltaic (PV) systems and use the electricity generated to charge electric vehicles. This study explores how the charging demand can be allocated to specific locations based on socio-economic parameters and determines whether PV integration is economically viable for EV charging. Two models are used, one with extensive spatial and traffic data to determine the charging demand for over 300 locations, and another with a time-series-based approach for four specific locations to analyze the seasonal dependencies. The results indicate that PV integration is economically advantageous when electricity purchase prices exceed 0.15 EUR/kWh. Higher electricity prices can lead to significant additional profits through PV integration. Slow charging and charging during the day are beneficial, as they increase self-consumption, making PV systems economically viable. However, fast-charging infrastructure should be combined with PV storage systems for effective PV integration.

Keywords: electric vehicle; charging infrastructure; photovoltaic; profitability



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1. Introduction

The electrification of motorized transport is a central part of the strategies to reduce CO₂ emissions in developed countries. For instance, German legislation for climate protection calls for a 65% reduction in greenhouse gas emissions by 2030, compared to 1990 (Bundes-Klimaschutzgesetz, §3 (1)). This has been broken down to a reduction in traffic-related emissions from 164 million tons of CO₂ in 2019 to 85 million tons in 2030. An appropriate contribution to this target would be to replace one-third of the internal combustion engine vehicles (ICEVs) in Germany with battery electric vehicles (BEVs) [1].

The impending shift towards sustainable transportation necessitates a heightened integration of electromobility into everyday life, with particular emphasis on meeting the charging infrastructure needs of tenants in multi-family housing complexes. In light of this imperative, this study is dedicated to the real estate sector, and specifically to the efforts undertaken by the housing industry to promote electromobility within its properties. Within the housing industry, a significant advantage lies in the availability of expansive roof areas adjacent to charging infrastructure, which provide conducive environments for the installation of photovoltaic (PV) systems. Utilizing the concrete case of WIRO GmbH's real estate holdings in Rostock, Germany, this research investigates various facets. WIRO GmbH [2] manages approximately 35,000 apartments in Rostock, a major German port city on the Baltic Sea with a population of ca. 210,000. The primary focus lies in analyzing the optimal locations within these properties for the establishment of charging infrastructure.

Simultaneously, we delve into an examination of the added value and potential challenges associated with the integration of photovoltaic systems into this charging network. This study aims to enhance the efficiency and attractiveness of electromobility for employees and private and commercial tenants, as well as other users of WIRO GmbH's real estate properties [3].

The question of what added value a PV-coupled charging infrastructure offers for privately owned single-family homes has already been discussed extensively in the research [4,5]. However, in Germany in particular, the proportion of the population renting is significantly higher than in other countries. With a share of over 50%, Germany has the highest proportion of the population living in rented accommodation [6]. Therefore, this study developed an approach that can transfer the question to the requirements of a housing association with mainly large multi-family buildings.

Two different approaches were pursued. The first approach serves as a preliminary estimate to obtain an initial idea of which buildings could be suitable for the combination of charging and PV infrastructure. The second approach is subsequent, uses developed time series and provides a more precise estimate of the economic viability, taking into account the seasonality of EV consumption and PV generation. In comparison with the detailed time-series method, it can be seen that an approximate approach can already deliver good results.

This paper is structured as follows: After a short review of recent developments and the literature in general, and specifically for the case of Rostock, the data and methods used in this study are described in Section 3. Results are presented in Section 4 and discussed in Section 5. The paper concludes with recommendations for similar concepts and further research.

2. Recent Developments and State of Practice

For Germany, BEV shares of around 30% by 2030 seems attainable considering trend extrapolations of registration data [7], cleanroom discussions with original equipment manufacturers [8] as well as models of the vehicle fleet depending on the termination date of ICEV sales [1].

Factors supporting this trend are the slowly decreasing number of ICEV models against a growing multitude of BEV models [9,10]. It is hoped that "affordable, competitively priced" [10] BEVs will become available in Europe on a larger scale. At the same time, a major challenge is to expand the charging network accordingly [11]. While the availability of charging options is elementary with respect to the intention to purchase an electric vehicle [12], a comparison of the situation in China reveals an interesting aspect about the importance of charging infrastructure: as the IEA observed in 2022, the sales-weighted average range of small BEVs sold in France, Germany and the United Kingdom was just under 300 km, compared to under 220 km in China. The IEA concludes that the broader availability of public charging points in China may, in part, explain why consumers there have been more willing to opt for lower driving ranges than their European counterparts [10].

As for the extent of charging infrastructure, the European Union Alternative Fuels Infrastructure Directive recommends one charging point per 10 BEVs [13]. Currently, Germany is trailing this target with one charging point per 25 BEVs, which comes with a 0.8 kW charging capacity per BEV [10]. In Rostock, 1139 battery electric vehicles (BEVs) were registered at the beginning of 2023, but Nicholas et al. [14] expect up to 24,000 BEVs in Rostock by 2030 that would need up to 2200 normal chargers and more than 100 DC fast chargers.

A prerequisite to installing charging infrastructure is to choose a location for it. Many studies about locating charging infrastructure have assumed a governmental viewpoint, aiming to provide for any sort of charging demand within given administrative limits. Likely realizations are "on-street public charging points, charging at work, fast-charging stations, using building domestic plugs and semi-fast charging in public areas" [15]. Corresponding models use geospatial analysis and optimization algorithms

to varying degrees [16–19], while some observe the need to shift from a demand-oriented approach to a coverage-oriented approach to reduce the range anxiety [20]. In addition, it is hoped that charging infrastructure will support grid stability with low and flexible energy consumption and be compatible with sustainable city planning [21].

To assess the local charging demand potential, it can be derived from the observed utilization rates of the charging infrastructure [22]. In the Netherlands, the occupation of charging infrastructure in large municipalities averages between 20 and 40% [12]. Alternatively, and for mid- to long-term planning, local transport demand assessments can be built from land-use and population data [18,19]. Shopping- or leisure-related uses in the walking distance of charging infrastructure have been shown to raise the utilization [23], and established travel behavior for passenger cars in general appears to be applicable to BEVs as well [24].

In Rostock, there have been several studies at the communal level aimed at reducing greenhouse gas emissions that support the installation of charging infrastructure. While the earliest one consulted for this study does not mention BEVs at all [25], a strategy for electric mobility [26] and the communal mobility plan [27] name charging infrastructure and other measures to promote electric motorized transport in their recommendations. Finally, the municipal utility SWRAG, responsible for the public electric grid, commissioned a charging infrastructure demand assessment [28].

3. Data and Methods

The overall aim of the method is to assess the economic viability of different PV locations. We used a more general tool for a first assessment of potentially good locations and a more detailed time-series-based tool for final decisions. Furthermore, the time-series tool was used for the validation of the general assessment tool and for the in-depth analysis of the economic viability.

An overview of the methodology is given in Figure 1. Based on an extensive compilation of relevant data, an analysis of the demand and a short-term forecast (for 2028) could be established. This fed into both the general assessment tool and the analysis of the time series of the demand and supply. The general assessment tool was calibrated and validated using the detailed time-series analysis. At the same time, the time-series analysis was used to model different strategies for commercializing PV-generated electricity.

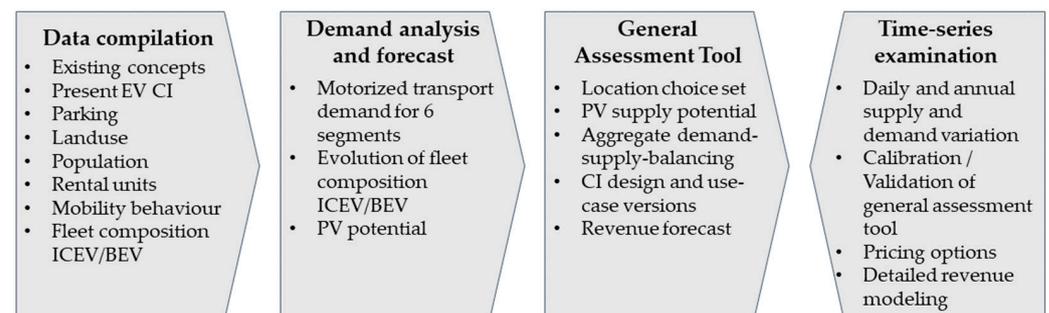


Figure 1. Flowchart of the overall methodology (BEV: battery electric vehicle; CI: charging infrastructure; ICEV: internal combustion engine vehicle; PV: photovoltaic).

3.1. Utilized Data

The data used for this study are mostly geospatial and transport behavior-related (Table 1). Most of the data are freely available or can be retrieved at the named sources. In addition to the datasets named in Table 1, literature studies, price requests and miscellaneous listings from WIRO GmbH (Employees, Car Fleet and usage, etc.) are evaluated in this study.

Table 1. Datasets used for this study.

Name	Used for
Geobasis-DE/BKG 2022 https://gdz.bkg.bund.de/index.php/default/open-data.html (accessed on 1 December 2019)	Administrative boundaries
Geoport.HRO/Hanse-und Universitätsstadt Rostock https://www.geoport-hro.de/desktop (accessed on 24 October 2022)	Buildings, parcels, local administrative units
OpenStreetMap https://www.openstreetmap.org/ (accessed on 8 April 2020)	Parking spaces, background
Bundesnetzagentur (federal networks agency) https://www.bundesnetzagentur.de/DE/Fachthemen/ElektrizitaetundGas/E-Mobilitaet/Ladesaeulenkarte/start.html (accessed on 26 October 2022)	Existing charging infrastructure
Stadtwerke Rostock AG SWRAG (Rostock utilities)	Additional charging infrastructure in 2023
Amt für Geoinformation, Vermessungs- und Katasterwesen MV (Office for Geoinformation, Surveying and Cadastre MV) https://www.laiv-mv.de/Geoinformation/ (accessed repeatedly between October 2022 and July 2023)	Aerial photography, background
Einwohnermelderegister Rostock (Registration Office, Rostock)	Registered residents
Kraftfahrt-Bundesamt (Federal Motor Transport Authority) https://www.kba.de/EN/Home/home_node.html (accessed on 26 October 2022)	Cars by registration office and propulsion
SrV 2018, Rostock [29] (mobility survey, Rostock)	Travel behavior
MiD 2017 [30] (mobility survey, Germany)	Travel behavior
WIRO GmbH: Property Data	Rented and administered units

The collected data were then used to describe the charging demands for six different segments, some of which could be addressed individually:

- a. Resident renters of WIRO housing units;
- b. Business renters of WIRO floorspace;
- c. Other businesses;
- d. Other residents;
- e. Service cars of WIRO GmbH;
- f. Commuting staff of WIRO GmbH.

The number of residents, whether they are WIRO renters (segment a) or other (segment d), are determined by assigning the number of renters provided by WIRO to their apartments. The remaining residents of the statistical block are then distributed over the other residential floorspace. For business uses (segments b and c), the quantifying measure is not the number of persons but the floorspace in combination with a certain type of use. This combination can be evaluated to estimate the volumes of the origin and destination traffic. Finally, service cars used by WIRO employees to perform their assignments and private cars used by the employees to get to work are quantified. The demand segments a, e and f can be served with private charging infrastructure, possibly personalized, with exclusive access. For the other segments, charging infrastructure would have to be publicly accessible, and more exposed to competition.

3.1.1. Charging Demand

The charging demand was generally calculated as the average kilometers traveled for residents, or visitors, taking into account only motorized trips. The charging demand was derived from the average kilometers traveled for a medium-term forecast with a share of BEVs in the regional passenger car fleet around 25%, an average consumption of 15 kWh/100 km and a utilization rate of charging points of 10%.

For residents (a. and d.), the mobility surveys provided values for 19 different types (e.g., young employed or unemployed, with or without regular access to a car, etc.). For

businesses (b. and c.), the charging demand was calculated for visitors and clients using trip generation factors taken from the “VER_BAU” composition [31] that is routinely used for traffic forecasting in Germany. Yearly averages and estimates for school and public holidays were derived using evaluations of the MiD2017 [30] and federal road traffic counts [32].

To further quantify the demand, a customized evaluation of mobility survey data for Rostock [29] was conducted. The survey took place in 2018, before the coronavirus pandemic. The data describe the inhabitant’s personal mobility on a normal working day outside the holiday seasons. The survey differentiates between 18 trip purposes and provides the average timespan between arrival and departure, depending on the hour of arrival. This yields an occupancy curve for the related parking spaces for every trip purpose. It is also possible to calculate the average parking times and the daily mileages of the parked cars for every hour of the day. Unfortunately, the sample sizes are too small for statistically viable values on an hourly level. As a proxy for the hourly variation in the charging demand, the occupancy curve provides an interesting alternative to the destination traffic curve. The difference between these increases with the average parking duration (Figure 2). For instance, parking durations at the workplace can extend over 10 h, with most of the vehicles arriving in the early morning. If the charging demand of employee cars could be evenly distributed over the total parking duration, the resulting cumulative demand curve would be rather flat. In most use cases, however, users will want their cars charged as soon and fast as possible, resulting in a spike in demand after their arrival. Thus, the destination traffic curve resembles the distribution of the charging demand at public charging stations, while private charging stations with exclusive resident or employee use could reasonably be modeled with occupancy curves. This would generally imply some sort of managed charging with longer durations, possibly supply-oriented.

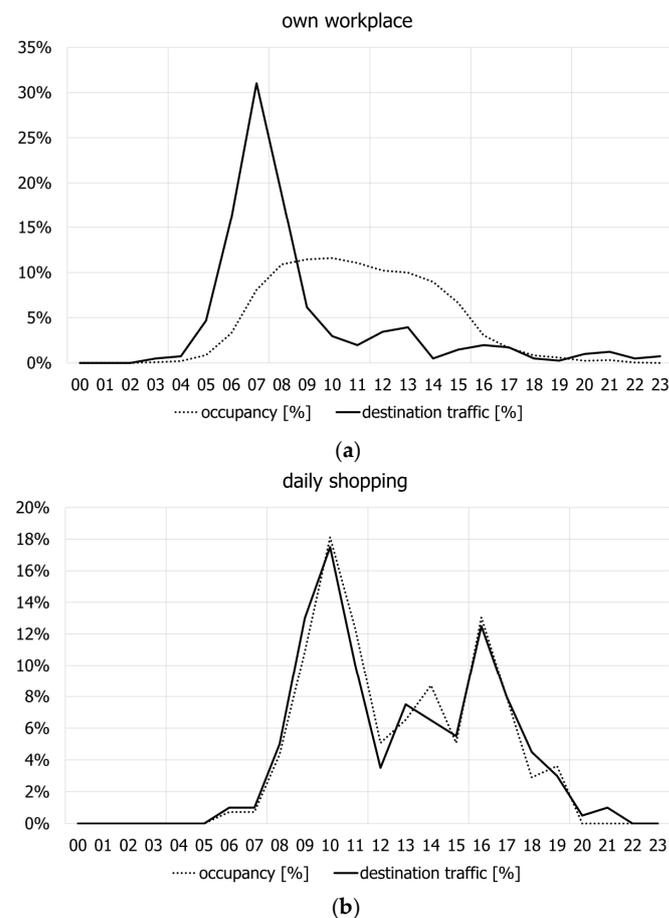


Figure 2. Juxtaposition of occupancy and destination traffic curves for weekdays and passenger cars in Rostock (a) for own workplace and (b) for daily shopping.

3.1.2. Location Assignment

A choice set of possible locations for new charging infrastructure was composed by intersecting parking spaces from OpenStreetMap with parcels owned or administered by WIRO GmbH. This choice set was then extended with known underground garages and further parking spaces managed by WIRO GmbH. The choice set of potential locations contains 331 locations spread out all over the city.

With the use of regenerative energy in mind, the potential supply of energy generated with photovoltaic installations on the rooftops of WIRO buildings was assessed using localized yield curves and an evaluation of the installations already in place. Roof areas and parking spaces were matched by analyzing which roof areas could be connected by underground cables to the parking lots without crossing public space. These matchings give only a preliminary indication of how much solar energy could be generated locally for charging purposes. They nevertheless provide a reasonable starting point to explore the individual potentials of locations.

3.2. General Assessment Tool

After calculating the charging demand at the address level for the whole of Rostock, it was used to develop a location assessment tool to be used for all possible locations. The first step in the development was to match the localized demand with the potential charging locations. For the potential charging locations, an initial demand catchment area was defined with a radius of 100 m for all demand segments.

However, one must be aware that the allocation of demands occurring somewhere in the urban fabric to the points of supply is not straightforward, especially in the context of charging infrastructure [33]. The attractiveness of a location is determined by two different modes of transport (car and foot) and their individual effects on accessibility. For this study, the demand of WIRO renters and staff was intersected with the 100 m radius catchment area of the charging locations. This use case generally implies the long-term rental of a particular parking space with its charging point, which must come within a convenient distance of the user's front door.

The demand from other users was aggregated on the level of statistical blocks. These describe relatively homogenous units in the urban structure and respect geographical boundaries, like train lines, waterways, etc. The average size of the statistical blocks with more than 100 inhabitants in Rostock is approximately 4.5 hectares, a bit more than the area covered by a 100 m radius (3.14 hectares). The aggregated demand in the statistical blocks was then intersected with the 100 m radius around the charging location (Figure 3). This means that demand from outside the 100 m radius may also spill into the catchment area if it occurs within an intersected statistical block.

The tool was prepared for 6 different use cases (Table 2). The targeted user group was either the general public (Nos. 1–3), served with publicly accessible charging infrastructure on private grounds, or WIRO tenants and staff (Nos. 4–6), who received individually assigned parking spaces with a charging point. These come with a monthly rent on top of the rent for the parking space. Considering slow charging with an alternating current (AC), a capacity of up to 11 kW and individually assigned charging points, the charging demand could be managed to some extent, resulting in a demand curve resembling the occupancy of the parking space (Nos. 1 and 4). At a semi-public charging station, users expect the maximum charging capacity for the whole duration of their stay, especially if they connect to a dual-current (DC) charger with an assumed capacity of up to 150 kW. This results in a load curve resembling the destination traffic (No. 3).

The data for the assessment tool were prepared for these 6 cases with a PostgreSQL/PostGIS database containing all the geospatial and demand data. They were then exported for display into EXCEL spreadsheets to visualize the balance of the local energy production and charging demand. The spreadsheets also allow for flexible parameter setting for the electricity prices, number of charging points and price and dimension of solar installations.

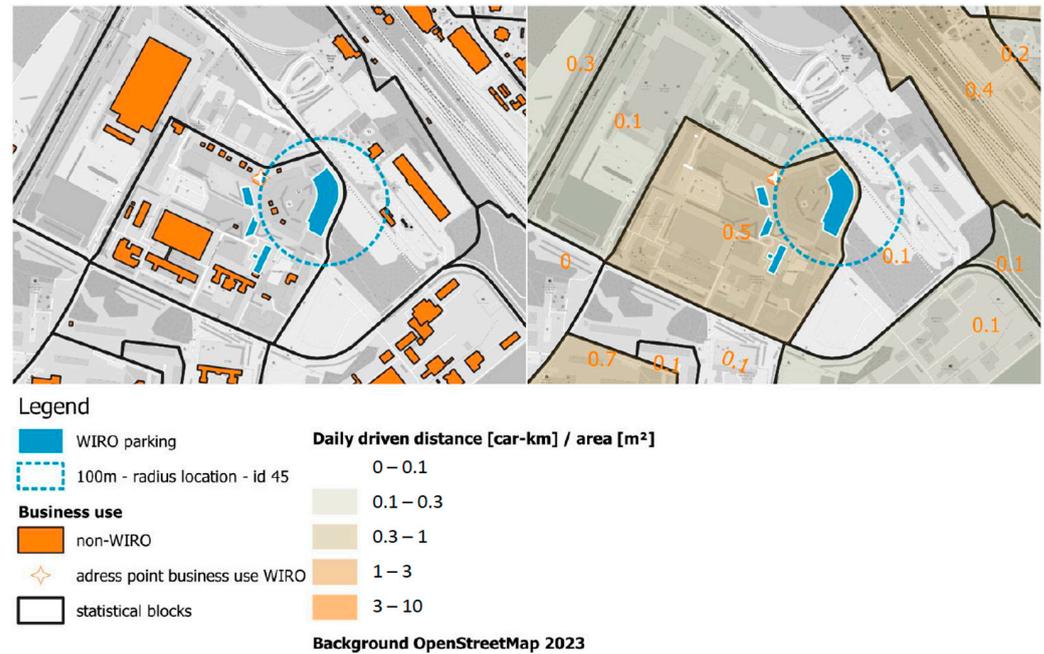


Figure 3. Allocation of demand by radius (**left**) vs. allocation of demand by radius and statistical block (**right**).

Table 2. Charging infrastructure use cases in the location assessment model: 1–3 for publicly accessible charging infrastructure, and 4–6 for private charging infrastructure.

No.	Demand	Charger Type	Demand Curve
1	Any (a–f)	AC	Occupancy
2	(semi-public)	AC	Destination Traffic
3	Within 100 m radius	DC	Destination Traffic
4	WIRO renters and staff (a, e, f)	AC	Occupancy
5	(private)	AC	Destination Traffic
6	Within 100 m radius	DC	Destination Traffic

3.3. Detailed Assessment using Time-Series-Based Analysis

For four specific locations, a more detailed time-series-based investigation was conducted. For this, it was necessary to generate high-resolution time series, with two distinct datasets: one capturing time-series data for the charging availability and another containing the charging demand during the periods of availability.

3.3.1. Charging Demand and Charging Availability Time Series

To create the time series for the charging availability, the distribution of the arrival time (see Figure 1) was used. For each day, a random arrival time is chosen based on the distribution function to ensure that the distribution is correctly represented. Starting from the time of arrival, the average parking duration for the hour in question is added, and this period is defined as the charging availability.

The basis for the energy demand for each day of the year was the daily driven kilometers multiplied by the described energy consumption factor (see Section 3). Given that the local mobility survey data only describe the average working day, the values for Saturdays, Sundays, public holidays and vacations were corrected with the corresponding factors, as described in this section. The required charging energy for each day is accumulated until the sum exceeds a defined threshold value, at which point a charging session should be initiated as soon as the charging availability is established, as indicated by the charging availability time series. This threshold could be reached, for example, when the battery level falls below a certain comfort level. In addition to the individual comfort level, which

is again dependent on the maximum range of the vehicle, there are many other reasons for initiating a charging process, such as opportunity charging. Because the behavioral patterns are still insufficiently researched and an analytical mapping of these criteria is difficult, a dataset with many public charging processes was evaluated. The empirical distribution of the energy per charging process was used as a basis here (see Figure 4). According to this distribution, a charging amount is randomly chosen for each day, which then defines the threshold.

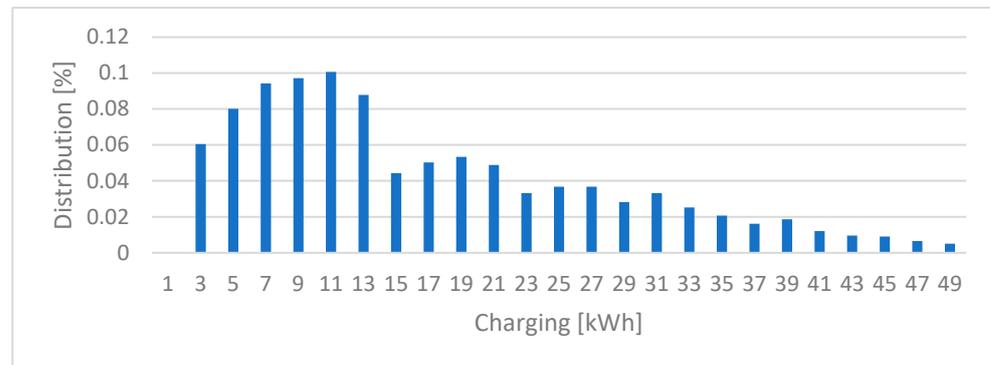


Figure 4. Distribution of the charged energy amount per stop based on measured values of about 300 charging stations.

When creating the charging time series, the maximum energy that can be charged per time step must be considered. Table 3 shows an example for slow and fast charging. If the parking duration is too short to complete the charging process, the unfulfilled demand is carried over to the next day. This process is iteratively continued until the condition is met. The process of time-series generation was performed for all 18 different trip purposes.

Table 3. Example allocation of a charging demand of 10 kWh for slow (11 kW) and fast (150 kW) charging, corresponding to the availability time series.

Timestamp	Charging Availability	Slow Charging [kWh]	Fast Charging [kWh]
8:00	False	0	0
8:15	True	2.75	10
8:30	True	2.75	0
8:45	True	2.75	0
9:00	True	1.75	0

Considering the identified charging demand and usage patterns for the locations, an appropriate number of time series for each trip purpose was chosen, defining a certain number of concrete charging sessions for each day. Individual charging sessions are characterized by the arrival time of the electric vehicle at the charging station, the charging demand, and the departure time. These charging sessions were then assigned to a pre-determined number of charging points. Thereby, the first vehicle with a charging demand arriving at the charging infrastructure is assigned to the first charging point. If another vehicle with a charging demand arrives at the parking spot while the first one is still present, it is assigned to the next charging point, and so on. If all the charging points are already occupied, a specific waiting time can be defined, indicating the waiting time in minutes until a charging station becomes available. If no waiting time is defined or it is exceeded, the charging session cannot be carried out and is not further accounted for, as it is assumed that, in this case, another location with charging infrastructure from a third party will be visited. The allocation of charging sessions to charging points also enables the determination of the maximum possible utilization under the considered conditions, such as the usage patterns and charging power.

For fast chargers, it is assumed that there is an incentive in place, such as a blocking fee, to encourage users to release the charging point almost immediately after completing the charging session. The charging point can then be directly used by a new vehicle, rather than waiting until the parking period at that location is over. This has a significant impact, particularly for residential users whose vehicles, for example, are connected to the charging point in the afternoon and are only released the next morning to drive to the workplace.

The charging time series resulting from the method described is visualized in Figure 5. It shows the aggregated charging energy for 100 vehicles with the purpose of parking at home with a slow-charging infrastructure (max. 11 kW of power per charging point). The weekday, Saturday and Sunday type days were differentiated, and the minimum and maximum charging requirements are shown in red dashed lines. The median charging energy at these times and type days is marked with the black line, and the 25–75 percentiles are highlighted in blue. The graph therefore also allows conclusions to be drawn about the simultaneities that occur.

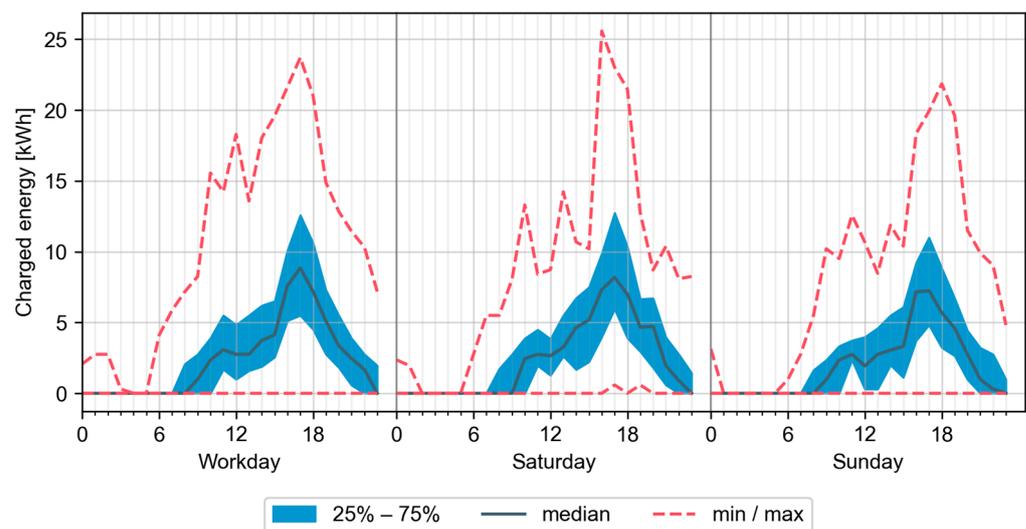


Figure 5. Aggregated charging time series for 100 vehicles with the destination locations of owners' residences for a charging infrastructure with a maximum charging capacity of 11 kW.

3.3.2. Integrating PV Generation

To better align the timing difference between the charging process and the volatile generation of photovoltaic electricity, PV battery storage systems were also taken into account. For this purpose, a storage model was integrated, which considers the maximum storage capacity as well as the charging and discharging powers and efficiencies.

In the first step, the influence of the self-consumption rate is investigated. Depending on the conditions, it may be mandatory that a part of the self-generated solar energy is also consumed directly on site, which is defined as the self-consumption share (see Formula (1):

$$\text{Self-consumption} = \text{Self-used PV energy} / \text{total PV generation} \quad (1)$$

However, the value of the self-consumed electricity depends mainly on the installation costs and the grid electricity price, as will be shown next. Figure 5 represents the necessary self-consumption shares that have to be achieved at different grid electricity prices and installation costs. For this purpose, the power production costs (also called the Levelized Costs of Electricity, abbreviated to *LCOE*) for photovoltaics were determined. The *LCOE* is calculated from the investment costs and the operating costs over the expected lifetime, which are allocated to the electricity production over the same period. The calculatory

interest rate is also taken into account. This results in a price per generated kilowatt hour of photovoltaic electricity (see Formula (2)):

$$LCOE = \frac{c_{inv} + \sum_{t=1}^n \frac{A_t}{(1+i)^t}}{\sum_{t=1}^n \frac{M_{t,el}}{(1+i)^t}} \quad (2)$$

where

- c_{inv} is the capital expenditure in euros;
- A_t is the total annual costs in euros in a year (t) (fixed and variable operating costs);
- $M_{t,el}$ is the quantity of electricity produced in the respective year in kilowatt hours;
- i is the calculatory interest rate;
- n is the economic life in years;
- t is the year of the utilization period ($1, 2, \dots, n$).

The $LCOE$ makes it possible to compare the cost of the photovoltaic electricity with the grid electricity price and the feed-in tariff. If the electricity production costs are below the feed-in tariff, then a photovoltaic system of any size already pays for itself and no minimum self-consumption is necessary (see Figure 5, left of the intersection of the lines with the x-axis).

4. Results

4.1. General Assessment Tool

The general assessment is documented with a map like Figure 3, which displays the location and its surroundings, the catchment area and the sources of the demand. The EXCEL spreadsheet displays the electricity generated by solar panels over the course of the day against the various demand segments (Figure 6). The user can adjust the number and type of charging points, electricity prices and size and price of the solar installations.

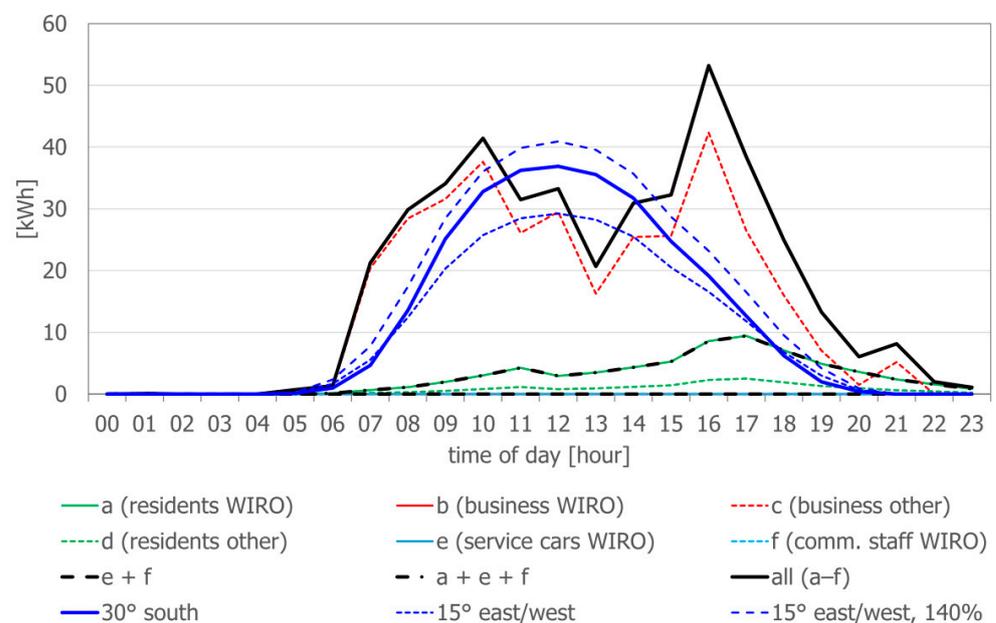


Figure 6. Exemplary view of location assessment tool results. Blue lines for locally generated electricity from solar panels, depending on exposition and size; other colors for various demand segments; black line for aggregated demand.

The spreadsheet provides average weekday revenues (or losses) depending on the inclination of the solar panels, the use of a local storage battery or electricity from the grid and the use case with the corresponding demand segments and revenues from renting the charging points.

4.2. Time-Series-Based Sensitivity Analysis (Microsimulation)

The development of electricity costs, which are a combination of the grid costs and PV generation costs, is uncertain. Therefore, the analysis includes the sensitivities of these parameters. Furthermore, PV power generation varies throughout the day and is significantly higher in summer than in winter. To quantify the impact of these wide variations, a time-series-based simulation, further referred to as a microsimulation, was performed to validate and extend the general assessment tool results.

4.2.1. The Strong Influence of Self-Consumption and Grid Electricity Costs

For different grid electricity costs, the three lines for the 0.15, 0.20 and 0.30 EUR/kWh grid electricity prices show the necessary shares of self-consumption. Figure 7 illustrates that with installation costs of 1700 EUR/kWp and electricity costs of 0.15 EUR/kWh, a minimum self-consumption of 60% has to be achieved, while with 1500 EUR/kWp and a grid electricity price of 0.30 EUR/kWh, 16% is sufficient.

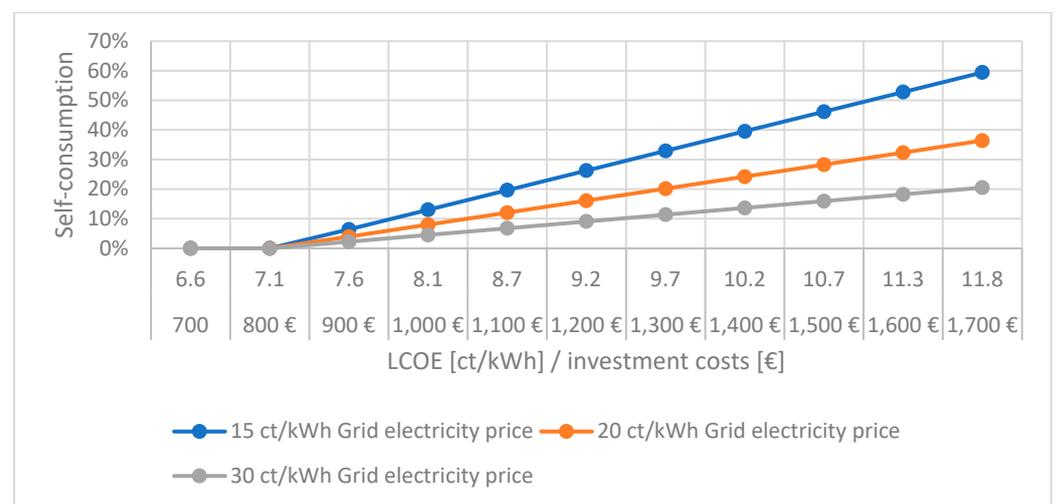


Figure 7. Illustration of the necessary self-consumption shares as a function of installation costs and grid electricity prices.

This illustrates that the self-consumption share is an important factor for the investigation of the economic profitability, which can be determined by the time-series-based analysis. The following analyses are shown for an example site with a charging demand of about 45 MWh per year, of which 3/4 is from residents and 1/4 is from the semi-public use from surrounding businesses. This leads to a usage pattern that shows an increased charging demand in the afternoon/evening, which does not seem optimal for PV integration at first but is a typical challenge for charging infrastructure for residents.

The self-consumption factors that are realistic and achievable are shown in Figure 8, which shows the simulated self-consumption shares for the mentioned example site with slow and high charging powers, and also for storage integration. While up to 40% of self-consumption can be realized at a slow-charging power, the self-consumption share at a high-charging power is only about 11%. Keeping in mind the minimum necessary self-consumption values, a coupling of photovoltaic systems with fast-charging infrastructure only seems to make sense with the simultaneous use of a battery storage system. Therefore, this application use case is also investigated. This enables self-consumption shares of up to 90% to be achieved. The size of the battery storage was assumed to be 40 kWh, as this was the most economically viable size for the example location.

Once the self-consumption values have been determined, the economic efficiency can be evaluated.

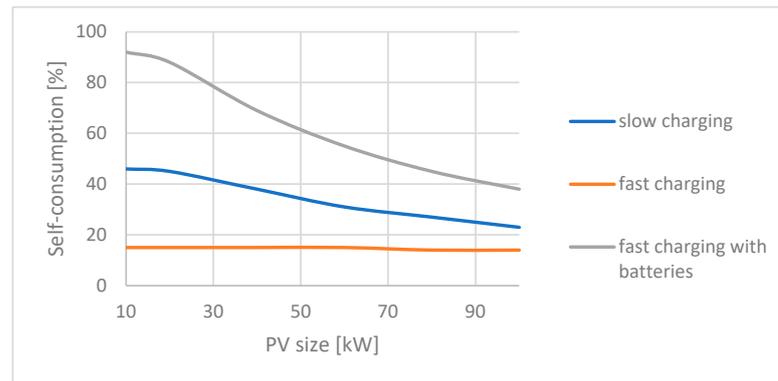


Figure 8. Comparison of the self-consumption shares of an example site at slow and fast charging powers (with and without battery storage) for photovoltaic systems of different sizes.

4.2.2. Benefits of PV Coupling

The use case considered in the study is defined below. A shared charging infrastructure is assumed (i.e., all users share a small number of charging points). The charging infrastructure is only accessible to a closed group of users, so it is not a public charging infrastructure. The PV system is connected directly to the charging infrastructure, meaning that only the surplus electricity is fed into the public grid. Other use cases, which are not discussed further in this study, are the installation of private charging points in rented parking spaces and a shared charging infrastructure that is available to the entire public.

For the economic evaluation, assumptions must be made regarding the investment costs, operating costs and operating income. Market and empirical values of the housing association were used for this purpose. Table 4 shows the economic parameters used in the calculations. As not all parameters are relevant for the use case demonstrated in this study, they are included in the calculations without values.

Table 4. Economic parameter assumptions.

Type	Description	Value	Abbreviation
Investment costs	Photovoltaic system	1400 EUR/kW	INV_{PV}
	Battery storage system	700 EUR/kWh	$INV_{storage}$
	Slow charging point	5750 EUR/CP	$INV_{CP,slow}$
	Fast charging point	40,000 EUR/CP	$INV_{CP,fast}$
Operating expenses	Electricity grid supply	0.15–0.30 EUR/kWh	$c_{grid\ energy}$
	Grid charges	0	$c_{grid\ charge}$
	Parking space opportunity costs	0 EUR/CP/m	$c_{park\ opp}$
	Backend	100 EUR/CP/a	$c_{backend}$
Operating income	Charging electricity sales	0.45 EUR/kWh	$i_{charging}$
	Feed-in tariff	0.065 EUR/kWh	$i_{feed-in}$
	Greenhouse gas bonus (THG)	0	i_{THG}
	Parking space rental	0 EUR/CP/m	$i_{parking}$

The “Electricity grid supply” describes the cost factor incurred for each kilowatt hour of energy drawn from the public electricity grid. “Grid charges” describe the grid fees that are due in order to transmit the photovoltaic electricity through the public grid. As we assume in this analysis that the PV systems are directly connected to the charging infrastructure, no transmission charges are due. “Parking space opportunity costs” describe opportunity costs that can arise because previously rented parking spaces are converted into parking spaces with charging infrastructure and the previous monthly income is lost. “Backend” costs are the IT infrastructure costs for operating and billing the charging points. “Charging electricity sales” are the revenue per kilowatt hour of energy charged that is generated through the sale of charging electricity. “Feed-in tariff” describes the

income from the sale of surplus PV electricity. “Greenhouse gas bonus (THG)” describes the revenue that can be generated by selling the greenhouse gases saved. As this is only possible with public charging infrastructure, this income is not included in the scenario under consideration. “Parking space rental” describes the revenue from a privately rented parking space. This is set to 0 in the use case under consideration, as a shared charging infrastructure is assumed.

Using the economic and technical parameters, it is now possible to determine the economic viability of the charging locations with and without PV installation. To do this, the net present value (*NPV*) (4) and the annuity (*ANN*) (5) are calculated. The net present value is calculated by multiplying the operating income and expenditure by the discount factor (*DF*). The investment costs are deducted from the result. This means that the investment is profitable if the result is positive, and that it is uneconomical if it is negative:

$$NPV = DF \times \left(\begin{array}{l} i_{\text{charging}} + i_{\text{feed-in}} + i_{\text{THG}} + i_{\text{parking}} \\ -c_{\text{grid energy}} - c_{\text{grid charge}} - c_{\text{park opp}} - c_{\text{backend}} \end{array} \right) - INV_{\text{PV}} - INV_{\text{storage}} - INV_{\text{CP,slow}} - INV_{\text{CP,fast}} \quad (3)$$

Because, as mentioned, not all parameters are required for the use case under consideration, the equation is simplified as follows:

$$NPV = DF * \left(i_{\text{charging}} + i_{\text{feed-in}} - c_{\text{gridenergy}} - c_{\text{backend}} \right) - INV_{\text{PV}} - INV_{\text{storage}} - INV_{\text{CP,slow}} - INV_{\text{CP,fast}} \quad (4)$$

The net present value (*NPV*) represents the total amount at the end of the period under consideration. As annual savings or costs are more descriptive, the net present value is converted to an annual value (*ANN*) using the annuity factor (*AF*). To do this, the net present value is multiplied by the following factor:

$$ANN = AF * NPV \quad (5)$$

The annuity factor (*AF*) is calculated as shown in (6). Both the period under review and the calculatory interest rate are considered:

$$AF = \frac{(1+i)^n \cdot i}{(1+i)^n - 1} \quad (6)$$

where

- *AF* is the annuity factor;
- *i* is the calculatory interest rate;
- *n* is the investment period.

In this way, the annuity is calculated once for the same charging location without (*ANN w/o PV*) and with (*ANN w PV*) PV integration, and the difference is calculated from both values:

$$ADDED ANN = ANN \text{ w/o PV} - ANN \text{ w PV} \quad (7)$$

This results in the additional (“ADDED ANN”) annuity due to PV integration. If the same location with PV integration generates a lower annuity, the additional annuity can also be negative. In order to show the strong dependency of the results on the grid electricity prices, these were varied between 0.15 and 0.30 EUR/kWh. Using the self-consumption factors shown in Figure 8 and the known generation data of the PV systems, it is possible to determine what proportion of the charged energy is covered by the PV system and what residual amount of electricity still needs to be purchased from the grid. Without a PV system, the entire charged energy has to be drawn from the power grid and the feed-in tariff does not apply. The investment costs for the PV system are not incurred in this case.

Figure 9 shows the added values of a PV-coupled charging infrastructure for the example site compared to a charging infrastructure without PV infrastructure for different electricity prices from 0.15 to 0.30 EUR/kWh. The figure illustrates the increase or decrease in the annuity due to the PV integration. A negative value means a loss due to the PV integration, and a positive value means a gain. At low electricity prices, there is little added value, or even a loss in the case of fast charging. With increasing electricity prices, PV coupling shows significant added values up to several thousand euros of additional profit. The value increases linearly with the electricity price.

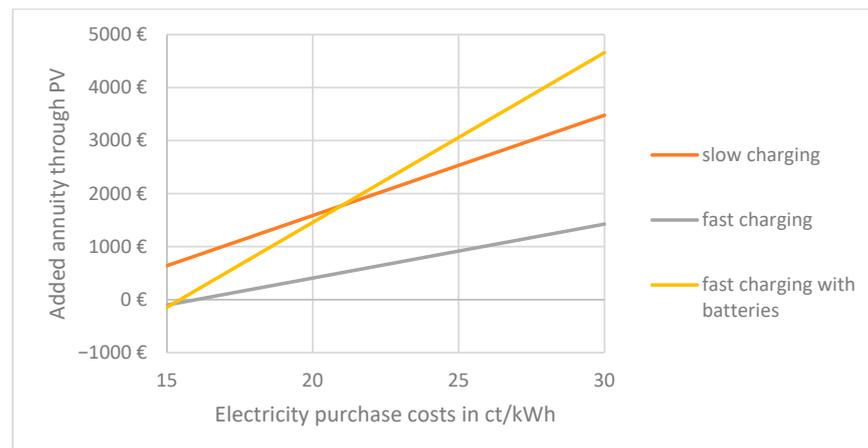


Figure 9. Comparison of the additional profit through photovoltaic integration for different electricity purchase costs.

4.2.3. Optimal Dimensioning of PV and Storage Components

The time-series-based analysis also enables the PV and storage components to be dimensioned depending on various influencing factors. In addition to the electricity price, these include the charging power and charging behavior. Figure 10 shows the added value of PV integration for different PV system sizes. The first group of bars in the diagram shows that the combination of a fast-charging infrastructure with PV battery storage leads to losses at low electricity prices. It clearly illustrates that a PV storage system does not always add value to a fast-charging infrastructure, as this depends on the different influencing factors.

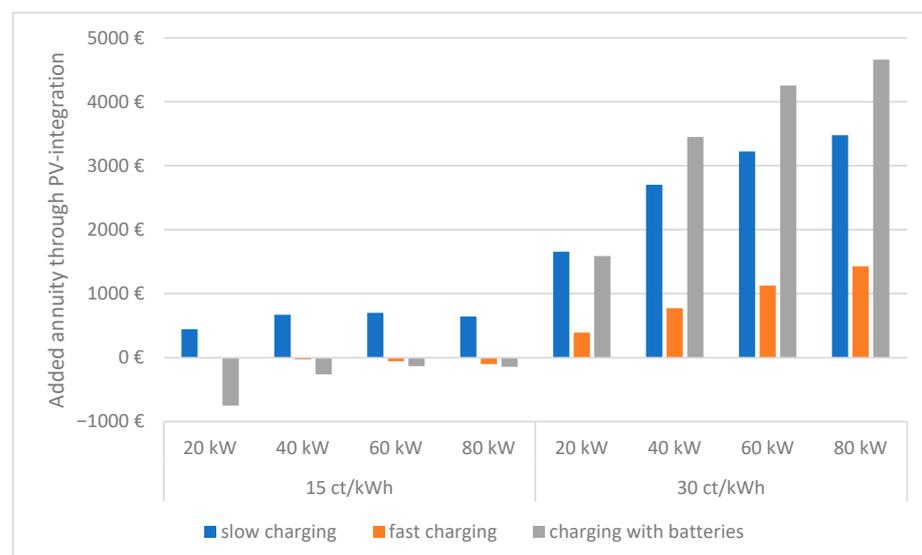


Figure 10. Comparison of the additional profits through photovoltaic integration for different electricity purchase costs and PV system sizes.

4.3. Comparison of General Tool and Time-Series Results

In order to keep the complexity at a reasonable level, the general assessment tool calculates the mean hourly consumption and generation values for an average day. To find out how precisely photovoltaic-coupled charging infrastructure can be modeled, a comparison was made between the in-depth time-series-based microsimulation and the general assessment tool.

For this purpose, the same technical (Table 5) and economic (Table 4) constraints were applied. The grid electricity price was assumed to be 0.30 EUR/kWh and the charging electricity sales price was set at 0.45 EUR/kWh. These boundary conditions were intentionally set, as the previous simulation showed that the added value of PV integration is more evident with higher purchase prices of electricity.

Table 5. Technical constraints for the four example sites: charging demand, numbers of charging points for fast and slow charging and sizes of photovoltaic system and storage.

	Adjacent Land Use			
	Residential	Touristic	Leisure	Mixed
Demand [MWh]	AC 43/DC 54	AC 111/DC 95	AC 60/DC 56	AC 38/DC 42
Slow Charging Points (count)	6	6	6	6
Fast Charging Points (count)	2	2	2	2
PV size [kW]	80	80	80	80
Battery size [kWh]	40	40	40	40

Also, the demand was set to be equal in both models for this examination, while it would normally differ slightly because of the daily changes in the demand patterns and limited charging capacity. Due to the architecture of the general assessment tool, the demand, set to be equal to that in the microsimulation, is capped in some peak hours where it exceeds the peak charging capacity assumed in the general assessment tool.

Figures 10–12 compare the profits with and without PV integration determined by the general assessment tool and the microsimulation. Without PV integration, the revenues are identical; with PV integration, there are some differences. Figure 11 shows the profits for slow charging. The results are basically close to each other, but because the microsimulation also determined lower self-consumption factors (compare the blue lines of Figure 14), slightly lower revenues are also the result.

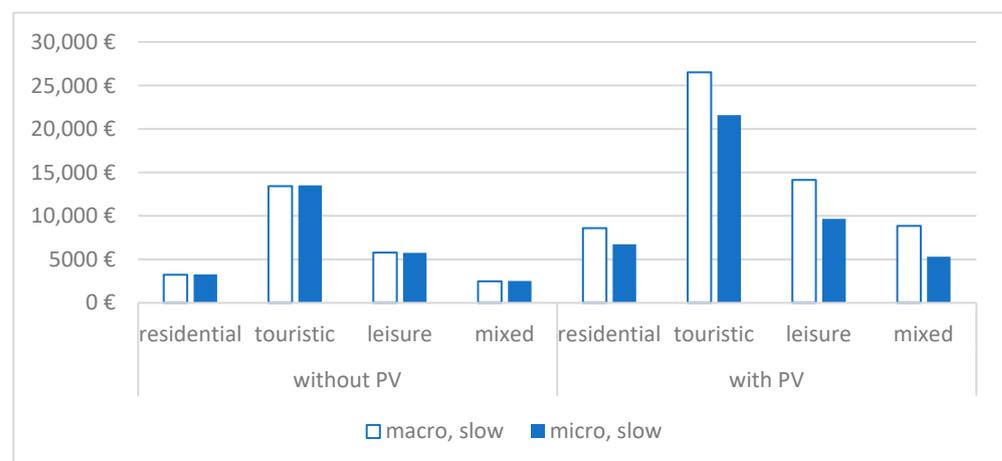


Figure 11. Comparison of results for slow charging between macrosimulation with general assessment tool and time-series-based microsimulation.

More significant differences can be observed when examining a fast-charging infrastructure (Figure 12). In this case, the self-consumption factors and therefore also the profits

calculated with the microsimulation are significantly lower (see Figure 12 and orange lines in Figure 14). With an additional battery storage, however, the results are quite similar again (Figure 13).

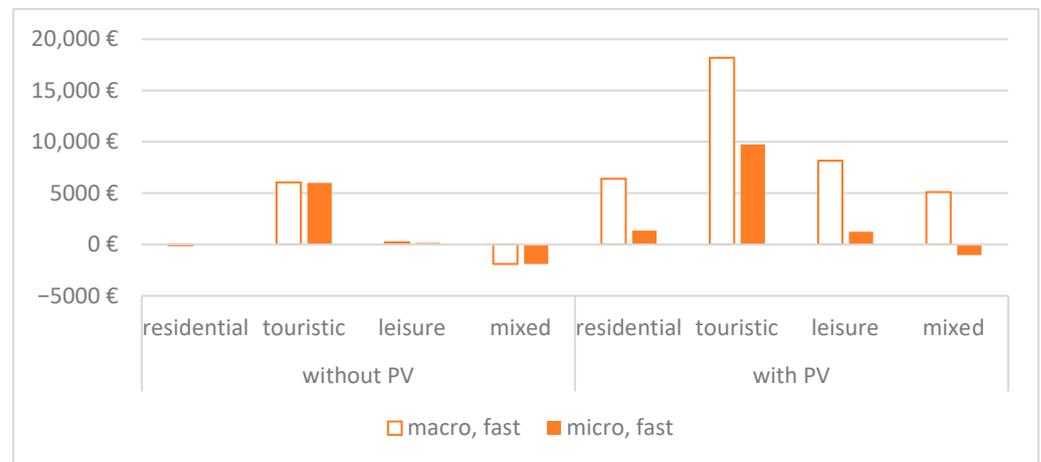


Figure 12. Comparison of results for fast charging between macrosimulation with general assessment tool and time-series-based microsimulation.

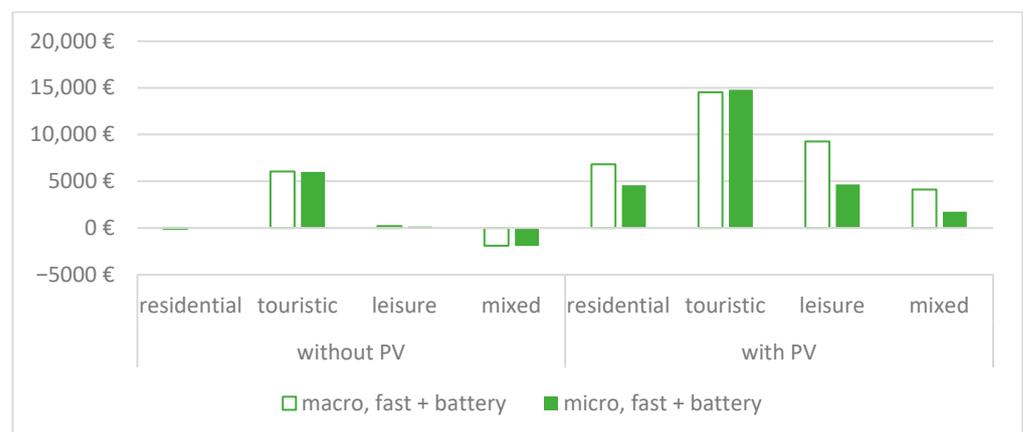


Figure 13. Comparison of results for fast charging with battery between macrosimulation with general assessment tool and time-series-based microsimulation.

The differences can be explained particularly with regard to the self-consumption factor. The fast-charging infrastructure, especially, causes high energy consumption in a short period of time. The charging power significantly exceeds the maximum power output of PV systems. This results in very low self-consumption values for fast-charging infrastructure, as shown in Figure 14 with the dotted orange line. Figure 14 compares the self-consumption factors calculated using the time-series-based microsimulation as dashed lines with the calculation by the macrosimulation using yearly averages of PV generation. Overall, there is an overestimation of the potential self-consumption in the macrosimulation.

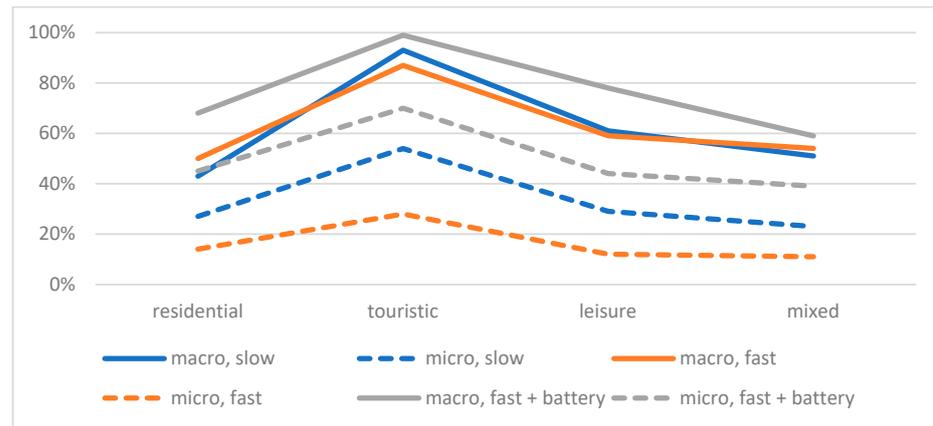


Figure 14. Comparison of the self-consumption factors between macrosimulation with general assessment tool and time-series-based microsimulation.

5. Discussion

The general assessment tool developed does not only use a detailed estimation of the transport demand arising from a variety of trip purposes, as many existing approaches do, to assess the demand potential for charging infrastructure, but it also considers the hourly variation in the demand and parking times and combines them with the supply of PV electricity, and it allows the operator to evaluate the economic viability of the charging locations, depending on the envisioned use cases. To achieve this, the general evaluation provides results for the supply and demand of PV electricity and charging infrastructure for the given catchment areas of charging infrastructure, as well as for the advisability of using grid electricity or battery storage. Calibrated with the results of the detailed time-series-based analysis, the general evaluation appears to be a reliable tool to determine the charging requirements for a high number of locations, considering the respective socio-economic factors and mobility patterns on site.

When using historical mobility data, as in this study, it should always be taken into account that mobility patterns are subject to change. Future studies that rely on mobility survey data to model the energy demand must consider the actuality of the travel behavior data used. Not only the coronavirus pandemic but also paradigmatic shifts in town planning and transport policy shape everyday travel behavior to a considerable extent. For Germany, results for the first nationwide mobility surveys after COVID-19 are expected for the end of the year 2024.

With respect to practical implementations, the integration of seasonal variation into the general assessment tool is desirable. This would provide the full scope of the power balance between the PV supply and demand in either summer or winter, which is necessary for the dimensioning and feasibility of the connection to the grid. On top of this, it would be worthwhile to study the complex balancing of the PV supply and demand from BEVs in different latitudes, which would come with more (or less) efficient PV generation on the one hand, but weaker (or stronger) seasonal effects on the other. Finally, the use of electricity from other decentral renewables, such as wind, might be considered.

6. Conclusions

Regarding a PV-coupled charging infrastructure, one of the most relevant results of the microsimulation is the necessity to consider the self-consumption factor, which combines the effects of the charging speed, charging behavior, seasonally varying PV generation and PV system size. The results show that high charging powers, especially, cause a strong reduction in the self-consumption factor. Because the self-consumption factor has a relevant influence on the economic efficiency, as explained in Section 4.2, a next step could be to improve the general assessment tool by integrating it there. Furthermore, self-consumption might be considered as a key performance indicator for potential sites.

The results of both approaches show that PV systems can be coupled with charging infrastructure and add economic value. How high this added value will be depends, in particular, on the following boundary conditions. On the one hand, if the electricity can be purchased from the grid at a low price, PV systems cannot create a significant advantage. On the other hand, if electricity prices rise, PV systems can show their full potential. In this case, the analyses clearly show that not only is an economic integration of PV systems into charging infrastructure possible, but that the profit can be multiplied in some cases. The added value increases linearly with the rising electricity purchase price. In this way, PV systems dampen the increase in the variable operating costs so that attractive charging tariffs can continue to be offered, and this can mitigate the risks from rising electricity prices and represent a significant competitive advantage. Furthermore, for PV integration, charging for the demand at times of day with high PV generation, as is the case, for example, in the commercial segment, is an advantage. Furthermore, a low charging power that does not exceed the supply from the PV system is needed. Alternatively, if fast chargers are to be used, PV storage should be considered.

It is important to mention that simulated charging processes were used for the calculation of the results, and the published empirical evidence on charging behavior is still limited. It is hoped that the relevant data situation will improve through relevant scientific publications and mobility surveys.

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