Charging Infrastructure Power Requirements for Flexibility Usage

Abstract—**Scenarios with differently dimensioned charging capacity are examined with regard to the utilization of the flexibility potential of heavy commercial vehicles. These vehicles are only charged at the depot during idle times. The comparison of the scenarios illustrates how strongly the increase in flexibility potential depends on the dimensioning of the charging infrastructure. The lower extreme is determined by the size of the charging time window. If it is fully utilized, no flexibility can be achieved. A brief economic classification of the investment costs for charging infrastructure with the same number of charging points is given. It was shown, that economic obstacles exist for ascending the flexibility potential and incentives are required for counter-financing.**

Index Terms—**battery electric truck, depot charging, fast charging, flexibility, system integration**

Acronyms

BET Battery Electric Truck

capex capital expenditure
CP Charging Point

EV Electric Vehicle
EVSE Electric Vehicle Supply Equipment

opex operating expense

SoC State of Charge

V2G Vehicle to Grid

I. Introduction

Flexibility is a key factor in terms of energy transition from fossil energy carriers towards renewable. In this context, flexibility means the ability to adapt the power consumption or generation depending on information and requirements from outside of the own property in addition to own operation constraints. This ability is required for the majority of electric loads and generators in the energy system to match demand and generation without outages.

There are different types of flexibility utilisation. On the one hand, these can be of a systemic nature and used for grid-friendly behaviour in the form of peak shaving, or they can be of a commercial nature and used to optimise energy consumption on the spot market. This can lead to very different ways of operating flexibilities, especially from Electric Vehicles (EVs). While some focus purely on self-consumption, other operating modes are designed more for the role of flexibility in the grid. The charging behaviour of electric cars can play a decisive role here due to their long idle times. Therefore use cases like using the flexibility for peak shaving as it was done by Van Kriekinge et al., can increase grid-friendly behaviour and economic benefits [1]. In addition to the systemic effects, various charging strategies also have an impact on the spot markets. As shown from Hanemann and Bruckner price peaks can be smoothed out when controlled charging strategies are used [2]. It has also been shown that this effect is particularly noticeable if, in addition to controlled charging, there is also the option for Vehicle to Grid (V2G) where the EV can feed back into the grid. Since no V2G-able Battery Electric Truck (BET) are available in Europe, the focus on this work lies on Grid to Vehicle.

Charged along the route, a single BET has no flexibility and is hard to accumulate for system service offers. However, depot-charging – i.e. accumulated charging load from grid perspective – has the potential for flexibility. BET charging in depots will require a high amount of power and energy. Since these vehicles have large batteries, the potential of flexible power demand and power supply – with bi-directional charging in the long-term – should not be underestimated. Will and Ocker find that BET will provide 23 GW of down-regulating flexible power in 2040 [3]. Nevertheless, in terms of Electric Vehicle Supply Equipment (EVSE) dimensions Speth and Plötz state, that 44 kW charging power is sufficient for most BET applications. EVSE with less maximum charging power means less capital expenditure (capex). This might lead to conflicting objectives: Slow charging with 44 kW might be sufficient to charge the vehicle during off-time but is not sufficient to make the charging process flexible. This conflicts with the expectations of flexibility potentials, which requires additional charging power and therefore additional capex.

This work takes initial steps to close the gap created by the conflict of objectives. Therefore, different scenarios of combinations of BET applications and EVSE power dimensions are simulated and analysed. Simulations with different fields of applications for BET and slow-charging EVSE show that on one hand it is true, that the vehicle can be fully charged in the given time. But on the other hand, the whole given time is necessary for charging. That means no flexibility is in the charging process. The scenarios provided by Will and Ocker will be complemented and analysed regarding the impact of different EVSE power dimensions.

The share of EVSE hardware purchase of the total capex

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is between 50 % and 60 % depending on further cost factors like power connection [5]. An estimation of capex (hardware purchase only) per kilowatt charging power for the different dimensions is then made. The higher expenses for higher charging power have to be compensated, if inflexible EVSE is to be counteracted.

II. Methodology

The general procedure performed in this work is shown in Fig. 1. The analysis consists of use cases, ramp-ups and scenarios. A use case describes a field of application of BETs and a number of units in a corresponding depot as shown in Table I, where *LH* stands for *line haul*, *RD* for *Retail / Distribution*, *Con* for *Construction* and *Wa* for *Waste*. Ramp-ups describe approximated numbers of vehicle for each field of application in Germany for different years. Scenarios are defined, which describe different maximum charging power levels for each BET concerning EVSE dimensioning per depot. A depot contains a set of BETs of a specific use case. A depot is mapped to a simulation which consists models for every BET. The simulation results in flexibility potential and is performed for every use case in every scenario. The computed potential is scaled up with the ramp-up estimations, which allows comparison between the scenarios. Finally capex calculations give an impression of cost differences between charging power scenarios and its resulting flexibility potential. The following sections provide more details.

Table I: Use cases considered in the scenarios as described by Will and Ocker [3, Tab. 2&3]

		LH 2	LH 3	RD 5	Con 7	Wa 11
Charging power	kW	300	50	150	150	50
Demand in depot[a]	kWh	400	350	250	475	300
Departure 1	h	06:00	07:00	05:00	08:00	07:00
Arrival 1	h	16:00	15:00	13:00	12:00	15:00
Departure 2	h			14:00	13:00	
Arrival 2	h			20:00	16:00	
Units per depot		50	45	30	10	30

a. Charging outside of the depot is not considered as flexible potential

A. Data and Model

The scenarios are modelled with the simulation described from Decher and Schäfers [6]. Each BET is modelled and simulated with its own energy demand and shift schedule. The results are – beside others – power profiles for every BET and the accumulated power profile representing the depot power profile. Data used are a combination of these from Will and Ocker [3] and empiric data from depot charging of electric waste collection vehicles. Shift schedules of BET are part of the use cases and are linked to the one described by Will and Ocker [3] and simulated with models described in Decher and Schäfers [6]. The use cases are slightly adjusted in energy demand. In this work, only demand occurring at the depot is considered. Table I lists the use cases used for the simulation. *Charging power* only applies for the base-scenario and is varied over the scenarios (see subsection II-B).

The comparison of the simulation and the reference analysis of Will and Ocker [3] in Table II shows that in tendency the results are similar. The results are grouped by four-hour buckets per day and consider only weekdays (Monday to Friday) without bank holidays. Assumptions about the ramp-up of vehicle numbers in Germany are taken from Will and Ocker [3, Tab. 4]. Flexibility is quantified with *energy*, *power* as well as *earliest* (t_0^F) and *latest* (t_1^F) possible time to start charging like shown by Decher and Schäfers [6, Tab. 2]. Therefore, a flexible load is within a time bucket if

$$t_{B,0} \leq t_0^F \leq t_{B,1} \vee t_{B,0} \leq t_1^F \leq t_{B,1}$$

with $t_{B,0}$ for the start of the time bucket and $t_{B,1}$ for its end (e.g. 04:00 – 08:00). The reference data are marked with *Lit.* and the simulation results with *Base*.

The reason for deviations between *Lit.* and *Base* are twofold: Randomization of departure and arrival times are performed for *Base* results, which leads to flexibilities although be present in bordering time blocks. The impact of this is considered low. The other reason is due to different calculation of the amount of flexible load. The calculation for *Lit.* is based on a estimated profile. Flexible load is then the deviation between the estimated profile and the new profile after a load shift. In the simulation for *Base* flexible load is equal to the whole amount of shift-able load, which leads to higher numbers. It is expected, that this does not influence the analysis of flexibility depending on charging power: In both cases a maximal possible charging power near to the required minimum results in no flexible load.

B. Scenario Creation

In a further step, the maximum power in the scenarios is modified and simulated. The simulations make sure, that the available charging power is sufficient to reach the necessary State of Charge (SoC) for the next route. If necessary, the maximal charging power is raised to the minimal required for corresponding SoC at departure. The minimum and maximum charging power as well as resulting average for each scenario are shown in Table III. The simulation results are then used to calculate the flexibility potential. Note that it is assumed, that the charging power is limited only by the EVSE respectively the Charging Point (CP)[1] and the BET is capable of the charging power. Therefore, the scenarios differ in the average charging power over all BET. Use cases and the number of vehicles in the ramp-up estimations are equal (see subsection II-B).

C. Flexibility Quantification and Visualisation

The quantification of the flexibility is done with the flexibility matrix provided by Jahic et al.. According to its equation ([7, eq. 6]) the matrix contains either the accumulated load or zero in each cell. Each row of the matrix represents a time step of the simulation. The columns represents the category

[1]In this work EVSE and CP are synonym, since no limiting factors through sharing power hardware of one EVSE between two or more CPs are considered.

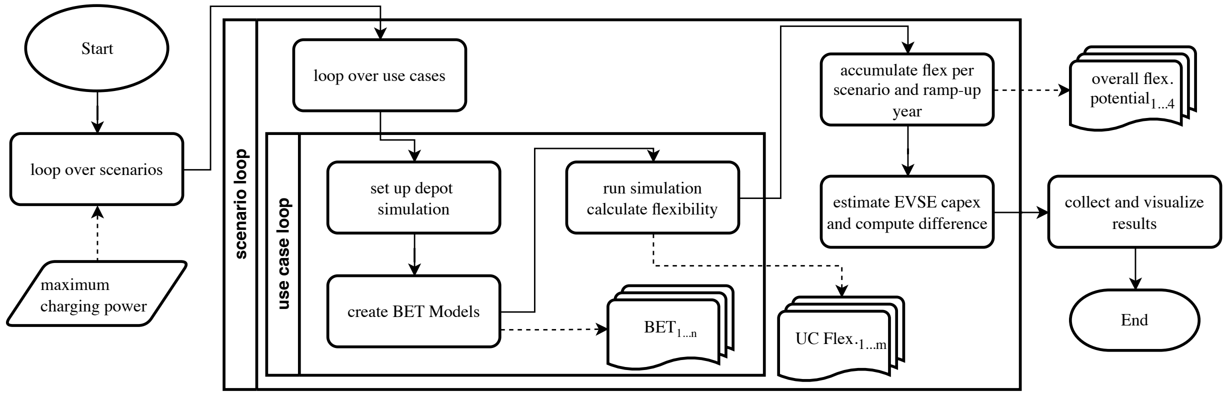

Figure 1: Procedure for synthesising results

Table II: Comparison of Will and Ockers results (*Lit.*) [3] with own simulation (*Base*): negative flexibility in MW

	00:00-04:00		04:00-08:00		08:00-12:00		12:00-16:00		16:00-20:00		20:00-23:59	
	Lit.	Base	Lit.	Base	Lit.	Base	Lit.	Base	Lit.	Base	Lit.	Base
2025	1,146	1,390	26	155	13	0	47	600	659	1,030	1,048	1,630
2030	5,960	7,541	77	915	39	0	138	2,775	3,981	5,709	5,765	8,445
2035	-	21,436	-	3,400	-	0	-	7,071	-	16,440	-	23,400
2040	22,593	30,084	137	5,450	70	0	245	9,598	16,095	22,480	23,113	32,800

Table III: Simulated scenarios and resulting average charging power over all CPs

scenario	ave.	min.	max.
	Power per CP in kW		
Base	130	50	300
slow-charging	90	44	150
150kW-charging	150	150	150
200kW-charging	200	200	200

of the load, which is equal to the number of minutes the corresponding load can be shifted ahead. The matrix contains the necessary information to assess the flexibility potential of a given load [7].

The flexibility matrix can be used to visualize the flexible load via a coloured bar plot according to Gerritsma et al. [8]. The height of the bar represents the amount of power in the corresponding time period. The colour indicates the category of the flexible load. The bar plots lacking the dimension of energy and therefore focus on power. In terms of visualization, this is acceptable to outline the impact of different power dimensions. Furthermore, the matrix and therefore the bar plot only considers shifting power to the future not to the past. With the assumption, that charging starts with the arrival of the BET this is acceptable, since this would be the earliest possible time to start charging. In this work the categorized bar plots are set into a 3D-plot to give an overview over the deviation of the flexible load between the scenarios.

D. Capex of EVSE Hardware Purchase

The capex calculation includes only the hardware purchase of the EVSE. Additional costs for installation, power connection, site preparation have to be considered as well. An overview of the total capex for charging infrastructure is given by Serradilla et al. [5]. Nationale Agenda Laadinfrastructuur finds hardware costs per unit as of 350 $\frac{€}{\text{kW}}$ with constant behaviour between 50 kW and 350 kW for 2020 [9]. Tsiropoulos et al. however find non-linear costs per unit in these power categories [10]:

$$50 \text{ kW}: 562.60 \text{ €/kW}$$
$$150 \text{ kW}: 466.67 \text{ €/kW}$$
$$350 \text{ kW}: 485.72 \text{ €/kW}$$

For charging power dimensions not equal to 50 kW, 150 kW or 350 kW the costs of the next higher power category are assumed. In the results, costs based on both sources are calculated.

It is estimated, that every BET has its own EVSE respectively CP which is capable of the corresponding charging power. Bundling several CP to a single EVSE would lead to cost efficiency effects but is not covered here since the requirements for such systems are individual for each field of application. The approximate calculation presented here aims to estimate the additional costs that must be compensated if more flexible charging infrastructure is to be incentivized.

III. Results

In the scenarios by Will and Ocker the available charging power is between 50 kW and 300 kW with an average of 130 kW over all vehicles in 2040.

Use case *RD 5* – representing retail and distribution routes – for example consists of 30 BET with a maximum charging power of 150 kW and an energy demand per day of 350 kWh

[3, Tab. 2&3]. Drawing the results of *Lit.* as a accumulated load profile with delay categories for use case *RD 5* in Fig. 2 gives an overview of the impact of available charging power on flexibility. The Figure shows the load between 12:00 and 08:00 on the next day in a regular working week. The combination of energy demand, charging power and time frame for charging results in load of the category *0* between 13:00 and 14:00 which means that no delay and therefore no negative flexibility is available. With the same maximum charging power, but with longer off-time until the next departure, the depot has a flexible load potential of 4 MW from 20:00. In this use case, the minimum charging power is limited by the short recharge period at midday, which enables flexibility in the evening.

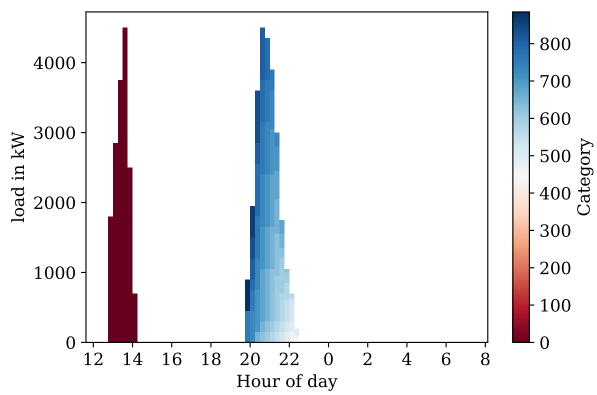

Figure 2: Example visualisation of a use case as categorised bar plot. Here use case *RD 5* in the *Base* scenario.

In use case *RD 5* the minimum charging power is limited by the recharge period around midday. In other use cases like *Wa 11* which represents waste collection, has one duty period and the vehicles are available for charging from 15:00 to 07:00 on the next day. The impact of different maximum charging power levels are shown in Fig. 3. It can be seen, that with a reduction to 44 kW the necessary charging time increases by one hour. Since this additional hour is closer to the departure time, the category decreases. Higher charging power like 150 kW respectively 200 kW results in peaks with high categories. This leads to higher flexibility potential, but although requires a energy management system to avoid uncontrolled load peaks. In use cases with long off-duty periods like in *Wa 11* the difference between the charging power levels are significant.

The results of every use case are then accumulated and divided into time buckets of four hours for every scenario. The resulting overall flexibility potential is shown in Table IV. The difference between the inputs of the scenarios is the maximum charging power installed on the depots of the corresponding use case. In Table IV can be seen, that the negative flexibility in the slow-charging scenario is significant lower compared to the *Lit.* scenario. The peak shift-able load (2040, 20:00-23:59) reduced from 32,8 GW by 44 % to 18,4 GW. The flexibility is not leveraged to zero, because it is estimated, that all EVSE on the depot have the same maximum power. Therefore, BET

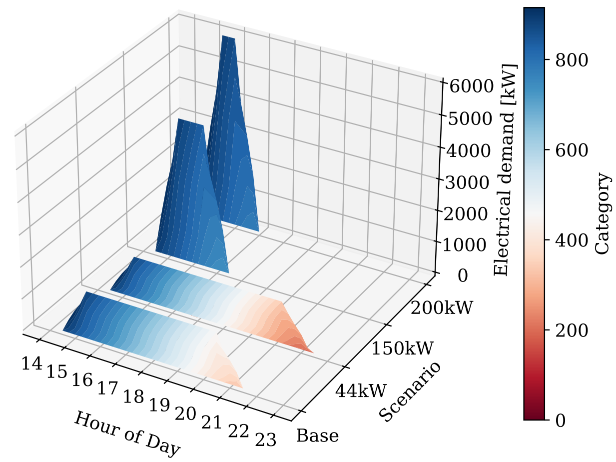

Figure 3: Use case *Wa 11* over simulated scenarios

with less energy demand can still offer flexibility. But the overall flexibility is significantly reduced.

Table IV: Comparison of flexible negative load in MW in scenarios and time buckets of the day

		2025	2030	2035	2040
00:00-04:00	base	1,390	7,541	21,436	30,084
	slow	809	3,889	10,898	16,505
	150	2,430	10,830	27,150	38,250
	200	3,240	14,440	36,200	51,000
04:00-08:00	base	155	915	3,400	5,450
	slow	155	915	3,400	5,450
	150	1,625	6,585	15,550	21,950
	200	2,467	10,148	24,213	34,427
08:00-12:00	base	0	0	0	0
	slow	0	0	0	0
	150	0	0	0	0
	200	0	0	0	0
12:00-16:00	base	600	2,775	7,071	9,598
	slow	205	879	2,221	3,165
	150	1,529	6,164	13,953	19,044
	200	2,039	8,219	18,604	25,392
16:00-20:00	base	1,030	5,709	16,440	22,480
	slow	376	1,805	5,326	8,055
	150	1,830	8,094	20,190	27,930
	200	2,607	11,552	28,853	40,107
20:00-23:59	base	1,630	8,445	23,400	32,800
	slow	976	4,541	12,286	18,375
	150	2,430	10,830	27,150	38,250
	200	3,240	14,440	36,200	51,000

Scenarios with higher average charging power (150 kW and 200 kW) show, that the flexibility potential increases. In the 200 kW-charging scenario, the absolute potential flexible load increases up to 51 GW in 2040. But although the time buckets with former irrelevant flexibility potential increases significantly by up to plus 530 % against the base scenario.

Fig. 4 visualizes the change of the flexibility potential from *Base* in every scenario in percent in ramp-up year 2040. In the scenario *slow-charging* the flexibility potential decreases in four of six time slots by approx. −45 % in the buckets 00:00 – 04:00 and 20:00 – 23:59 as well as approx. −65 % in the buckets 12:00 – 16:00 and 16:00 – 20:00. Scenarios *150 kW* and *200 kW* gain additional flexibility potential in time buckets before departure. With less charging power, this time period is more likely blocked for latest possible charging operations. With higher charging power the required time period to fully charge the battery shrinks. This effect can be seen in bucket 04:00 – 08:00 which has few flexibility potential in Base and slow scenarios and rapidly increasing potential in 150 kW and 200 kW scenarios.

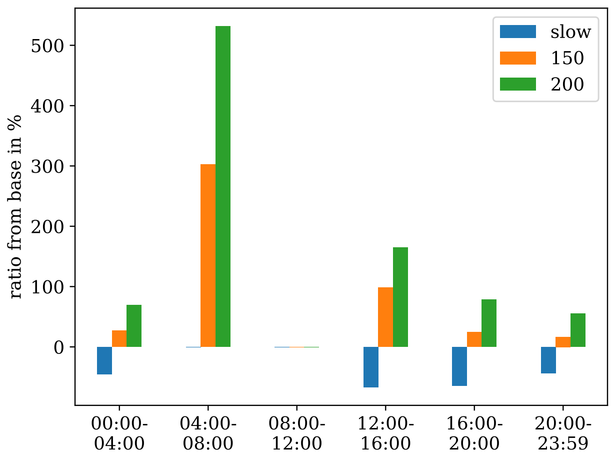

Figure 4: Relative change in flexible load from Scenario *Base* in 2040

Regarding the capex for depot operators low-power EVSE is less expensive and by now no incentives exist to accept higher capex (i.e. lower operating expense (opex)). Table V shows the deviation of the capex against *slow-charging* scenario in thousand Euro, where the first number is based on Nationale Agenda Laadinfrastructuur and the second on Tsiropoulos et al. [9, 10]. Use cases *RD 5* and *Con 7* have no additional costs in scenarios Base and 150kW-charging, which is due to charging power dimensions that are already above or equal to 150 kW. Therefore, the additional costs in the 200 kW-charging scenario of 525.000 € to 814.000 € respectively 175.000 € to 271.000 € are the lowest of all use cases. All other use cases needs additional capex to change the maximum power of their EVSEs from the minimal necessary to fully charge the BET (i.e. scenario *slow*). The highest additional capex to move from minimum necessary charging power to the Base-scenario described by Will and Ocker occur in use case *LH 2* with 4.3 M € to 6.0 M €. *LH 2* has the highest deviation between the charging power in the Base-scenario (i.e. 300 kW) and the minimum required power for fully charged BETs (i.e. 55 kW).

IV. Discussion

This work emphasizes the significant influence of the minimum charging power on the flexibility potential. Fulfilling expectations and raising the flexibility potential of BET depot charging requires additional expenses. These expenses have to incentivized, otherwise there may be significantly less flexibility provided and BETs depots may become inflexible loads to the energy system.

Table V: CAPEX deviation from base scenario per use case (numbers for whole depot) in thousand €

	additional capex[a] against *slow*		
UC	Base	150kW-charging	200kW-charging
LH2	4,288 to 6,002	1,663 to 2,217	2,538 to 3,574
LH3	95 to 152	1,670 to 2,036	2,457 to 3,257
RD5	0	0	525 to 814
Con7	0	0	175 to 271
Wa11	63 to 101	1,113 to 1,357	1,638 to 2,172

a. First number is based on [9], second on [10].

However, simplifications have been made: In the results shown in Table IV the amount of time a load can be shifted is not taken into account. If a load can be shifted for at least 5 minutes, it is considered as flexible. It was estimated, that a SoC of 100% is required on departure. Soften this requirement will lead to further flexibility. Costs are expected as the main obstacle to rise available charging power and several overall-capex are not considered in this work. It is although expected, that quantity and further discounts would apply, which are not considered in this work.

However, incentivize more powerful EVSE comes with the requirement to avoid uncontrolled peak loads. One possible solution could be to tie the incentives to specific setting and requirements for an EMS, which prevent unwanted charging operations.

V. Conclusion and Outlook

It was shown, that economic obstacles exist for ascending the flexibility potential of BETs. The slow-charging scenario is the one with the lowest capex and therefore the must likely one but also the one with the lowest flexibility potential. This scenario has notable less powerful EVSE than scenario *Base*. How to incentivize the higher capex should be part of further research.

The considered use cases are not analysed concerning their impact on flexibility potential. It is to be expected, that some use cases have the potential to overrule other use cases and therefore should be addressed first. Further research is needed to identify and prioritise the use cases.

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References

[1] G. Van Kriekinge, C. De Cauwer, N. Sapountzoglou, T. Coosemans, and M. Messagie, “Peak shaving and cost minimization using model predictive control for

uni- and bi-directional charging of electric vehicles," *Energy Reports*, vol. 7, pp. 8760–8771, 2021. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S2352484721013445

[2] P. Hanemann and T. Bruckner, "Effects of electric vehicles on the spot market price," *Energy*, vol. 162, pp. 255–266, 2018. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0360544218314774

[3] C. Will and F. Ocker, "Flexibility Potential of Smart Charging Electric Trucks and Buses," *World Electric Vehicle Journal*, vol. 15, no. 2, p. 56, Feb. 2024, number: 2 Publisher: Multidisciplinary Digital Publishing Institute. [Online]. Available: https://www.mdpi.com/2032-6653/15/2/56

[4] D. Speth and P. Plötz, "Depot slow charging is sufficient for most electric trucks in Germany," *Transportation Research Part D: Transport and Environment*, vol. 128, p. 104078, Mar. 2024. [Online]. Available: https://linkinghub.elsevier.com/retrieve/pii/S136192092400035X

[5] J. Serradilla, J. Wardle, P. Blythe, and J. Gibbon, "An evidence-based approach for investment in rapid-charging infrastructure," *Energy Policy*, vol. 106, pp. 514–524, Jul. 2017. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S030142151730232X

[6] S. Decher and H. Schäfers, "Assessing flexibility in battery electric truck charging depots considering grid impact," in *IET Conference Proceedings*, ser. 15, vol. 2024, Jan. 2025, pp. 270–276. [Online]. Available: http://digital-library.theiet.org/doi/10.1049/icp.2024.3761

[7] A. Jahic, F. Heider, M. Plenz, and D. Schulz, "Flexibility Quantification and the Potential for Its Usage in the Case of Electric Bus Depots with Unidirectional Charging," *Energies*, vol. 15, no. 10, p. 3639, May 2022. [Online]. Available: https://www.mdpi.com/1996-1073/15/10/3639

[8] M. K. Gerritsma, T. A. AlSkaif, H. A. Fidder, and W. G. V. Sark, "Flexibility of Electric Vehicle Demand: Analysis of Measured Charging Data and Simulation for the Future," *World Electric Vehicle Journal*, vol. 10, no. 1, p. 14, Mar. 2019. [Online]. Available: https://www.mdpi.com/2032-6653/10/1/14

[9] Nationale Agenda Laadinfrastructuur, "Kosten laadinfrastructuur logistiek laden op privaat terrein," Nationale Agenda Laadinfrastructuur, Agenda, Dec. 2022. [Online]. Available: https://agendalaadinfrastructuur.nl/ondersteuning+gemeenten/documenten+en+links/bibliotheek+-+logistiek/bibliotheek+logistiek/handlerdownloadfiles.ashx?idnv=2404030

[10] I. Tsiropoulos, P. Siskos, and P. Capros, "The cost of recharging infrastructure for electric vehicles in the EU in a climate neutrality context: Factors influencing investments in 2030 and 2050," *Applied Energy*, vol. 322, p. 119446, Sep. 2022. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0306261922007759