World Electric Vehicle Journal

Communication

Flexibility Potential of Smart Charging Electric Trucks and Buses †

Christian Will [1,*] and Fabian Ocker [2]

1 Daimler Truck AG, Fasanenweg 10, 70771 Leinfelden-Echterdingen, Germany
2 TenneT TSO GmbH, Bernecker Straße 70, 95448 Bayreuth, Germany
* Correspondence: christian.will@partner.kit.edu

† This article is a revised and expanded version of a paper entitled "Flexibility potential of smart charging of electric trucks and buses", which was presented at 36th Electric Vehicle Symposium & Exposition, 11–14 June 2023, Sacramento, CA, USA.

Abstract: In addition to passenger vehicles, battery-electric trucks and buses could offer substantial flexibility to the energy system. Using a Bass diffusion model, we extrapolated the unidirectional charging needs and availability of trucks in five of eleven typical applications, as well as city buses, for Germany until 2040. Combined, these heavy-duty vehicles could provide up to 23 GW of down-regulating flexibility potential (i.e., in case of excess power supply) in 2040. The resulting revenues could contribute to reducing electricity costs for depot operators. These results illustrate the need to provide easy and automated market access to heavy-duty vehicle fleets.

Keywords: heavy-duty electric vehicles; electric trucks; electric buses; smart charging; flexibility potential

Citation: Will, C.; Ocker, F. Flexibility Potential of Smart Charging Electric Trucks and Buses. *World Electr. Veh. J.* **2024**, *15*, 56. https://doi.org/10.3390/wevj15020056

Academic Editors: Joeri Van Mierlo and Genevieve Cullen

Received: 22 December 2023
Revised: 13 January 2024
Accepted: 30 January 2024
Published: 7 February 2024

1. Introduction

The European electricity grid is maintained and operated by unbundled grid operators for ultra-high and high voltage levels by so-called transmission system operators (TSOs). TSOs co-create and partly operate markets to solve physical challenges such as frequency deviations or bottlenecks in the grid (i.e., congestions). These are referred to as ancillary services [1] and can be divided into four flexibility segments: two ancillary services, balancing power and congestion management, as well as congestion alleviation and the wholesale market. These flexibility segments consider regulatory, technological, and economic framework conditions, as well as the involvement of key stakeholders. Due to the increasing share of electricity generation from renewable sources, as well as the increasing electrification of heating and transport sectors, more flexibility will be needed in the future, in particular on the demand side. The first two segments are the most promising for the integration of demand-side flexibility from electric vehicles. They are briefly introduced in the following discussion, and the temporal order of market closures in Germany is provided in Figure 1.

- **Balancing power** provides upward regulation (supplying additional energy to the grid) and downward regulation (drawing excess energy from the grid) to guarantee a constant equilibrium between electricity generation and consumption, and thus maintain a stable system frequency of 50 Hertz at any time. In particular, the uncertainty of wind and solar generation forecasts is an important driver for the increasing need for flexibility to keep the system in balance. German TSO TenneT expects the need for flexibility to grow by up to 3 GW by 2030. Balancing power is procured in three "qualities" representing different speeds and durations of intervention, namely, frequency containment reserve (FCR), automatic frequency restoration reserve (aFRR), and manual frequency restoration reserve (mFRR). All three are procured through auctions until a certain time on the previous day (D-1).
- **Congestion management** aims to solve an energy transmission (or distribution) problem by making use of remedial actions, such as redispatch and feed-in management.

The task is to match market outcomes with the physical restrictions of the grid during real-time operation. Locational shifts in generation (wind and solar), increasing peak supply, and new demand centers increase needs in this segment. TenneT expects additional flexibility needs in this segment of up to 9 GW by 2030.

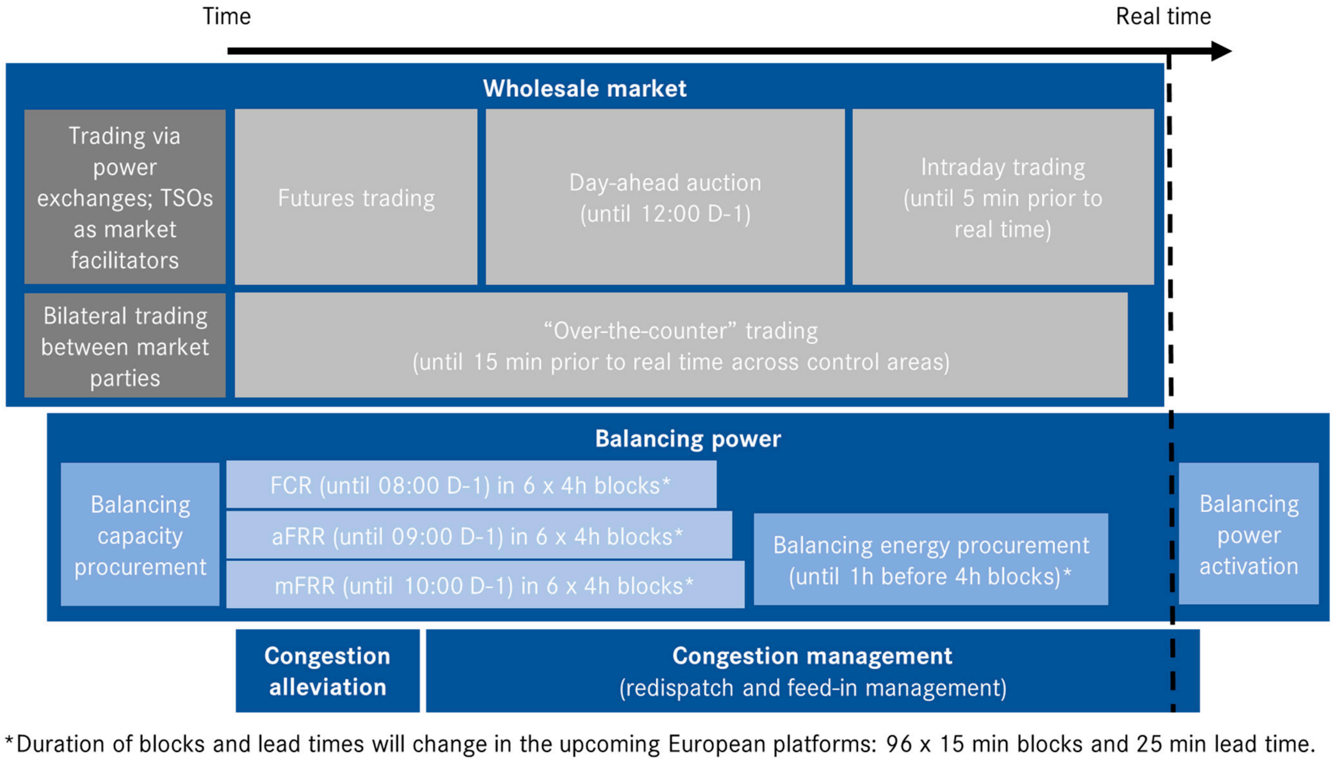

Figure 1. Temporal sequence of market closures for flexibility segments (dark blue) in Germany.

Although the use of battery-electric vehicle (BEV) passenger cars to provide flexibility to the power grid has been investigated extensively (e.g., [2–5]), the body of research regarding the flexibility potential of battery-electric trucks and buses is much smaller. Although the technical implementation of smart charging should be similar for all vehicle sizes [6], the impact of electric truck and bus charging on electricity grids appears significant due to larger batteries, longer distances travelled, and larger charging powers [7,8]. Although buses have well-planned routes with high temporal synchronization [9], truck use cases are diverse (cf. Section 2). Initially, Borlaug et al. found that the early ramp-up of short-haul, predictable truck use cases can likely be accommodated with existing infrastructure in the US [10]. However, this may change with increasing penetration of the technology to more demanding use cases [11]. As a first step, minimizing depot peak-load already strains the grid less and lowers electricity costs for truck fleets due to reduced demand charges [12]. Taljegard et al. [13] showed that a completely electrified transport sector using bidirectional charging, including trucks and buses, could reduce necessary investments in the energy system to meet peak-power by 50% in Sweden, Germany, the UK, and Spain.

In contrast, we aimed to investigate in detail the flexibility and remuneration potential on a per-depot level, focusing on comparing different vehicle use cases. We considered unidirectional conductive direct current (DC) charging using the CCS2 charging standard (combined charging system). As a refined market framework is currently in place only for balancing power, our quantitative analysis focused on this flexibility segment rather than congestion management.

This feasibility study examined how electrified medium- and heavy-duty trucks and city buses can provide flexibility to the energy system by investigating key economic, regulatory, legal, and technical aspects. This paper is structured as follows. Section 2 describes our methodological approach and use case assumptions. Results for initial considerations, technical flexibility, and remuneration potential are discussed in Section 3. Section 4 presents our conclusions and discusses future work.

2. Materials and Methods

The approach taken in this study was twofold (cf. Figure 2). First, expert workshops with representatives from Daimler Truck and TenneT were held. Second, flexibility and marketing potential were derived for a range of use cases and extrapolated over exemplary market ramp-ups.

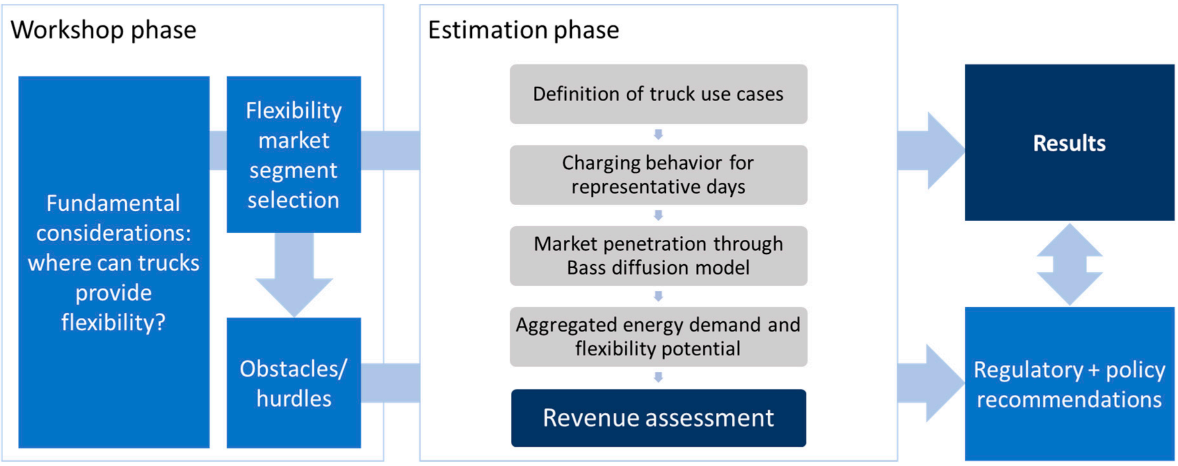

Figure 2. Graphical representation of methodology.

The goals of the workshops were to establish a common understanding of the subject matter between two vastly different industries, further focus our approach, and coordinate the quantification methodology. In total, four online workshops were conducted during the time span of 12 April 2021 until 18 May 2021. The number of participants in these workshops ranged between 10 and 14 employees of TenneT and Daimler Truck. The experience level ranged from expert level (technical, regulatory, or economic) to project leads (of other related projects of TenneT and Daimler Truck) and manager level. The workshops were structured as follows: focus presentations by participants on specific topics, participants were split in multiple groups for deep dives, and participants worked together using a prepared digital whiteboard.

The following three tables describe the parameters used to describe a city bus use case (Table 1) and major truck use cases (Tables 2 and 3). The city bus use case was based on a large, electrified depot in a major German city. Unlike in truck use cases, columns in Table 1 describe spectrums for various parameters rather than specific routes or use cases.

Table 1. Parameters for the "city bus" use case.

Available battery capacity	kWh	350	
Max. available charging power	kW	80	
Energy demand per day	kWh	Min 200	Max 550
Time departure 1	h	Earliest 05:30	Latest 08:30
Time arrival 1	h	Earliest 11:00	Latest 15:00
Time departure 2	h	None, or earliest 13:30	None, or latest 17:00
Time arrival 2	h	None, or earliest 19:00	None, or latest 24:00
Vehicles in example depot		149	

Table 2. Parameters for "line haul" (LH 1–3) and "retail/distribution" (R/D 4–6) use cases.

		LH 1	LH 2	LH 3	R/D 4	R/D 5	R/D 6
Available battery capacity	kWh	600	600	600	600	400	400
Max. available charging power	kW	300	300	50	50	150	150
Energy demand per day	kWh	650	600	350	575	350	400
Time departure 1	h	05:30	06:00	07:00	08:00	05:00	05:00
Time arrival 1	h	17:00	16:00	15:00	16:00	13:00	13:00
Time departure 2	h	-	-	-	-	14:00	14:00
Time arrival 2	h	-	-	-	-	20:00	20:00
Variability of departure		avg.	avg.	large	low	low	low
Vehicles per example depot		50	50	45	20	30	30

Table 3. Parameters for "construction" (Con 7–9) and "waste" (Wa 10–11) use cases.

		Con 7	Con 8	Con 9	Wa 10	Wa 11
Available battery capacity	kWh	600	400	400	400	400
Max. available charging power	kW	150	50	50	50	50
Energy demand per day	kWh	475	300	275	375	300
Time departure 1	h	08:00	08:00	08:00	07:30	07:00
Time arrival 1	h	12:00	16:00	16:00	15:30	15:00
Time departure 2	h	13:00	-	-	-	-
Time arrival 2	h	16:00	-	-	-	-
Variability of departure		average	average	average	low	very low
Vehicles per example depot		10	10	10	15	30

Line haul segments (LH 1–3) summarize a wide variety of long, medium, and short haul applications, transporting all types of goods either on demand or on daily return trips. Retail and distribution routes (R/D 4–6) are usually shorter but more plannable (cf. "variability of departure"), and often include multiple trips per day to retail locations, supermarkets, or distribution locations.

Construction uses cases (Con 7–9) include transportation of building material or equipment to and from construction sites as well as haulage within the site. Waste collection in urban environments and transport between collection and deposition/incineration sites are further prime uses cases for electrification (Wa 10–11).

Although stylized, these parameters allowed detailed modelling of flexibility potentials for exemplary depots for every use case. Flexibility potential is a function of battery state-of-charge and charging power; i.e., the energy volume that can be made available for flexibility marketing. We assumed minimizing peak load as the default charging strategy and as the baseline for the assessment of flexibility potential. Within the limits of ensuring that vehicles are fully charged for their next route, the vehicles' state-of-charge, and the available charging power, charging load could deviate from the minimum depot load schedule, and this flexibility could be offered to the energy market. In an extensive Excel tool, this calculation was conducted for every example depot for the average weekday.

For the flexibility calculation, we assumed that a sufficiently sized grid connection existed or would be built at the depot to enable installed chargers to be simultaneously used at maximum capacity. In combination with over-night idle times, these assumptions allowed for the deterministic calculation of positive (delayed charging processes) and negative (accelerated charging processes) flexibility potential in MW per depot. The potential was assumed to be equal for every day of the week; weekends and bank holidays were not modelled.

In the next step, we created a ramp-up scenario for every use case for Germany using a Bass diffusion model [14] as applied by Ensslen et al. [15] for passenger BEV. Innovation coefficients were used to calculate the share of diesel vehicles being replaced by BEVs over time. The scenario was based on expert assessments (the vehicle ramp-up at the basis of this analysis represents a potential scenario and does not represent a sales prognosis of Daimler

Truck AG), market data [16], and an external source for the bus use case [17]. Furthermore, each use case had a cap on its electrification potential at full diffusion due to the limitations of BEVs, e.g., regarding the range, cargo load, or power demand of ancillary consumers, which was accounted for in the scenario. Looking only at use cases most relevant for flexibility marketing (i.e., with sufficient idle time and early electrification potential), we focused the discussion on five of eleven truck use cases and the city bus use case. Their scenario ramp-up numbers are listed in Table 4.

Table 4. Ramp-up approximation of number of vehicles on the road in Germany.

Use Case	2025	2030	2035	2040
Line haul 2	1200	9300	29,000	37,000
Line haul 3	8300	31,300	68,000	94,000
Retail 5	5000	22,800	58,000	86,000
Construction 7	200	2300	13,000	22,000
Waste 11	1500	6500	13,000	16,000
Total of all use cases	**30,900**	**151,700**	**411,000**	**606,000**
City bus	6900	20,300	31,000	36,000

The flexibility potential per depot were then scaled to the entirety of Germany and aggregated for flexibility marketing. Revenue calculations were based on market data for 2020 and 2021 from the German balancing market platform regelleistung.net [18], and considered both theoretical revenues from the power bid as well a conservative energy bid. Note that we did not model costs, and therefore did not make any claims regarding profitability. Likely cost components, e.g., include increased grid fees, software licenses, prequalification, and market access fees.

3. Results

3.1. Expert Workshops

As the workshops brought together a mix of participants from different levels of expertise across a range of topics from two different industries, opinions, and therefore results, were faceted and diverse. Nevertheless, the workshop series yielded three key take-aways:

1. Logistics businesses will not use electrified vehicles if there is no positive business case, based, e.g., on vehicle price, electricity costs, or incentives for earning additional revenue by providing flexibility services.
2. Promising flexibility segments include balancing power and congestion management (i.e., redispatch).
    a. Although for balancing power the asset location (e.g., the depot) is less important, it is crucial for congestion management because spatial bottlenecks in the electricity network need to be solved.
    b. Technically, trucks and buses can participate in all three balancing types: FCR, aFRR, and mFRR. However, the “higher quality” balancing types (FCR and aFRR) are most suitable because the charging of batteries can be adjusted quickly, and trucks and buses have enough capacity that can be shifted.
    c. In Germany, the regulatory framework for loads and storages under “Redispatch 3.0” is yet to be shaped, while in the Netherlands the so-called GOPACS platform already offers market-based remuneration. Depot operators only provide the redispatch service if they reduce their electricity costs from a market-based remuneration. Therefore, it was decided to focus the following quantification on balancing power within the currently available market framework.
3. The crowd balancing platform “Equigy” enables a more efficient provision of balancing power and congestion management from decentralized, distributed flexibility sources.

a. The crowd balancing platform is not a marketplace, but creates the framework conditions for decentralized prequalification and efficient accounting for the increasing amount of small and distributed assets. This ultimately lowers market entry barriers.

Beyond these key takeaways, many other topics were discussed. Opinions diverged regarding the following points:

4. Not all participants in the workshops agreed that marketing flexibility potential on the wholesale power market should be out-of-scope due to the wholesale markets' strong liquidity and ease of use.
5. The focus on solely Germany was discussed across several workshops. The reason for this discussion was that markets for balancing power are largely integrated in Europe; thus, changes to integrate electrified busses and trucks often requires European regulatory changes.
6. Regarding technical challenges to the integration of electrified busses and trucks, there are differences between countries in which Equigy operates. For example, the Netherlands already uses a practical implementation in which EVs can provide aFRR, but this is not yet the case for Germany.

3.2. Flexibility and Revenue

Positive and negative flexibility potentials (in MW) for grid operation are illustrated in Table 5. Technical flexibility potential is substantial for line haul and retail truck use cases, and large bus depots also play a substantial role in the early morning hours. With a theoretical potential for over 4 GW of positive and negative flexibility from 4 pm to 4 am (peaking at over 23 GW of negative flexibility in the 20:00–24:00 4 h block and at over 7 GW of positive flexibility in the 00:00–04:00 block), all examined use cases combined could have a significant impact on, for example, the balancing power market in 2040. For context, the current demand in 2022 for positive and negative balancing power in Germany is approximately 7.1 GW.

Table 5. Maximum positive and negative (−) flexibility potential for Germany in 2025, 2030, and 2040 [MW].

	00:00–04:00	04:00–08:00	08:00–12:00	12:00–16:00	16:00–20:00	20:00–24:00
2025	+529 −1146	+13 −26	+4 −13	0 −47	+266 −659	+354 −1048
2030	+2210 −5960	+46 −77	+13 −39	0 −138	+1238 −3981	+1613 −5765
2040	+7066 −22,593	+154 −137	+23 −70	0 −245	+4183 −16,095	+5542 −23,113

Figure 3 illustrates the potential revenue from flexibility provision, and therefore the reduction potential for the total cost of ownership [EURct/kWh] for truck customers. In practice, depot operators may have electricity contracts with flexibility aggregators who grant remuneration or rebates on electricity prices in exchange for flexibility. The revenue potential is larger in the aFRR market, and the largest revenue results for truck use cases were line haul 2 and waste 11, while the bus use case and truck use case retail 5 had the lowest potential. For aFRR, the revenue potential could be significant, given that average electricity prices for German industry are approximately 20 EURct/kWh. If transport companies could facilitate flexibility marketing reliably, significant rebates on their electricity costs would be possible.

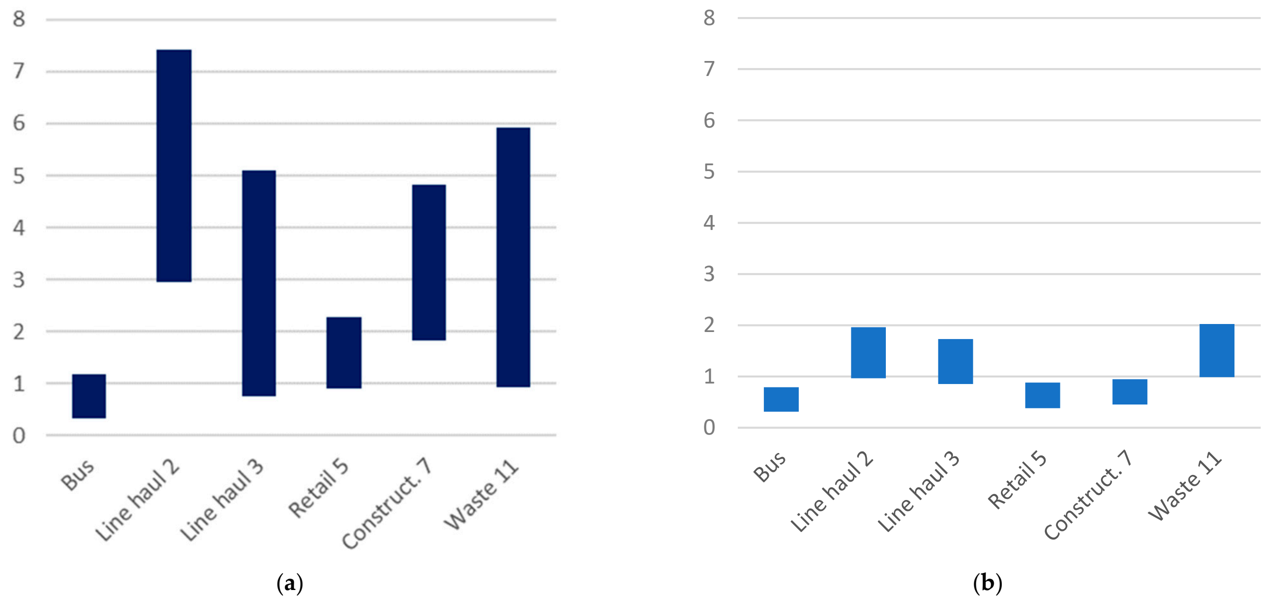

Figure 3. Range of maximum possible revenue per consumed kWh from (**a**) aFRR (capacity and energy) and (**b**) FCR in EURct/kWh (minimum revenue with 2020 prices, maximum with 2021 prices).

There are several limitations to these findings. First, the analysis did not allow for profitability conclusions because only the revenue side was presented (i.e., costs were not included). Second, the flexibility potential assumed that it could be offered over the entire bid timeframe, which is not possible in practice because actual flexibility delivery can considerably reduce the potential. Furthermore, flexibility potentials were based on only a selection of bus and truck use cases (six of twelve) and considered only weekdays (neither weekends nor bank holidays). Finally, we used market data from 2020 and 2021 to illustrate revenue ranges; predictions of future prices require further analysis.

4. Discussion

This study laid the foundation for a mutual understanding of the interaction of energy and transport sectors by assessing the flexibility and revenue potentials of electrified trucks and buses. We showed the significant technical potential of shifting charging times of specific truck and bus use cases to offer balancing power. Furthermore, this offering could lead to notable revenues that should be used to compensate depot operators for the flexibility provided.

Policy recommendations for balancing power include prequalification criteria, which should avoid redundancy and minimize costs for balancing service providers (e.g., by establishing largely automated prequalification processes). Furthermore, vehicle operators' risk of insufficient state-of-charge must be nullified through smart IT solutions. Due to a current lack of marketability, we excluded congestion management from the quantification analysis of this study, despite the expected impact of truck and bus charging on distribution grids [5,6]. A market-based approach should complement the existing cost-based provision of redispatch services and address these decentralized generation or consumption assets, for which there is no mandatory participation in the current redispatch regime. This means that an attractive market solution is needed to allow voluntary participation by consumers and businesses, rather than mandatory load reductions.

5. Conclusions

The electricity system is changing: a growing share of volatile renewable production meets higher and more dynamic loads on all consumption levels. This study investigated how demand–response in the form of battery-electric trucks and buses could offer substantial flexibility to the energy system. In a small series of expert workshops, we built a common understanding of the key aspects of this topic and aligned a research approach. Consequently, we used a Bass diffusion model to extrapolate the unidirectional charging needs and availability of trucks in five of eleven typical applications, as well as city buses, for Germany until 2040. Combined, these heavy-duty vehicles could provide up to 23 GW of down-regulating flexibility potential (i.e., in case of excess power supply) in 2040. The resulting revenues could contribute to reducing electricity costs for fleet operators, thereby improving the attractiveness of zero-emission technologies. These results illustrate the need to provide easy and automated market access to heavy-duty vehicle fleets.

A full economic examination regarding the profitability potential is advisable in future work. This includes, in particular, a quantitative assessment of the cost side and of the effects of delivering balancing energy on the flexibility potential. Further research is needed to quantitatively compare other marketing options, e.g., congestion management, intraday arbitrage trading, or even pure behind-the-meter cost minimization using on-site solar generation. A logical expansion of the model could integrate bidirectional charging, which should further increase flexibility potentials, especially when considering weekends and public holidays. Furthermore, a technical pilot could be informative regarding open topics in standardization or availability of equipment.

Author Contributions: Conceptualization, C.W. and F.O.; methodology, C.W. and F.O.; software, C.W. and F.O.; validation, C.W. and F.O.; formal analysis, C.W. and F.O.; investigation, C.W. and F.O.; resources, C.W. and F.O.; data curation, C.W. and F.O.; writing—original draft preparation, C.W. and F.O.; writing—review and editing, C.W. and F.O.; visualization, C.W. and F.O.; supervision, C.W. and F.O.; project administration, C.W. and F.O.; funding acquisition, C.W. and F.O. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

Acknowledgments: We would like to thank the co-authors and participants from both companies for their invaluable input and support. This study did not benefit from public funding.

Conflicts of Interest: Christian Will is employee of Daimler Truck AG and Fabian Ocker is employee of TenneT TSO GmbH. The paper reflects the views of the scientists, and not the company.

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