Daimler Truck

TenneT

Flexibility marketing options for charging processes of electric medium-duty and heavy-duty commercial vehicles

Feasibility study by Daimler Truck AG and TenneT TSO GmbH

30.06.2022

Contact information to project leads:

Daimler Truck AG: Christian Will, christian.c.will@daimler.com
TenneT TSO GmbH: Dr. Fabian Ocker, fabian.ocker@tennet.eu

Daimler Truck

Table of contents

Abbreviations

aFRR	Automatic Frequency Restoration Reserve (formerly Secondary Reserve)
mFRR	Manual Frequency Restoration Reserve (formerly Tertiary/Minute Reserve)
BEV	Battery Electric Vehicle
BRP	Balancing Responsible Party
BSP	Balancing Service Provider
CBP	Crowd Balancing Platform
DSO	Distribution System Operator
FCR	Frequency Containment Reserve (formerly Primary Reserve)
OEM	Original Equipment Manufacturer
TSO	Transmission System Operator
V2B	Vehicle-to-Business
V2G	Vehicle-to-Grid
V2H	Vehicle-to-Home

Daimler Truck

Executive Summary

Purpose, target and approach – This feasibility study examines how electrified trucks and busses can provide flexibility to the energy system. The focus is on ancillary services, particularly in Germany. For this, the key economical, regulatory, legal and technical aspects along TenneT's flexibility segments of "balancing power", "congestion management", "congestion alleviation" and "wholesale market" are investigated. This study creates awareness regarding possible use cases for and revenues from unidirectional smart charging applications for relevant stakeholders in the energy and automotive sector. The approach taken in this study is twofold: first, expert workshops with relevant experts from Daimler Truck and TenneT were held, and secondly, flexibility and marketing potential was modelled.

Results of the expert workshop sessions – There are three key take-aways:

1. Daimler Truck's customers are businesses, which will not use electrified vehicles if there is no positive business case (i.e. that is dependent on, e.g., vehicle price, electricity costs, incentives for earning additional revenue by providing flexibility services).
2. Promising flexibility segments are balancing power and congestion management (i.e. redispatch).
   - While for balancing power the asset location (e.g. depot) is less important, it is crucial for congestion management because spatial bottlenecks in the electricity network are to be solved.
   - Technically, trucks and busses can participate in all three balancing types FCR, aFRR and mFRR. However, the "higher quality" balancing types FCR and aFRR are most suitable because charging of batteries can be adjusted quickly, and they have enough capacity that can be shifted.
   - For the investigated use cases, typical hours of participation can range between 4 pm to 4 am.
   - In Germany, the regulatory framework for loads and storages under "Redispatch 3.0" is still to be shaped, while in the Netherlands the 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.
3. The Crowd Balancing Platform "Equigy" enables a more efficient provision of balancing power and congestion management from decentral, distributed flexibility sources.
   - The Crowd Balancing Platform is not a marketplace, but it creates the framework conditions for a decentralized prequalification and efficient accounting for the increasing amount of small and distributed asset. This ultimately lowers market entry barriers.

Results of the flexibility and market modelling – The flexibility potential [MW] is quantified as positive and negative flexibility potential for TenneT's grid operation and is illustrated in the following table. The flexibility potential is substantial for the line haul and retail truck use cases[1] and also large bus depots play a substantial role in the early morning hours. With a theoretical potential of over 4 GW of positive and negative flexibility from 4 pm to 4 am (peaking at over 23 GW of negative flexibility in the 4-hour-block 20:00-24:00 and at over 7 GW of positive flexibility in 00:00-04:00), all examined use cases combined could have a significant impact on, for example, the balancing power market in 2040: the current demand in 2022 for positive and negative balancing power in Germany is around 7.1 GW.

---
[1] The vehicle ramp-up at the basis of this analysis are a potential scenario and do not represent a sales prognosis of Daimler Truck AG.

Daimler Truck

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	13	4	0	266	354
	-1,146	-26	-13	-47	-659	-1,048
2030	2,210	46	13	0	1,238	1,613
	-5,960	-77	-39	-138	-3,981	-5,765
2040	7,066	154	23	0	4,183	5,542
	-22,593	-137	-70	-245	-16,095	-23,113

The following figure illustrates the reduction potential for the total cost of ownership [EURct/kWh] for Daimler Truck's customers through revenue from flexibility provision. In practice, depot operators may have electricity contracts with flexibility aggregators who grant remuneration or rebate on electricity price in exchange for provided flexibility. The revenue potential is larger on the aFRR market, and the largest revenue results for truck use cases line haul 2 and waste 11, while the bus use case and truck use case retail 5 have the lowest potential. For aFRR the revenue potential can be very significant given average electricity prices for German industry at around 20 EURct/kWh. If transport companies could facilitate flexibility marketing reliably, significant rebates on their electricity costs would be possible.
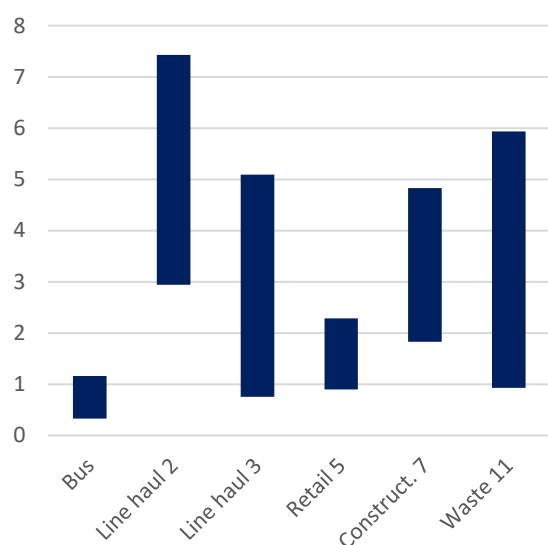
a) aFRR (capacity & energy)   b) FCR
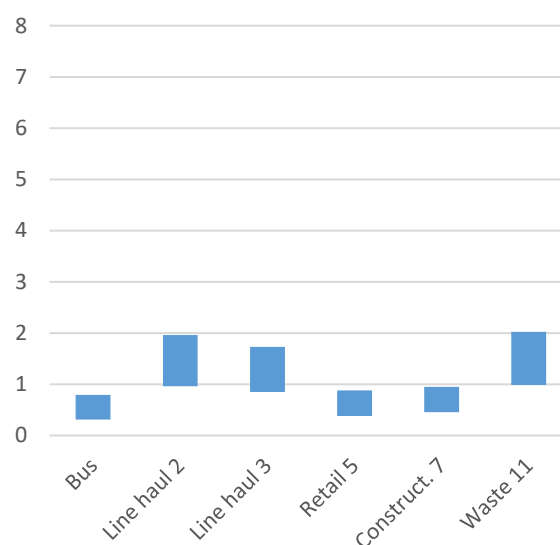
Range of maximum possible revenue per consumed kWh from flexibility segments, in EURct/kWh
(minimum revenue with 2020 prices, maximum with 2021 prices)

There are several limitations to these findings. First and foremost, the analysis does not allow for profitability conclusions because only the revenue side is presented (i.e. costs are not included). Second, the flexibility potential assumes that it can be offered over the entire timeframe, which is in practice not possible because actual flexibility delivery can reduce the potential considerably. Furthermore, the flexibility potentials are based only on a selection of bus and truck use cases (6 out of 11) and consider only weekdays (neither weekends nor bank holidays). Finally, we used market data from 2020 and 2021 to illustrate revenue ranges, but predictions of future prices are challenging.

Mutual positions for policy recommendations – For balancing power, the prequalification criteria should avoid redundancy and minimize costs for balancing service providers (e.g. by establishing largely automated prequalification processes) and the risk of insufficient range for vehicle operators should be minimised through the use of smart IT solutions. For congestion management, a market-based approach should complement the existing cost-based provision of redispatch services and address these decentralised 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 for voluntary participation from consumers rather than mandatory load reductions.

Pilot project and next steps – This study laid the foundation for a mutual understanding of Daimler Truck and TenneT regarding flexibility and revenue potentials from electrified trucks and busses. Prior to a physical pilot project, a full economic examination regarding the profitability potential is advisable. This includes in particular a quantitative assessment of the cost side and of the effects of the delivery of balancing energy on the flexibility potential. For this, Daimler Truck can cooperate with suitable partners like utilities or aggregators. For a subsequent pilot project, Equigy is one possibility for providing balancing power, but it can also work via an already existing balancing service provider.

Structure of this study – Section 2 introduces to Daimler Truck's bus and truck use cases, while Section 1 gives an overview of TenneT's four flexibility segments. In Section 2, the approach to determine the flexibility potential is illustrated. Sections 4 and 5 discuss the marketing potentials for balancing power and congestion management. Section 6 presents scalability potentials to national dimensions, both regarding the Crowd Balancing Platform Equigy and flexibility potentials until 2025, 2030 and 2040. In Section 7, related regulatory aspects are discussed and in Section 8, aspects regarding Vehicle-to-Grid bidirectional charging are presented. Section 9 states mutual positions for policy recommendations.

Daimler Truck   TenneT

1   TenneT's flexibility segments and focus of this study

The electricity grid is maintained and operated by grid operators, such as TenneT as transmission system operator (TSO) for the ultra-high and high voltage levels. For this, they co-create and partly operate markets to solve physical challenges such as frequency deviations or bottlenecks in the grid (so-called congestions). These are referred to as ancillary services (dena, 2022). TenneT distinguishes four flexibility segments: the two ancillary services balancing power and congestion management as well as congestion alleviation and wholesale market. TenneT's flexibility segments consider regulatory, technological and economic framework conditions as well as the involvement of key stakeholders. The segments are briefly introduced in the following 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 the constant equilibrium between electricity generation and consumption and, thus, maintain a stable system frequency of 50 Hertz at any time. In particular, the uncertainty in wind and solar generation forecasts is an important driver for increasing need for flexibility to keep the system in balance.

- **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 the market outcomes, which only partly consider the physical electricity grid, with the physical restrictions of the grid during real time operation. The locational shift of generation (wind and solar), increasing peak supply and new demand centres increase needs in this segment.

- **Congestion alleviation** is congestion management with a long time horizon (above several years). This means that it aims to prevent congestion by planning the grid and its components in advance by making use of services from the market, without compromising flexibility potential for other, more short-term flexibility segments.

- Organising flexibility on the **wholesale market** utilises the fact that the variability of wind and solar generation is to a large extent predictable. This variability is primarily managed through the wholesale market (day-ahead and intraday), where mismatches in generation and consumption in the portfolios are traded between market parties. TenneT supports the development of short-term markets because it reduces the amount of ancillary services needed close to or in real time.

TenneT expects additional flexibility needs in the four segments in the order of magnitude for 2030:

- up to 3 GW for balancing power in Germany (up to 2 GW in the Netherlands),

- up to 9 GW for congestion management and alleviation in Germany (up to 5 GW in NL),

- up to 2 GW of flexibility for the wholesale market in Germany (up to 12 GW in NL).
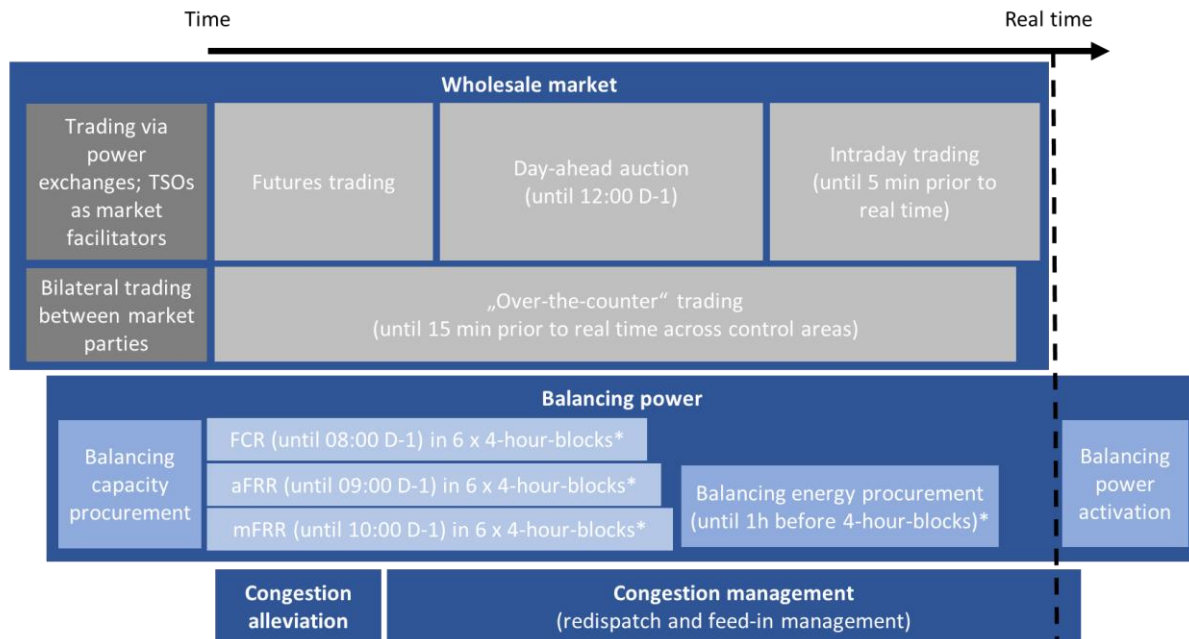
*Duration of blocks and lead times will change in the upcoming European platforms: 96 x 15 min blocks and 25 min lead time.

Figure 1: Temporal order of market closures for flexibility segments (dark blue)
in Germany as of May 2022

The focus of this feasibility study are the promising flexibility segments of balancing power (Section 4) and congestion management (Section 5), i.e. redispatch in a potential future market-based regime of Redispatch 3.0 in Germany for devices that are not covered by Redispatch 2.0 legislation and the already existing market-based regime of the system "GOPACS" in the Netherlands. In the segment wholesale market, TenneT plays a passive role since transmission system operators (TSO) are market facilitators rather than active trading parties. Therefore, this segment focuses mainly on regulatory aspects (see Section 7). The segment congestion alleviation will not be in scope for this project since in this segment capacities are organised for years rather than hours.

2   Bus and truck use cases

The following chapter describes eleven generalized truck use cases and one extrapolated customer example for a bus depot for which the electrification of vehicles is planned. The use cases are the basis for consecutive considerations on the availability of flexibility and the ensuing quantification of revenue potentials. Key premises for each use case are summarised in the tables below. Table 1 summarises the metrics and units used for the description of the use cases.

Table 1: Metrics and units used for the description of the use cases

Metric	Unit	Additional description
Min required SOC	%	Minimum state of charge needed for daily route(s)
Available battery capacity	kWh	As installed in the vehicle
Max. available charging power	kW	As installed at example depot
Energy demand per Veh. & day	kWh	Derived from exemplary daily mileage
Time departure 1	h	Vehicle leaves depot for first shift
Time arrival 1	h	Vehicle returns to depot after first shift
Time departure 2	h	Vehicle leaves depot for second shift
Time arrival 2	h	Vehicle returns to depot after second shift
Variability of departure		High if vehicles leave all at same time due to tight trip schedules
# vehicles in example depot		Number of vehicles operating out of example depot
Comment		(If applicable)

All numbers are exemplary, drastically reduced for the quantification and may not be representative of real usage behaviour for all customers.

2.1 City bus

A rapidly growing electric bus market leads to higher demand for innovative vehicle models, like the eCitaro, worldwide and particularly in Europe. Due to the complexity of the bus business, connected software solutions for organising and charging buses are also required.

For the operation of eBuses, fleet operators currently choose one of two charging concepts: (1) Either through a centralized charging infrastructure at the bus depot for all buses to return to after their shifts, or (2) by opportunity charging via pantographs during a route when vehicles stop at bus stops to let in passengers or at dedicated turning opportunities. In the following, we consider case (1) depot charging. In Europe, typically between five and 200+ buses operate out of individual depots and will be charged using this approach. Due to the predominantly identical timetables, power and energy requirements can be assumed immutable from Monday to Thursday. On all other days, consumption is usually below the standard days of the week. Therefore, we focus on these weekdays and will simulate an upper bound of the energy demand and therefore consider not the maximum of the flexibility potential (i.e. we do not account for the additional flexibility on non-weekdays).

Generally, each city assigns bus routes and schedules individually, which results in unique charging and idling patterns. For the example shown in this report, 149 buses from a major German city are recharged with at most 80 kW in the central depot. Anonymised data on arrival and departure times, route lengths, locations, downtimes and loading times serve as the basis for the calculations. The battery capacity of each vehicle is 350 kWh. An indispensable prerequisite is that a bus may only be sent on its route fully charged. The energy requirement for each bus is between 200 kWh and 550 kWh per day. A summary is provided in Table 2.

Table 2: Premises for the use case "city bus"

Min required SOC	%	100	
Available battery capacity	kWh	350	
Max. available charging power	kW	80	
Energy demand per veh. & 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	Latest 17:00
Time arrival 2	h	Earliest 19:00	Latest 24:00
Variability of departure		(based on real travel-data)	
# vehicles in example depot		149	
Comment		Sometimes return on following day	

2.2 Line haul

Line haul is *the* classic truck application. We see these vehicles on the road every day as the heavy-duty trucks carrying a wide variety of goods across the continent and enabling life to be as convenient as we know it. We define three use cases, depending on the distance travelled and repeatability of routes.

A typical long haul driver (use case 1) often travels alone. However, if customers need an urgent delivery, the logistics provider may send two drivers in one truck: One driver can rest while the other continues to drive, thereby minimising idle time while meeting regulatory requirements for rest periods. Under European law, the driving limit per day for a driver operating a 12 t or higher vehicle is 9 hours but that can be extended to 10 hours twice a week (European Commission, 2020). Included in this period are mandatory 45 min break periods for every 4.5 hours of driving. Therefore, a typical drive is approximately 8 hours with an average speed of 70 km/h before reaching the day's final destination. Trips may take multiple days and cover a lot of ground; therefore, public charging opportunities are often required for this use case.

Use case 2 on the other hand can be serviced in a single day and typically consists of a one-shot drive from depot to depot or a special delivery with return trip. The great variety in applications forces operators to install a faster charging infrastructure. Use case 3 handles regional on-demand transports with high flexibility but over shorter distances. A summary is provided in Table 3.

Daimler Truck

Table 3: Premises for the three use cases "line haul"

		1	2	3
Min required SOC	%	100%	100%	100%
Available battery capacity	kWh	600	600	600
Max. available charging power	kW	300	300	50
Energy demand per veh. & day	kWh	650	600	350
Time departure 1	h	05:30	06:00	07:00
Time arrival 1	h	17:00	16:00	15:00
Time departure 2	h	-	-	-
Time arrival 2	h	-	-	-
Variability of departure		average	average	large
# vehicles per example depot		50	50	45
Comment		return on following day		

2.3 Retail / Distribution

Supplying goods to where they are needed, distribution to retail, industrial or other locations for the "last (couple of hundred) miles" is a very important use case in trucking. Due to relatively low average speeds and minimal motorway driving, this use case is slightly less energy intensive than many other applications. Together with relatively short routes, distribution routes will be among the first to be serviced by electric trucks. Distribution trucks usually operate within a small, often urban radius. This allows for multiple trips per day depending on the distance to the retail customers. In most cases, slow overnight charging at the depot will suffice to service all routes of the day.

Table 4: Premises for the three use cases "retail/distribution"

		4	5	6
Min required SOC	%	100%	100%	100%
Available battery capacity	kWh	600	400	400
Max. available charging power	kW	50	150	150
Energy demand per veh. & day	kWh	575	350	400
Time departure 1	h	08:00	05:00	05:00
Time arrival 1	h	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		low	low	low
# vehicles per example depot		20	30	30
Comment			2 full shifts	2 full shifts

Use case 4 has the largest mileage and therefore uses a larger truck. However, the fixed routes allow for slow overnight charging. Use cases 5 and 6 have lower mileage but service two full shifts. Therefore, the truck may recharge in the lunch break at a higher charging power. Routes for three use cases generally are planned out in detail, with optimised routes and low variability. A summary of all distribution use cases is provided in Table 4.

2.4   Construction

Another group of use case can often be seen on Europe's motorways, unfortunately often while stuck in traffic: construction. It is another important use case with significant volume, but likely not the first in line for electrification. The high investment costs for the vehicle is harder to offset due to the lower driving mileage available. Furthermore, the higher ground clearance necessary to drive in unpaved terrain makes fitting and securing batteries in the chassis more complex and, by extension, more expensive. Energy consumption of specific body machinery must also be considered, e.g. concrete pumps.

Use cases 7 and 8 may be close to some of the distribution use cases described above, e.g. the transportation of material to the construction sites. Use case 7 requires longer or more trips and the lunch break offers potential for faster recharging. Use case 9 covers a lot less mileage and the majority of trips are shorter under high loads, e.g. within the construction site. Construction fleets are usually a bit smaller and are parked at the depot over night or on the construction site. A summary of all construction use cases is provided in Table 5.

Table 5: Premises for the three use cases "construction"

		7	8	9
Min required SOC	%	100%	100%	100%
Available battery capacity	kWh	600	400	400
Max. available charging power	kW	150	50	50
Energy demand per veh. & day	kWh	475	300	275
Time departure 1	h	08:00	08:00	08:00
Time arrival 1	h	12:00	16:00	16:00
Time departure 2	h	13:00	-	-
Time arrival 2	h	16:00	-	-
Variability of departure		average	average	average
# vehicles per example depot		10	10	10
Comment		2 half-shifts		

2.5   Waste

The final group of use cases focuses on one specific "residual" product: waste. Waste collection is characterized by short to medium trip distances, hundreds of stops and large energy consumption due to continuous braking and accelerating as well as the powering of compression mechanisms. Routes, however, are planned to the minute, mostly within urban areas, and have great potential for electrification. Electric trucks in this use case offer a sizeable advantage over diesel or gas trucks as

most city inhabitants would likely appreciate a quieter collection process. Daily mileage is still relatively high since rural collection routes and transport of bulk waste from city depot to processing hub are included in these use cases. The charging scenario suitable for waste vehicles is almost exclusively depot charging. A summary of all waste use cases is provided in Table 6.

Table 6: Premises for the two use cases "waste"

		10	11
min required SOC	%	100%	100%
Available battery capacity	kWh	400	400
max. available charging power	kW	50	50
Energy demand per veh. & day	kWh	375	300
Time departure 1	h	07:30	07:00
Time arrival 1	h	15:30	15:00
Time departure 2	h	-	-
Time arrival 2	h	-	-
Variability of departure		low	very low
# vehicles per example depot		15	30
Comment			

3   Approach to determine the flexibility potential

Based on selected use cases for trucks (5 out of 11 use cases) and city busses (1 use case), an Excel tool was used to quantify the flexibility potentials for unidirectional charging (for bidirectional charging see Section 8). The flexibility potential is a function of battery state of charge and charging power, i.e. the energy volume that can be made available for ancillary services such as balancing power.

- Positive flexibility potential increases when charging processes can be delayed or slowed down because scheduled charging happens at a higher power level and there is still sufficient time to fill the battery at a later point in time.

- Negative flexibility potential increases when charging processes can be shifted forward or accelerated because scheduled charging happens at a lower power level than technically possible.

The underlying charging strategy is "minimum network load": an optimisation reduces the peak load of the entire depot (limitations in available grid connection or high power prices in grid fees are typical reasons to minimize the peak load), while ensuring that the vehicles are fully charged for their next route. Vehicles charging rates are reduced if many vehicles are at the depot at the same time and vice versa. Please note that the simulation does not allow for deviations in energy consumption on routes or in arrival or departure times throughout the year. That means that optimisation happens with perfect foresight for the energy demand of the following day.

For the sake of understanding and although we refer to this in the later Section 4.3.2, we present the network load for the bus use case in Figure 2 (blue curve): the x-axis denotes the hours of the day [h]

(we use a 15 min resolution) and the y-axis denotes the network load [kW]. The derived flexibility potential is illustrated in Figure 3: the x-axis represents the hours of the day (15 min resolution), while the y-axis states the flexibility potential [kW]. The area below (above) the solid (dotted) curve is the maximum available energy [kWh] that can be offered as positive (negative) flexibility potential. Note that in practice this amount will not be offered to the market entirely because of uncertainty: If balancing power must actually be provided, the power draw for the vehicles must be adjusted to make up for energy charged earlier (negative flexibility potential) or later (positive flexibility potential) than originally planned. If balancing power was needed for the entire duration of the contracted period, there would be no time left to make up for the deviation from planned charging power. Furthermore, a balancing power call reduces flexibility for the remainder of the day. Therefore, the flexibility curves depicted are only valid if no call occurs.

To better illustrate this point, the grey curve in Figure 2 depicts the network load with exemplary deliveries of balancing power for the bus use case. From 22:45 until 23:45, the delivery of positive balancing energy in the amount of 1,280 kWh ("A" in the figure) is illustrated, while from 03:45 until 04:45 the delivery of negative balancing energy in the amount of 1,120 kWh (C) is shown. Note that the new network load curve deviates from the load curve of the original schedule. The energy not charged due to the delivery of positive balancing energy is shifted to be charged in the periods from B, C and D. Due to the subsequent delivery of negative balancing energy in C, less energy is needed for the remainder of the night. This leads to a lower charging power in D than originally scheduled. Furthermore, the delivery of negative balancing power increases the peak network load substantially to 5,300 kW (compared to 4,180 kW without the delivery of balancing power).

What are the effects of delivering balancing energy on the flexibility potential? Figure 3 shows the flexibility potential according to the original charging schedule. Adapting to the delivery of balancing energy would require continuous re-calculation of the flexibility potential which is out of scope for this study. Therefore, the stated flexibility potentials represent an upper bound and do not account for the delivery of balancing energy. In principle, the effects of balancing energy delivery are twofold: they decrease the flexibility potential in the direction of the respective delivery, while they increase the flexibility potential in the opposite direction.
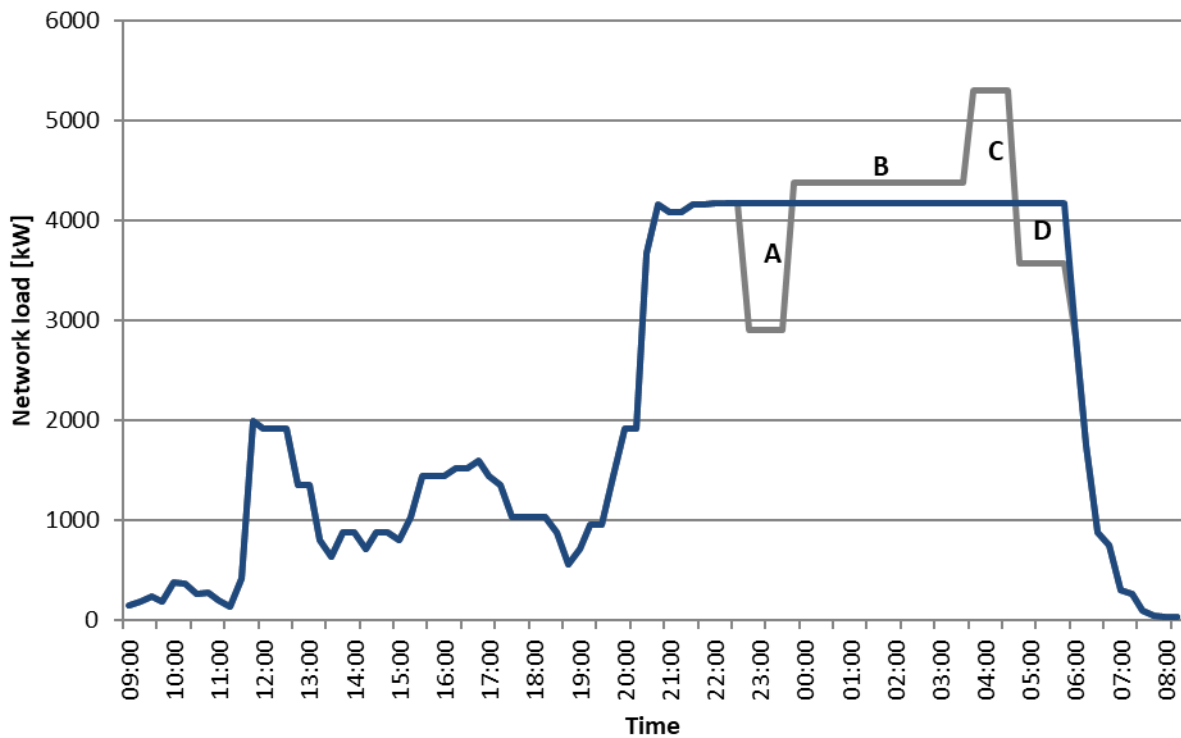
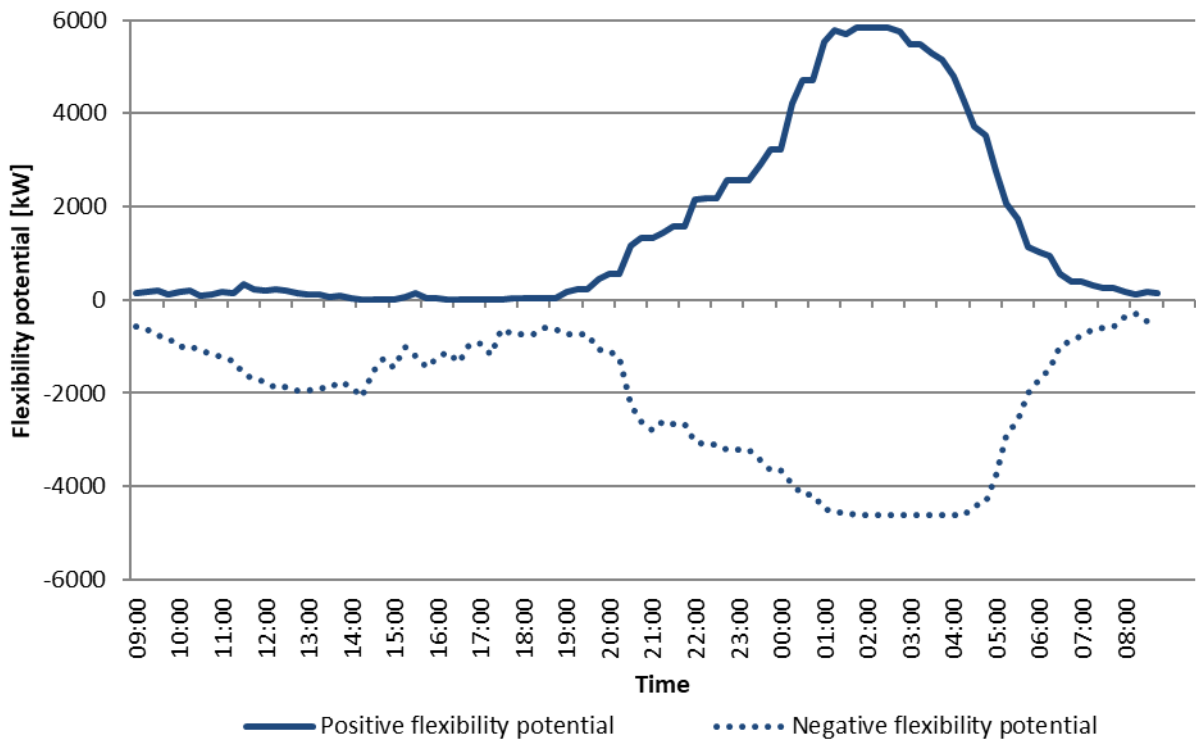Figure 2: Network load for the bus use case (blue) and exemplary balancing power activation (grey)

Figure 3: Flexibility potential for the bus use case (149 vehicles)

4 Marketing potentials for balancing power

This section discusses the marketing potential for the flexibility segment "balancing power". First, we present general background information, followed by technical and economic aspects that were discussed in the experts workshops. For a preliminary economic assessment, we quantify the revenue potentials and derive revenue ranges for the different use cases. Note that we do not quantitatively assess the cost structure but solely describe potential cost elements. This means that profitability conclusions cannot be drawn from this economic assessment.

4.1 Background information

This subsection is mainly an excerpt from Ehrhart and Ocker (2021). Electricity wholesale trading is done at forward markets (more long-term) and spot markets (point of delivery is within hours). Spot markets include a "day-ahead" and an "intraday" market. The day-ahead auction is considered as the central electricity marketplace for the following day, while intraday trading is done close to real time to adjust to changing circumstances. Traded energy volumes at the wholesale market usually differ from the actual production and demand. The reason is that contracted volumes are based on predictions of supply and demand. A deviation persisting until real time has a direct influence on the grid frequency and exchanges between control areas in alternating current systems: if too much (little) energy is supplied, the grid frequency increases (decreases) or actual exchanges between control areas deviate from planned exchanges, which can in the worst case lead to blackouts. To avoid this, TSOs apply balancing power for stabilization. Three different balancing types are distinguished:

- Frequency Containment Reserve (FCR, formerly Primary Reserve)
- Automatic Frequency Restoration Reserve (aFRR, formerly Secondary Reserve)
- Manual Frequency Restoration Reserve (mFRR, formerly Tertiary or Minute Reserve)

They differ in the reaction times of 30 s, 5 min and 12.5 min, which is depicted in Figure 4. Each of the types comprises separate procurement auctions. In general, the market volumes of the three balancing types are small compared to the volumes traded at the wholesale market: in Germany, the balancing capacities procured are around 600 MW for FCR, around 3,500 MW for positive and negative aFRR and around 3,000 MW for positive and negative mFRR, while average wholesale demand is around 60,000 to 70,000 MW.
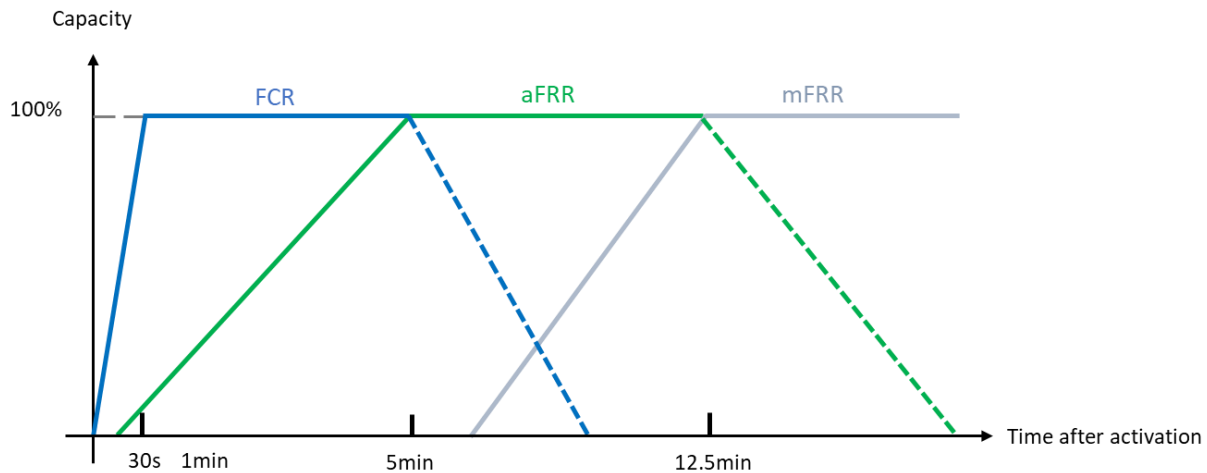
Figure 4: Temporal order of the three balancing types, based on Ocker, Braun and Will (2016)

The deviation of contracted production or consumption is separated in overproduction (e.g. from wind plants during a storm) or underproduction (e.g. from solar plants during a cloudy day). Thus, balancing power needs to provide increased and decreased energy supply (or decreased and increased energy consumption respectively), which is implemented via two products: for the "positive product" (negative product) suppliers (henceforth "balancing service providers, BSP") provide upward (downward) regulation. Balancing power provision requires a prequalification. BSPs encounter two types of cost (revenues): "capacity cost" for reserving balancing capacity [megawatt, MW], and "energy cost (revenues)" for the delivery of balancing energy [megawatt hour, MWh]. Note that for the energy provision there may exist also revenues for the BSP: for negative balancing energy, operators of conventional (i.e. thermal) power plants save costs for fuel and CO_2 certificates. In Germany (and many other European countries), capacity costs are recovered through grid fees imposed on end consumes, while energy costs are accounted to imbalanced parties via the imbalance price.

FCR is procured on a pan-European level. BSPs submit a two-dimensional bid: a capacity offer [MW] and a capacity bid [Euro/MW] and those with the lowest capacity bids are awarded and need to be able to provide both positive and negative balancing energy (so-called symmetric product). For settlement, uniform pricing (all awarded BSPs are paid a uniform price) is applied. The activation of FCR directly steers decentralized assets according to the deviation of the grid frequency from 50 Hertz (linear activation between 49.8 and 50.2 Hertz), i.e. each unit and group providing reserve capacity, respectively, requires a frequency meter. Note that provided FCR energy is not paid and balance groups are not corrected for provided FCR energy. If reserve providing units (e.g. one charging station) are combined to a reserve providing group (e.g. a bus depot) the reserve providing group has to react according to the frequency deviation. Hence, FCR provision can be flexibly allocated to individual devices. There are daily FCR auctions, with a gate closure time at 08:00 am day-ahead and bid validity periods of six 4-hour-blocks (00:00-04:00, …).

For aFRR and mFRR, there exist separate markets for a combined procurement of balancing capacity and balancing energy as well as a procurement of solely balancing energy. In the combined markets for aFRR and mFRR, BSPs submit three-dimensional bids: a capacity offer [MW], a capacity bid [Euro/MW] and an energy bid [Euro/MWh]. This implies that BSPs who were awarded with their

capacity bid are obliged to offer also an energy bid in the balancing energy market. In the balancing energy markets for aFRR and mFRR, BSPs submit solely a capacity offer and an energy bid. Those BSPs with the lowest capacity bids (energy bids respectively) are awarded. For settlement, pay-as-bid pricing (awarded BSPs are paid their bid prices) is applied, but in mid-2022 it will switch to or uniform pricing (awarded BSPs are paid one uniform price). Ultimately, the delivery of balancing energy is activated according to a merit-order of energy bids, i.e., BSPs with the lowest energy bids are utilized first and, thus, for the longest timespan. In Germany, there exist daily auctions for aFRR and mFRR, with a gate closure time at 09:00 am and 10:00 am day-ahead, a split in positive and negative balancing products and bid validity periods of six 4-hour-blocks (00:00-04:00, …, 20:00-24:00). For the balancing energy markets (positive and negative product), the bid validity period is also split in six 4-hour-blocks, with a gate closure of 30 min prior to the 4-hour-blocks. Note that in mid-2022 it will change to a bid validity period of 15 min (e.g. 04:15-04:30) and the gate closure time will be 25 min. For aFRR and mFRR, it is important to note that until mid-2022 the procurement auctions are carried out on a national level and after that a common European merit-order for balancing energy activation will be implemented.

Balancing power procurement and activation is the physical means to cope with imbalances. The financial settlement of balancing energy costs is done via the imbalance settlement price. A balancing responsible party's (BRP) difference between the planned and actual generation, consumption and exchange with other balance groups multiplied with the imbalance settlement price gives the imbalance cost or revenues (typically penalty payment, if deviation of balance group is in the same direction as deviation of control area whereas revenues can be achieved if deviation of a balance group is in opposite direction of deviation of control area (i.e. imbalance costs) in a 15 min imbalance settlement period. The calculation of the imbalance settlement price considers the activated balancing energy bids, but also other additional elements. To avoid the penalty payment, market parties can close open positions by trading on the short-term wholesale market, particularly on the intraday market. In some countries (e.g. Netherlands, Austria) passive balancing is allowed, i.e. an intentional imbalance of a balance group in opposite direction of the imbalance of the control area. In Germany this is not allowed so far.

In principle, truck and bus batteries can participate in all three balancing markets. In practice, FCR and aFRR are most suitable: given the batteries' potential to almost instantly react on frequency deviations, they are ideal candidates to provide the "high quality" balancing service of FCR and aFRR (compared to mFRR). In Germany, for example, around 500 MW of mainly large-scale stationary batteries are already prequalified for FCR provision. Therefore, we focus on FCR and aFRR in this study. A sole participation in the balancing energy market (i.e. without a capacity payment) may also be a possibility, if, for example, charging with negative aFRR energy is cheaper than charging with "normal" electricity from the grid (which is not in the focus of this study).

4.2   Technical aspects

Facilitating the shifting of charging times for thousands of vehicles in response to frequency deviations requires extensive data flows between different stakeholders. Thus, the first technical challenge is the secure communication in combination with the large data exchange volume. In the future, the Equity Crowd Balancing Platform (see Section 6.1) can potentially act as a neutral information exchange platform between the flexibility provider, i.e. the aggregator of vehicle flexibility, and the TSO (who is not steering the assets). At the moment there is a lack of technical coordination, both in Europe and

within Germany due to number of players, for example due to the high number of DSOs. Furthermore, standards must be defined on how steering signals are relayed to the charger or vehicle and which data is necessary from these components in order to optimize energy flows and create these steering signals. The short latency of the batteries as a requirement for prequalification as well as trucks being part of the holistic demand response within the customer depot were identified as pro arguments for balancing power. While individual vehicles have limited energy storage in batteries, aggregated fleets in depot promise larger energy volumes for flexibility marketing.

4.3   Economic assessment

The economic assessment (i.e. profit, which equals revenue minus cost) in this study consists of quantitative and qualitative elements. For revenues, we quantitatively assess the potentials from FCR and aFRR, whereas for costs, we solely describe them qualitatively. This means that there cannot be drawn any conclusions regarding the actual profitability of the investigated use cases.

4.3.1   Cost elements

As mentioned before, BSPs encounter different types of cost (or revenues): capacity costs and energy costs (revenues). Capacity costs include opportunity cost of not selling energy on a different electricity market, but include also traditional fixed costs such as costs for prequalification, for metering, for a larger grid connection to allow for more flexibility or for necessary software. On the contrary, energy costs (revenues) include costs (revenues) which only occur when the asset is actually used for providing balancing energy. Thus, these variable costs include, e.g., costs of battery degradation, costs for grid levies and tariffs for energy drawn from the grid, or, if applicable, marketing fees (e.g. via an aggregator). Furthermore, aggregators of vehicle flexibility must consider costs for the replacement procurement of energy: if, for example, positive aFRR is provided, vehicles do not charge as planned, but the energy is booked in the balancing group of the TSO. This energy must then be procured intraday at short notice so that the target SOC can be achieved for the vehicles. Conversely, if negative aFRR is provided, the charging plan must be adjusted and, if necessary, revenues from the sale of the "excess" energy must be considered.

Furthermore, the delivery of balancing power can increase the peak network load substantially (see Figure 2), which leads to higher network fees for the customer. Network fees in Germany consist of an energy component (EURct/kWh) and a power component (EUR/kW), the latter usually billed on the highest load peak by the customer of the year. The distribution between the two components changes in response to full load hours and grid layer of the connection. Note that full load hours describe the number of hours an energy resource would need to run at full capacity (kW) to generate or use the energy (kWh) it did in its real operation throughout the year. Full load hours are therefore an alternative measure for the degree of utilization of an energy resource. On average, 20% of the network fees at medium voltage connections under 2,500 full load hours are the result of the power component. Above this full load hour threshold more than 70% of the network fees come from the power component (BNetzA 2015).

To show a specific example, we compare below the grid fees for Stuttgart and Bayreuth in 2022. The left-most column defines the voltage level from high voltage (top) to low voltage (bottom),

"Jahresbenutzungsdauer" means full load hours. The pricing structure is very similar but the actual price level deviates notably from DSO to DSO.

Leistungspreissystem für Entnahmestellen mit registrierender Lastgangmessung	Jahresleistungspreissystem			
	Jahresbenutzungsdauer T$_m$ < 2.500 h/a		Jahresbenutzungsdauer T$_m$ >= 2.500 h/a	
	Leistungspreis €/kWa	Arbeitspreis Cent/kWh	Leistungspreis €/kWa	Arbeitspreis Cent/kWh
Hochspannungsnetz	13,66	3,80	90,05	0,74
Umspannung Hoch-/Mittelspannung	14,23	3,96	93,82	0,77
Mittelspannungsnetz	14,42	4,39	93,80	1,22
Umspannung Mittel-/Niederspannung	16,53	4,82	97,33	1,58
Niederspannungsnetz	18,63	5,43	75,58	3,15

Figure 5: Network fees table for Stuttgart in 2022 (Stuttgart Netze 2022)

Entnahmeebene	Preisregelung I		Preisregelung II		Schnittpunkt der Preisregelungen
	Leistungspreis	Arbeitspreis	Leistungspreis	Arbeitspreis	
Mittelspannung	11,63 €/kW*a	3,75 ct/kWh	89,34 €/kW*a	0,64 ct/kWh	2.500 h/a
Umspannung in NS	11,31 €/kW*a	4,97 ct/kWh	129,66 €/kW*a	0,24 ct/kWh	2.500 h/a
Niederspannung	12,93 €/kW*a	5,48 ct/kWh	92,34 €/kW*a	2,30 ct/kWh	2.500 h/a

Figure 6: Network fees table for Bayreuth in 2022 (Stadtwerke Bayreuth 2022)

4.3.2 Network load and flexibility potential

In the following we present the network load and flexibility potential for the truck and bus use cases.

Bus use case

A pool of city buses was simulated using real data (see Table 2). The pool consisted of 149 buses which had different schedules and different routes and, thus, the amount of energy needed by the buses for the different routes differed. The maximum battery capacity in the buses is 350 kWh. The assumed charging system can provide a maximum of 80 kW per bus and there is one charging point per bus.

Due to the nature of the schedules adopted by the buses and considering that the buses must be fully charged, the grid load peaks from around 01:30 to 04:30 (see Figure 2). The reason is that at these hours nearly all buses are connected to the grid. From around 06:30 to 20:30 most buses operate and are not connected to the grid; i.e. grid load is lower compared to the late-night hours. In Figure 3 the flexibility potential of the pool of buses is plotted. The flexibility potential is highest when many buses are connected to the grid and not fully charged - this is at late night hours.

Truck use cases

The network loads and flexibility potentials for the five truck use cases are given in Figure 7 and Figure 8. For the sake of a better understanding, we exemplarily describe the line haul use cases 2 and 3 in

more detail. The negative flexibility potential in the truck use case 2 is six times as large as in use case 3. Recall that the flexibility potential is a function of battery charging state and charging capacity. With use case 2 we have a charging power of 300 kW, while with use case 3 we have 50 kW. However, in our example use case 2 plans only with a constant charging power of around 41 kW and spreads out the charging process for the entire duration of the overnight idle time (14 hours). For the transport company, this offers a fallback option if faster charging were required in an emergency. At the same time, this offers a lot of freedom to accelerate charging if negative balancing power is required. At a charging power of 50 kW as in use case 3, this optimization potential becomes substantially less. Conversely, reducing the charging power as much as possible reduces the positive flexibility potential substantially, as less load can be shed if need be.

4.3.3   Revenues

Recalling the market structure of the balancing power markets (cf. Section 1), the revenues consist either only of the balancing capacity payment (for FCR and for aFRR, if no activation of balancing energy), only the balancing energy payment (aFRR balancing energy market) or both the balancing capacity payment and the balancing energy payment (aFRR balancing capacity and energy market, if balancing energy is activated). It is important to state that balancing prices and, thus, payments for BSPs vary over days, weeks and seasons and future price levels are uncertain, particularly against the backdrop of the various fundamental changes in market design on the way to a decarbonized system.

Annual revenues comparison

We compare the annual revenue potentials for FCR and aFRR (Table 7). Note that the complete quantitative assessment and the underlying assumptions are included the Appendix. The revenues of aFRR balancing capacity provision are below the revenues of FCR provision. When considering also aFRR balancing energy provision the picture changes: revenues of aFRR balancing capacity and energy are higher than the revenues of FCR provision for the bus use case and the truck use cases 2, 5 and 7. With over 238,000 Euro/a, truck use case 2 has the largest revenues of aFRR balancing energy provision. This high figure can be attributed to the large negative flexibility potential of over 13 MW in the three 4-hour-blocks 00:00-04:00, 16:00-20:00 and 20:00-24:00.

Table 7: Comparison of annual revenues [Euro/a] of aFRR and FCR provision in 2020

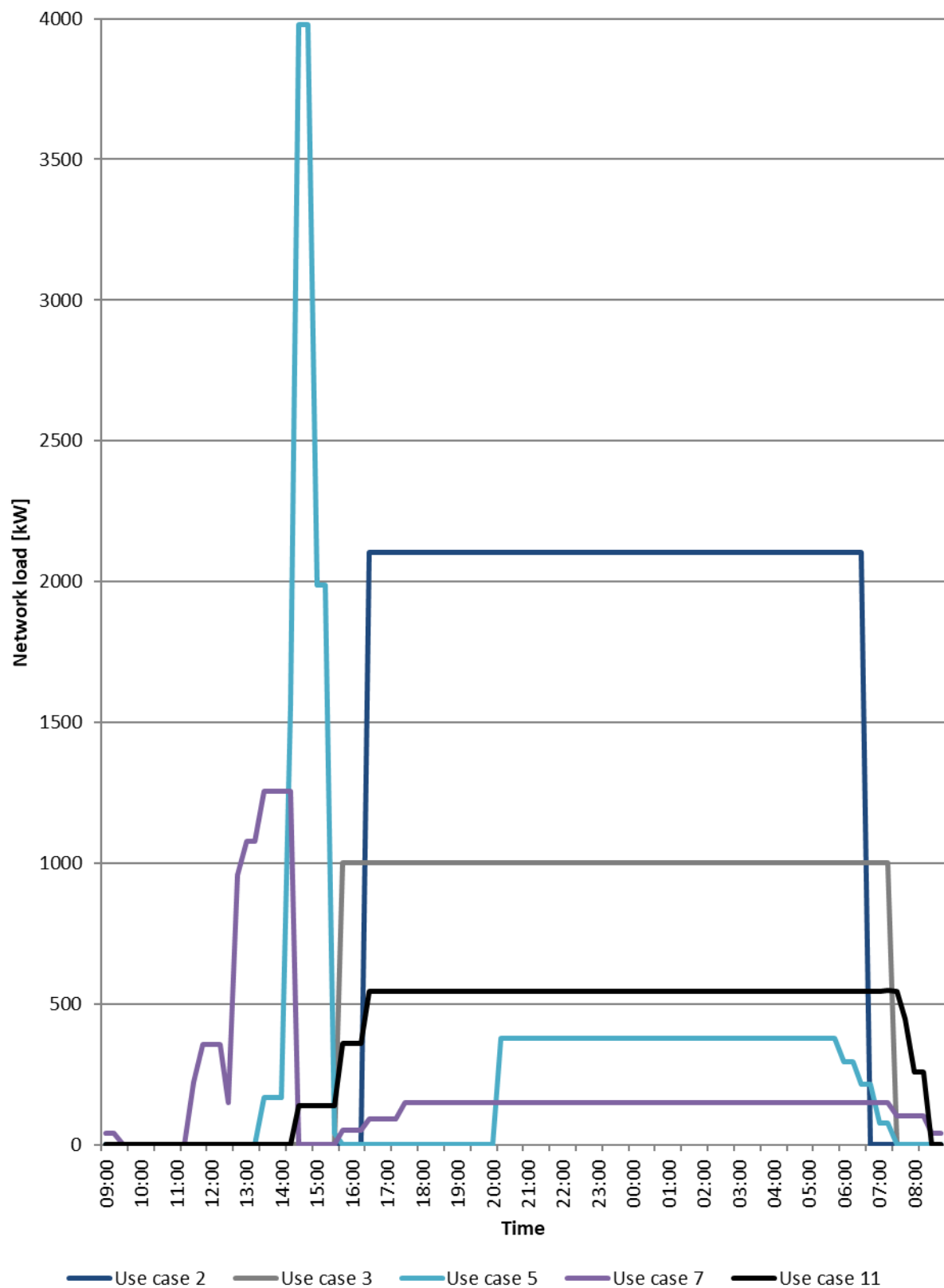|	Bus use case	Truck use cases				
		Line haul 2	Line haul 3	Retail 5	Constr. 7	Waste 11
Veh. per depot	149	50	45	30	10	30
aFRR capacity	15,493	53,651	7,177	6,837	4,913	5,407
aFRR energy	32,959	184,416	24,815	18,654	18,590	17,251
aFRR capacity and energy	**48,452**	**238,066**	**31,993**	**25,491**	**23,503**	**22,658**
FCR	**46,274**	**78,137**	**36,208**	**10,766**	**5,823**	**23,972**

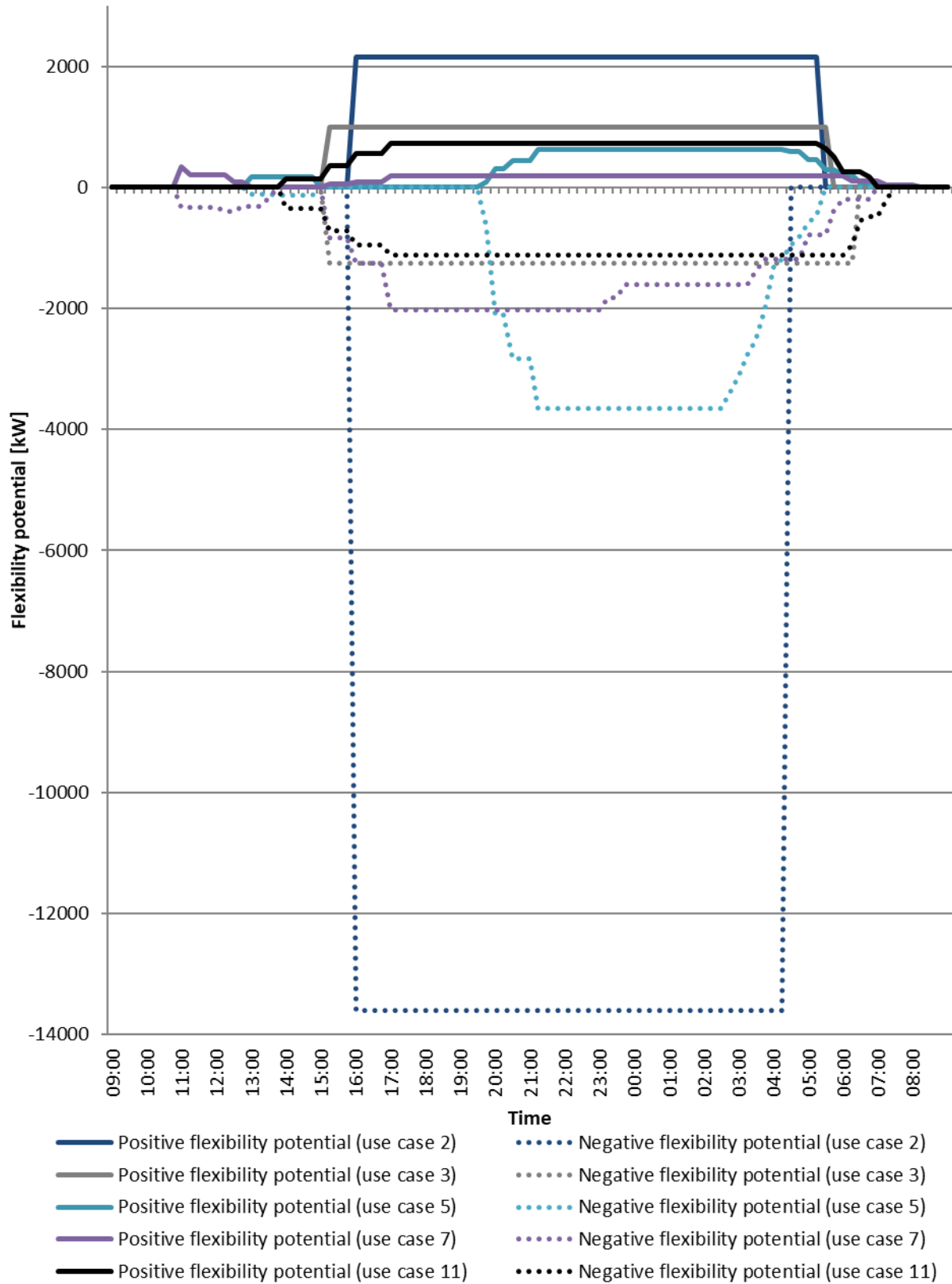Figure 7: Network load for the truck use cases

Figure 8: Flexibility potentials for the truck use cases

4.3.4   Limitations of the quantitative assessment

The most important limitation of the presented economic assessment is that no profitability conclusions can be drawn because only the revenue side is assessed quantitatively for an exemplary year. Future studies may want to investigate this further.

In addition, the flexibility potential denoted in the use cases above shows that capacities can be offered over a long time frame. In practice, if an activation takes place, this reduces the available capacity for the remainder of the night. For example, in truck use case 2, the large negative potential of over 13 MW suggests that energy can be taken out of the system for the entire time frame. If negative activation occurs, the trucks' batteries are being charged earlier than strictly necessary, which means they cannot be charged again at a later stage, nullifying the negative potential. Consequently, this means that the combined revenues of aFRR capacity and energy provision as well as FCR represent an upper bound. The higher the capacity revenue under assumption of non-energy provision, the lower the energy revenue and vice versa.

Furthermore, the modelled flexibility potential and the associated revenues per year are based on weekdays and do not consider weekends or bank holidays. Since the considered bus and truck use cases do not foresee working on these days (i.e. there is more flexibility available), the presented flexibility potential is underestimated. In this feasibility study, we did not model this in more detail for the sake of complexity, but it needs to be considered when interpreting the results.

Finally, the underlying prices of the analyses in sections 5.4.3 to 5.6.5 are based on market data in 2020. This implies that significant increased prices in the balancing markets as a result of the Ukraine war as well as upcoming market adjustments such as the European balancing energy markets in mid-2022 and the corresponding effects on balancing prices are not included. In general, predictions of future balancing prices and the activation probability are challenging because there are several trends with opposing effect directions. Heiman et al. (2022) recently modelled future balancing prices [Euro/MW] for Germany for different scenarios in 2030 (see Figure 9). The results indicate an increase of prices for all three balancing types, particularly for positive aFRR and mFRR, ranging up to 200 Euro/MW per hour.
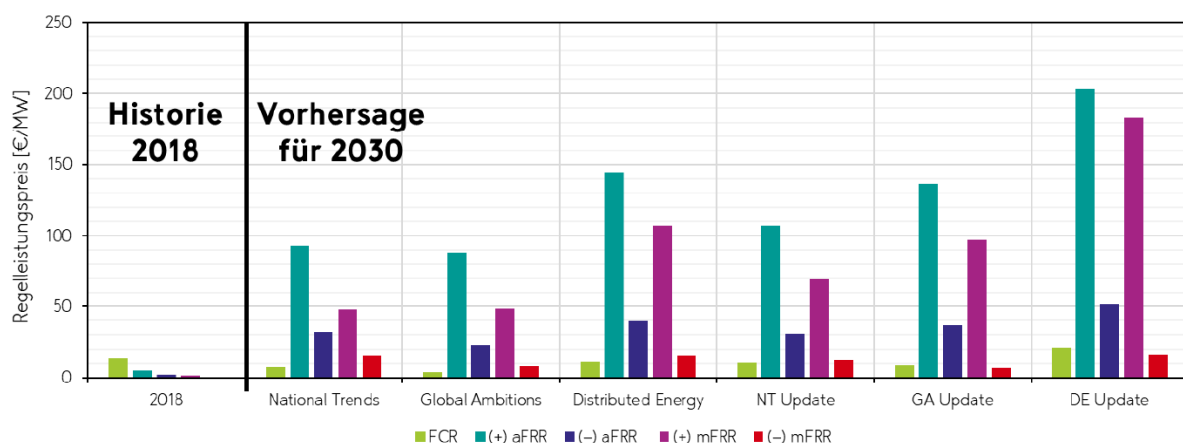

Figure 9: Predictions for future balancing prices [Euro/MW]; source: Heimann et al. (2022)

The revenue analyses with capacity prices of 2021 underpins this trend: prices of FCR increased around factor two, aFRR prices increased even stronger around factor ten. The comparison of annual revenues [Euro/a] of aFRR and FCR provision in 2021 are given in Table 8. Now the revenues of aFRR balancing capacity provision are above the revenues of FCR provision for the three truck use cases 2, 5 and 7. When considering also aFRR balancing energy provision, revenues of aFRR balancing capacity and energy are higher than the revenues of FCR provision for all considered bus and truck use cases.

Table 8: Comparison of annual revenues [Euro/a] of aFRR and FCR provision in 2021

	Bus use case	Truck use cases				
		Line haul 2	Line haul 3	Retail 5	Constr. 7	Waste 11
Veh. per depot	149	50	45	30	10	30
aFRR capacity	108,629	490,804	44,854	53,608	47,500	33,937
aFRR energy	63,099	110,922	171,718	11,220	14,396	110,252
aFRR capacity and energy	171,728	601,725	216,571	64,828	61,896	144,189
FCR	116,860	158,794	73,584	24,968	12,140	49,203

4.3.5   What do these revenues mean for a transport company?

The nominal revenues shown in Table 7 and Table 8 are difficult to appraise without further context. In order to ease interpretation, we calculate potential revenue per kWh used for charging from marketing flexibility in aFRR and FCR markets (Figure 10). The values can be interpreted as an upper bound for a possible rebate on electricity price as provided by an aggregator pooling flexibility in PEV charging processes. The given range comes from dramatic price increases from 2020 to 2021. Please bear in mind that these numbers do not allow for a full economic assessment as the costs of facilitating flexibility were not quantified (cf. chapter 4.3.1).

In general, revenue potentials are far larger on the aFRR market. The largest potential results for truck use cases 2 and 11, especially with 2021 prices. The bus use case and truck use case 5 have the lowest potential. Especially for aFRR the revenue per kWh can be very significant given average electricity prices for German industry in these years at around 20 EURct/kWh (BDEW, 2022). If transport companies could facilitate flexibility marketing reliably, significant rebates on their electricity costs would be possible and therefore further improvement of the total cost of ownership of electric heavy-duty vehicles.
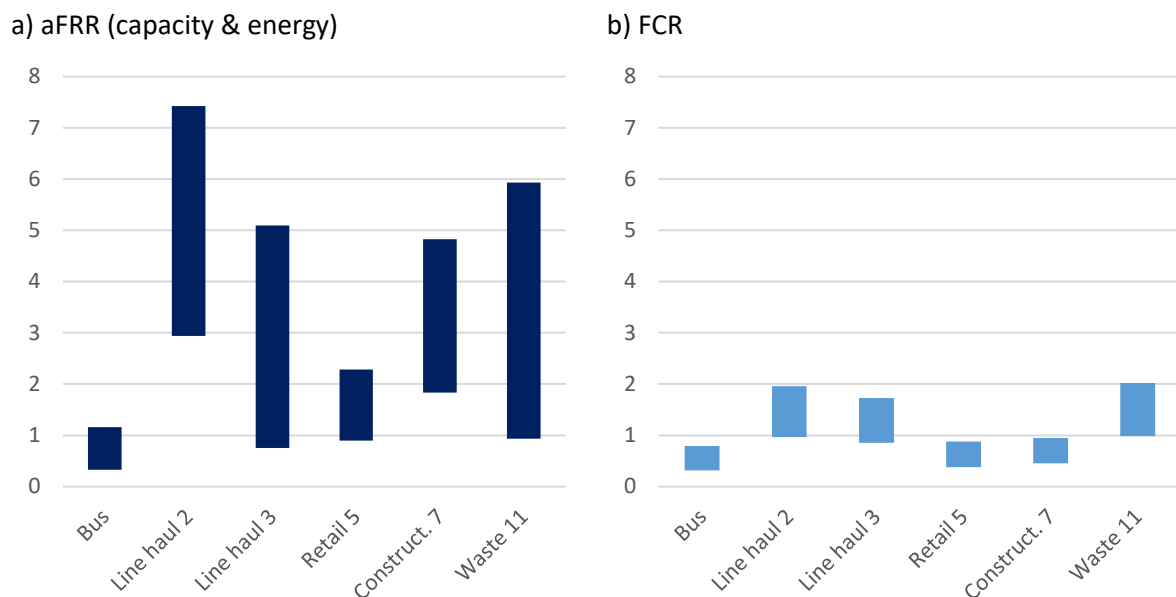
a) aFRR (capacity & energy)

b) FCR

Figure 10: Range of maximum possible revenue per consumed kWh from flexibility segments, in EURct/kWh (minimum revenue with 2020 prices, maximum with 2021 prices)

5   Marketing potentials for congestion management

This section turns to the marketing potential for the flexibility segment "congestion management". Note that in the following we refer solely to redispatch and no other measures for congestion management. First, we present general background information, then we discuss economic aspects which were discussed in the experts workshops. Note that the technical aspects are similar as for balancing and are described in Section 4.2.

Grid expansion is accompanied by lengthy approval procedures and, thus, it can mostly not keep pace with the expansion of renewable energies. This means that bottlenecks in the affected grid regions are occurring more and more frequently. Bottlenecks manifest in overloaded lines or transformers, leading to safety shutdowns and increased maintenance. In order to eliminate network bottlenecks, the system operators have network-related (in particular network switching) and market-related measures (redispatch, feed-in management and countertrading) at their disposal. Redispatch refers to the intervention in the market-based schedule of the generation units and storage to shift the feed-in to prevent line overloads (preventive redispatch) or to eliminate line overloads (curative redispatch). Feed-in measures relate to curtailment of renewable energy generators in time where their supply would otherwise endanger grid stability. Redispatch measures can be applied within and across control areas and are planned according to grid simulations starting one week before real time. By reducing the feed-in power of one or more power plants "in front of" the bottleneck while simultaneously increasing the feed-in power of one or more other power plants "behind" the bottleneck region, the total feed-in power remains unchanged. This means that, in contrast to balancing power, the physical location of the asset is essential. Redispatch results in additional costs compared to the planned use of power plants because power generation from power plants with lower variable costs is usually replaced by power plants with higher variable costs. For example, in 2019 a total of almost 7 TWh of conventional generation was "shifted" by the German TSOs and 291 Mio. Euro was spent for congestion management measures. These costs are relayed to the end consumer through the grid fees.

The implementation of the "NABEG 2.0" (amended grid expansion acceleration law) in October 2021 fundamentally changed the redispatch regime in Germany ("Redispatch 2.0"). All generation and storage facilities with a nominal output of more than 100 kW are included in the redispatch process based on planned values. In contrast to the previously separate feed-in management measures, renewable energy and combined heat and power systems are also included in the redispatch process with accounting and financial compensation. Redispatch 2.0 does not cover consumer units which can be controlled outside of the industrial loads covered by the shutdown ordinance and also not generation and storage units smaller than 100 kW. Hence, the charging stations for electric vehicles, battery storages in households and electric vehicles are not covered by Redispatch 2.0. In accordance with §13a EnWG, generation plants and storage systems receive appropriate remuneration if the active power and reactive power feed-in or active power consumption are adjusted. Appropriate within the meaning of the law means that the operator of the redispatched unit is, economically speaking, neither better nor worse off as a result of a redispatch measure than without the measure. The remuneration for redispatch measures is therefore purely cost-based, with no possibility of being able to achieve an economic advantage by providing a redispatch service over other market-based ancillary services. Note that saved expenses of a plant operator are to be offset against the expenses. This means that the TSO pay the plant operator in case of upward regulation (forced increase of power output), while the plant operator (typically) pays the TSO in case of downward regulation (forced decrease of power output).

In the Netherlands, there already are economic incentives to provide redispatch. The grid operators TenneT, Stedin, Liander, Enexis Groep and Westland Infra are running the market-based redispatch platform "GOPACS". GOPACS makes use of flexible power from the market which can contribute to solving (expected) congestion in the electricity grid. It works in a way that is consistent with key European directives that relate to market-based mitigation of grid congestion and offers large and small market parties an easy way to generate revenues with their available flexibility and contribute to solving congestion situations. The collaboration among the grid operators also prevents congestion in one part of the electricity grid from causing problems elsewhere in the electricity grid at one of the other grid operators. The platform optimizes optimal asset activation including its location and the respective DSO pays the difference. For GOPACS the grid operators collaborate with the intraday market platform of ETPA. They are currently negotiating with other market platforms to connect these to GOPACS as well. The other Dutch DSOs Enduris, Coteq and Rendo, support the initiative and are investigating how they can participate in GOPACS.

The individual billing of small-scale flexibility providers is expensive for TSOs on DSO levels. Furthermore, the costs that occur for TSOs influence the costs for DSOs, i.e. there is a reduction potential in both ways. Finally, in the future, the market-based redispatch model may develop into a similar system as balancing power, including specific roles like a "congestion service provider" with a dedicated information on the location of the asset.

6 Scalability: Expanding potentials to national dimensions

6.1 Equigy-Crowd Balancing Platform

One of the major challenges of the ongoing transformation of the electricity system from central to a more decentralized system will be the integration of a large number of (privately owned) distributed flexibility devices, such as home storage batteries, electric vehicles and heat pumps. However, most of

the existing processes and IT systems in the sector are yet designed for managing only a couple of hundreds of power plants in a multi-MW range but not millions of individual devices. Hence, the provision of ancillary services for e.g. balancing and congestion management will require a different approach to cope with a multiplicity of connected devices, market players and products, as well as ensuring controllable, trustful and secure data exchange.

Against this background a consortium of European TSOs jointly founded Equigy and created the Crowd Balancing Platform (CBP) to set a European standard and enable the balancing of the renewable energy supply of the future. Equigy is a TSO-owned entity with TenneT, Swissgrid and Terna as founding members (Austrian Power Grid APG and Transnet BW joined later). Equigy was established to support TSOs in their role as market facilitator, it will run the CBP and actively grow the ecosystem, i.e. will implement use cases in new countries as well as new markets and services. Additionally, Equigy will support TSOs in national project and use case implementations. Figure 11 depicts a general overview of the CBP incl. TSOs, DSOs, aggregators and OEMs (original equipment manufacturer).
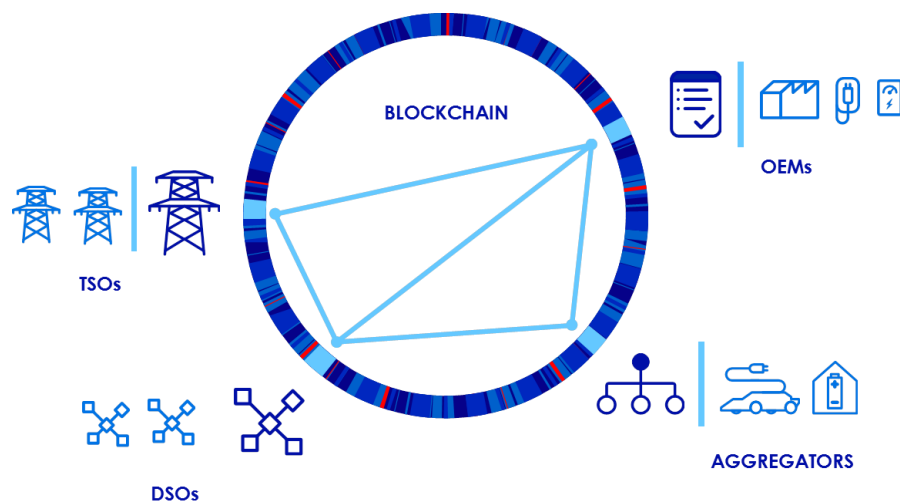
Figure 11: Schematic representation of the Crowd Balancing Platform and possible partners

The CBP aims to enable small scale flexibility resources to provide ancillary services for balancing markets and congestion management by integrating device data from back-end systems via the blockchain. For aggregators and OEMs, the CBP can provide new opportunities to allow a more efficient pooling of flexibility potentials of individual devices and offer the aggregated flexibility, for ancillary services by a BSP. Additional revenues from ancillary services may not only lower the total cost of ownership for device owners and customers but may also engage electricity consumers to actively participate in the energy market. Hence, participation in the CBP cannot only provide individual economic benefits but also benefits to the power system and society.

In Germany, the first use case that is implemented on the Equigy-CBP is the provision of redispatch services. Together with pilot partners Viessmann, BMW, Greencom, be.storaged and others aggregated flexibility potentials from distributed devices (such as heat pumps, EVs, night storage heaters and home battery systems) are offered via CBP interfaces to TSOs and hence, can be activated for congestion management purposes.

6.2 Flexibility potentials in 2025, 2030 and 2040

In Section 4.3, we assessed the aggregate flexibility potential for use case-specific depots. To estimate the impact that the flexibility of the selected bus use case and truck use cases may have on the electricity system, we scale these values to the entirety of Germany. The values listed below are extrapolated based on a ramp-up scenario for the vehicles and the flexibility potentials from Table 13.

The ramp-up potential is a result of a bass diffusion model (Bass, 1969) as applied by Ensslen et al. (2019) to electric passenger vehicles. Innovation coefficients are used to calculate the share of diesel vehicles being replaced by BEV over time. The coefficients for the truck use cases are assumptions provided by Daimler Truck. For busses the German market analysis "E-Bus Radar 2021" (pwc, 2022) served as a basis for the coefficients. The total number of diesel trucks per use case is provided by the market data service MAPIS (2022). Furthermore, each use case has a cap on electrification potential at full diffusion due to the limitations of BEV in, e.g., range, cargo load, or power demand of ancillary consumers. The diffusion results for the Truck use case Line haul 2 are shown in Figure 12. Ramp-up numbers for all use cases to be discussed in detail are listed in Table 9.
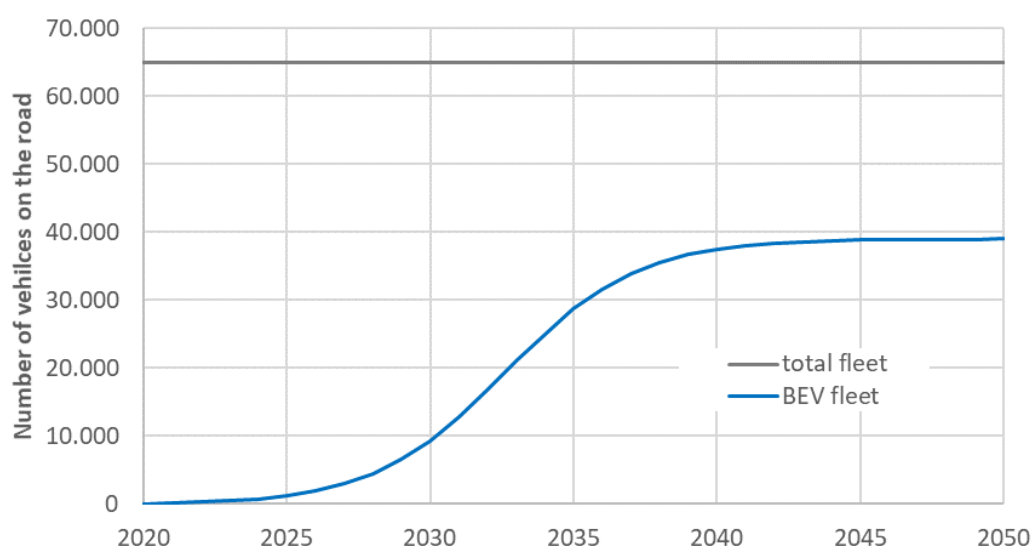
Figure 12: Exemplary ramp-up of battery electric trucks for use case line haul 2 in Germany

Table 9: Ramp-up approximation of number of vehicles on the road in Germany

Use case	2025	2030	2035	2040
Line haul 2	1,200	9,300	29,000	37,000
Line haul 3	8,300	31,300	68,000	94,000
Retail 5	5,000	22,800	58,000	86,000
Construction 7	200	2,300	13,000	22,000
Waste 11	1,500	6,500	13,000	16,000
All use cases	30,900	151,700	411,000	606,000
City bus	6,900	20,300	31,000	36,000

Flexibility potentials based on this ramp-up can be found in Table 10 to Table 12 for the years 2025,

2030, and 2040. In later years, the flexibility potential becomes quite substantial, particularly for the line haul and retail truck use cases. Also large bus depots could play a substantial role in the early morning hours. With a theoretical potential of over 4 GW of positive and negative flexibility from 16:00-04:00 (peaking at over 23 GW of negative flexibility from 20:00-24:00 and at over 7 GW of positive flexibility from 00:00-04:00), all examined use cases combined could have a significant impact on the balancing power market in 2040: Recall from Section 4.1 that the current demand in 2022 for positive and negative balancing power in Germany is around 7.1 GW.

Table 10: Maximum positive (+) and negative (-) flexibility potential for Germany in 2025 [MW]

2025 [MW]	Bus use case	Truck use cases					Sum
		Line haul 2	Line haul 3	Retail 5	Constr- uction 7	Waste 11	
00:00 -	149	52	184	104	4	36	**529**
04:00	-170	-327	-232	-338	-24	-56	**-1,146**
04:00 -	12	0	0	0	1	0	**13**
08:00	-26	0	0	0	0	0	**-26**
08:00 -	4	0	0	0	0	0	**4**
12:00	-13	0	0	0	0	0	**-13**
12:00 -	0	0	0	0	0	0	**0**
16:00	-47	0	0	0	0	0	**-47**
16:00 -	0	52	184	0	2	28	**266**
20:00	-28	-327	-232	0	-25	-48	**-659**
20:00 -	26	52	184	53	4	36	**354**
24:00	-51	-327	-232	-351	-32	-56	**-1,048**

Table 11: Maximum positive (+) and negative (-) flexibility potential for Germany in 2030 [MW]

2030 [MW]	Bus use case	Truck use cases					Sum
		Line haul 2	Line haul 3	Retail 5	Constr-uction 7	Waste 11	
00:00 -	438	401	696	473	46	156	**2,210**
04:00	-499	-2,531	-875	-1,540	-272	-243	**-5,960**
04:00 -	36	0	0	0	9	0	**46**
08:00	-77	0	0	0	0	0	**-77**
08:00 -	13	0	0	0	0	0	**13**
12:00	-39	0	0	0	0	0	**-39**
12:00 -	0	0	0	0	0	0	**0**
16:00	-138	0	0	0	0	0	**-138**
16:00 -	0	401	696	0	21	120	**1,238**
20:00	-81	-2,531	-875	0	-287	-207	**-3,981**
20:00 -	75	401	696	239	46	156	**1,613**
24:00	-149	-2,531	-875	-1,599	-368	-243	**-5,765**

Table 12: Maximum positive (+) and negative (-) flexibility potential for Germany in 2040 [MW]

2040 [MW]	Bus use case	Truck use cases					Sum
		Line haul 2	Line haul 3	Retail 5	Constr-uction 7	Waste 11	
00:00 -	777	1,597	2,089	1,783	436	385	**7,066**
04:00	-885	-10,071	-2,628	-5,808	-2,603	-598	**-22,593**
04:00 -	64	0	0	0	90	0	**154**
08:00	-137	0	0	0	0	0	**-137**
08:00 -	23	0	0	0	0	0	**23**
12:00	-70	0	0	0	0	0	**-70**
12:00 -	0	0	0	0	0	0	**0**
16:00	-245	0	0	0	0	0	**-245**
16:00 -	0	1,597	2,089	0	202	295	**4,183**
20:00	-144	-10,071	-2,628	0	-2,741	-510	**-16,095**
20:00 -	133	1,597	2,089	903	436	385	**5,542**
24:00	-264	-10,071	-2,628	-6,031	-3,520	-598	**-23,113**

7 Related regulatory aspects in Germany

7.1 Local grid services

One possibility for electric vehicle customers to reduce their grid charges in Germany is offered by §14a of the "Energiewirtschaftsgesetz", regulating a reduced grid fee for controllable consumption: they receive up to 80% reduced grid charge for the respective period as economic compensation. This initially applies to the low voltage level but is to be expanded with follow-up legislation. It targets heat pumps, charging equipment and electricity storage systems and specifically applies to electric vehicles. The goal is, as with all other remuneration schemes in this context, to lower peak loads and relieve the grid. In order to be able to participate in the scheme in the future, the charging infrastructure and grid connection point must be certified to meet automatic calls of the distribution system operator in a specified time frame. In early 2022, two models are discussed:

- The electricity consumer or prosumer offers up to a total of 120 min of flexible power consumption per day, meaning that the grid operator may adapt load when necessary. Grid operators may utilize flexibility at any time in the day and directly steer available power.
- Customer and grid operator agree on a static time frame in which a maximum of 50% of the contracted power connection may be used for balancing. This option is only valid in the first three years of the contract and aims to reduce uncertainty for the consumer. The reduction may only be used in the event of actual grid congestion.

Some e-mobility electricity rates already take advantage of this scheme today. However, the adoption of the law has been postponed due to diverging views of various stakeholders and new developments are expected in the course of 2022. Furthermore, §14a only applies to loads connected to the low-voltage level and will therefore not be available for most truck and bus depot operators. While the scheme is scalable to many connection points, business electricity tariffs and grid fees are often more complex. It remains to be seen how larger flexibilities can be utilized in the near future. Therefore, deriving reliable figures for cost saving potentials are not possible at this moment.

7.2 Steerable loads ("Abschaltbare Lasten")

The German "Abschaltbare Lastenverordnung (AbLaV)" is a 2012 ordinance that was amended on 01.10.2016. It is intended to promote the use of interruptible loads in industry to stabilize the transmission grid and, thus, ensure security of supply. Relevant loads are power-intensive industrial processes which can be deactivated or throttled for a short time, which are characterized by a very high, continuous power consumption and which are mostly found in the processing industry. The signals to reduce load are initiated by the TSOs and sent to the companies either directly or via a virtual power plant. The provision of the switch-off potential is remunerated with a capacity price. If actual switching is performed, an additional energy price is paid. The capacity and energy prices are determined in auctions administered by the TSOs.

There exist two products which, similar to balancing power, differ in the reaction time (i.e. the speed of the actual disconnection):

- "Sofort abschaltbare Lasten" are loads that can be switched off immediately and must be available in less than 350 ms if a frequency measurement is carried out directly on site. If the

shutdown commands are transmitted remotely from a control system to the production facility, a response time of less than one second is permitted.

- "Schnell abschaltbare Lasten" are loads that can be switched off quickly and have to be ready in less than 15 minutes. No frequency measurement is required, the switch-off command is transmitted remotely from the control centre.

Note that the ordinance expires on 01.07.2022 and that a prolongation (and the associated market design) is currently discussed, but no final decision has been taken yet.

8   Vehicle-to-Grid and bidirectional charging

In contrast to electric vehicles with unidirectional charging infrastructure, electric vehicles with bidirectional charging infrastructure can convert the electrical energy stored in their batteries as direct current back into alternating current. This allows that, for example, consumers in the same building are supplied with electricity from the vehicle (so-called vehicle-to-home, V2H) or that energy is fed back into the electricity grid and, thus, vehicles act as mobile battery storage in the electricity and ancillary service markets (so-called vehicle-to-grid, V2G).

To utilize the energy-economic potential of mobile battery storage for the future energy system an intelligent interaction between electric vehicles, charging infrastructure and energy system is necessary. In the research project "Bidirectional Charging Management - BDL", funded by the Federal Ministry of Economics and Climate Protection, such an approach for a holistic integration of bidirectional electric vehicles into the energy system is therefore being developed in a pilot operation with 50 BMW i3s capable of bidirectional charging and tested on the basis of various use cases. V2H and Vehicle-to-Business (V2B) include use cases in buildings and on users' properties. V2G, on the other hand, includes all use cases that affect the energy market (e.g. intraday optimisation) as well as grid and ancillary services (Forschungsprojekt Bidirektionales Lademanagement BDL, 2022).

Comparing our results from above, bidirectional charging would allow for significantly more flexibility potential as positive and negative balancing power calls can be marketed multiple times, which could increase saving potentials. However, facilitating V2G requires additional investments in hardware and software on the vehicle, charger and grid side. If high charging powers are used, vehicle owners may have to heed accelerated battery degradation, depending on the speed of discharge. Especially for commercial applications, systems have to be in place that guarantee a sufficiently charger battery at the scheduled time of departure. Furthermore, the flexibility market design and regulation must be adapted to permit integration of such distributed, mobile and, depending on the remuneration scheme, possibly less reliable energy sources.

9   Mutual positions for policy recommendations

To fully utilize the added value of millions of individual mobile electricity storage units in the future, the regulatory framework must be adapted to the requirements of the new flexibility options in addition to the further technical development of electric vehicles and charging infrastructure. In the following, regulatory hurdles for a practical implementation of the individual energy industry use cases of charging management are identified and possible solution concepts are presented.

9.1 Balancing power

In the expert workshops it was concluded that first adaptations for stationary storage must be ruled which then open the path towards decentralized flexibility such as electric vehicles as mobile storage units. Finally, it was argued that regulation does not pose a consistent framework for storages. There is a technical definition of storages that allows the taking part in redispatch, balancing power etc. but not in the regulatory role. Here for unidirectional loading, the role of final consumption is being used, since there is no feed-in of energy into the grid.

From a technical viewpoint, electric vehicles can already use their flexibility potential for balancing power today. However, so far only one "quasi-stationary" electric vehicle in Amphion's control area has been prequalified for the primary control power market in 2018 in accordance with the specifications for stationary battery storage. For the prequalification of individual electric vehicles or a pool of electric vehicles, such as commercial vehicle depots, for the provision of balancing power, there are still no official specifications available for electric vehicles. Against the background of the increasing number of electric vehicles expected in the coming years and increased transparency on trip schedules and reliable idle times for commercial vehicles, the provision of balancing power from electric vehicles can represent an important expansion of the BSPs. Therefore, TenneT and the other German TSOs started to work on a further development of the prequalification requirements to create the necessary conditions for electric vehicles to access the balancing power market in large volumes. Important aspects are stated in the following (see also Forschungsprojekt Bidirektionales Laden, 2022):

- **Non-redundant prequalification requirements to minimize cost.**

- **Establishment of largely automated prequalification processes** for the efficient provision of balancing power from small-scale, decentralized assets.

- **Possibility to change the composition of the pool within a quarter hour** to replace the electric vehicles that have been disconnected from the grid.

- **Development of procedures that lead to a significant reduction in the amount of data** to be kept available and exchanged to provide proof of activation.

- **Eliminate risk of insufficient range** for vehicle operators through binding user limits, e.g. minimum range or departure time.

9.2 Congestion management

The increasing decentralization of electricity supply will not only be limited to the generation side, but it will also include the storage and direct on-site consumption of the generated or stored electrical energy in some new application areas, particularly electric vehicles. Even if significantly more assets are included in the redispatch process as a result of Redispatch 2.0, the flexibility potential of these newly created millions of individual decentralized flexibility options is not taken into account or can only be used on a voluntary basis for congestion management measures. Thus, the existing regulatory framework with a cost-based redispatch regime lacks the economic incentive for small-scale flexibilities for voluntary participation. But also, from the perspective of the network operator, small-scale flexibilities with a cost-based redispatch can hardly be used because the cost basis often cannot be determined, or the billing effort is very high. Therefore, in addition to the existing legal

requirements, 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 redispatch according to § 13a New. Furthermore, the coordination of TSOs and DSOs plays an important role if both actors want to make use of the same flexibility unit; this if referred to as grid operator coordination (German: "Netzbetreiberkoordination"). The different system operators want to have control on how much energy can be drawn at which point of time from their grid to ensure grid stability (Forschungsprojekt Bidirektionales Laden, 2022; Ried, 2021).

In Germany, the existing regulatory framework with a cost-based redispatch regime lacks the economic incentive for small-scale flexibilities for voluntary participation. But also, from the perspective of the network operator, small-scale flexibilities with a cost-based redispatch can hardly be used because the cost basis often cannot be determined, or the billing effort is very high. Therefore, in addition to the existing legal requirements, 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 redispatch according to NABEG 2.0. This means that an attractive market solution is needed to allow for voluntary participation from consumers rather than mandatory load reductions.

A hybrid redispatch system would also correspond to the new role of consumers defined in the EU Clean Energy Package. In the future, flexible consumers should be able to participate in the energy markets as active customers in order to make the potential of millions of flexible and decentralized consumers, generators and storage facilities usable for different areas of application. Accordingly, the Clean Energy Package also provides for market-based use of all flexibly controllable generation and storage facilities and loads for congestion management in order to be able to use the entire flexibility potential for redispatch. A hybrid system creates an economic incentive for decentralized flexibility options to actively participate in congestion management. The merit order in such a hybrid system is composed of the cost-based potentials of the obligatory participating generators or storage assets and the market-based potentials of the voluntarily participating assets. A market-based offer would only be utilized if it is economically more efficient than a cost-based offer. For this, the costs/prices of flexibility and their physical effect on the bottleneck are taken into account in order to be able to eliminate a bottleneck with the lowest total costs from a system perspective.

9.3   Local grid services

After the draft bill on controllable consumer equipment was withdrawn at short notice at the beginning of 2021, the previous §14a EnWG regulations on controllable consumer equipment in the low voltage grid are still valid (albeit irrelevant for most heavy-duty vehicle use cases due to the low-voltage restriction). In the upcoming amendment of the legal regulations on the provision of local grid services, it should therefore be taken into account that, in addition to the direct control of individual installations, the possibility of specifying a maximum power (positive or negative) by the distribution grid operator at the grid connection point for a limited period of time and agreed in advance is mandatory. The time and scope of the possible power input must be communicated to the market participants in a transparent and comprehensible manner and with sufficient lead time, in particular for balancing group management and the marketing of the remaining flexibility. In addition, it must be ensured that, in the event of an acute congestion, the capacity can also be allocated on an ad hoc basis.

The legal changes should be accompanied by a roadmap, so that the affected market participants have planning security at an early stage.

9.4 Regulatory and technical environment

Furthermore, there exist hurdles in relation to taxes, levies, surcharges and grid fees as well as control, communication and data logging. For example, in Germany bidirectional charging stations or electric vehicles must pay the full taxes, levies and surcharges as well as grid fees for the electricity drawn from the public grid if it is fed back into the grid at a later point in time as a system service. To avoid the associated double burdens, charging facilities for electric vehicles with V2G assignment should be defined as storage units in the German regulatory framework and thus be equated with stationary electricity storage facilities.

Even though the nationwide rollout of smart metering systems (German: "intelligent Messsysteme, iMSys") has already begun in Germany, there are still regulatory and organizational uncertainties with regard to their concrete use for the provision of system services. In addition to the necessary consideration of FCR as an energy use case in the stage model of the Federal Office for Information Security (German: Bundesamt für Sicherheit in der Informationstechnik, BSI) , the IT requirements of the prequalification conditions in particular must be further developed in such a way that in future the existing iMSys infrastructure can be fully used for the provision of control reserve. Irrespective of this, it must be ensured that the data required for verification can be provided with existing measuring devices and communication channels by the time the iMSys rollout is completed.

References

Bass (1969): A New Product Growth for Model Consumer Durables, in: Management Science, Vol. 15(5).

BDEW (2022): BDEW-Strompreisanalyse Januar 2022, https://www.bdew.de/service/daten-und-grafiken/bdew-strompreisanalyse/

BNetzA (2015): Bericht der Bundesnetzagentur zur Netzentgeltsystematik Elektrizität, https://www.bundesnetzagentur.de/DE/Fachthemen/ElektrizitaetundGas/Netzentgelte/Strom/Netzentgeltsystematik/start.html

dena (2022): dena-Studie Systemdienstleistungen 2030, https://www.dena.de/themen-projekte/projekte/energiesysteme/dena-studie-systemdienstleistungen-2030/

Ensslen et al. (2019): Simulating Electric Vehicle Diffusion and Charging Activities in France and Germany, in: World Electric Vehicle Journal, Vol. 10(4).

European Commission (2020): European Commission Rules on Driving Time and Rest Periods, https://ec.europa.eu/transport/modes/road/social_provisions/driving_time_en

Ehrhart, K.-M. and Ocker, F. (2021): Design and regulation of balancing power auctions: an integrated market model approach, in: Journal of Regulatory Economics, Vol. 60.

Forschungsprojekt Bidirektionales Laden (2022): Laden Bereitstellung von Systemdienstleistungen aus Elektrofahrzeugen mit bidirektionalem Lademanagement. BDL-Positionspapier zu Vehicle-to-Grid-Anwendungen, https://www.ffe.de/veroeffentlichungen/positionspapier-zur-bereitstellung-von-systemdienstleistungen-aus-elektrofahrzeugen-mit-bidirektionalem-lademanagement/

Heimann et al. (2022): Whitepaper – vier Hypothesen für den Energiehandel 2030, umlaut, https://www.umlaut.com/de/stories/die-entwicklung-des-energiehandels-bis-2030-eine-zukunftsbetrachtung

MAPIS (2022): Markant price monitor (MPM), https://www.markant.com/en/our-services/market-price-analysis/mapis

Ocker, F., Braun, S. and Will, C. (2016): Design of European Balancing Power Markets, Proceedings of the 13th International Conference on the European Energy Market.

pwc (2022): E-Bus-Radar: Wie elektrisch ist der öffentliche Nahverkehr in Deutschland?, https://www.pwc.de/e-bus-radar

Ried, S. (2021): Gesteuertes Laden von Elektrofahrzeugen in Verteilnetzen mit hoher Einspeisung erneuerbarer Energien Ein Beitrag zur Kopplung von Elektrizitäts- und Verkehrssektor, https://publikationen.bibliothek.kit.edu/1000130549/106402484

Stadtwerke Bayreuth (2022): Netzentgelte & Preise | Netzentgelte Strom, https://www.stadtwerke-bayreuth.de/ueber-uns/netz/netzentgelte-preise

Stuttgart Netze (2022): Veröffentlichungen | Netzentgelte, https://www.stuttgart-netze.de/ueber-uns/services/veroffentlichungen/

Appendix

Revenue calculations for 2020

Revenues of Automatic Frequency Restoration Reserve (aFRR) provision

We first identify to what extent **balancing capacity for aFRR** can be offered in the six 4-hour-blocks, i.e. without the activation of balancing energy for aFRR. Later, we also consider the activation of balancing energy. We identify the maximum flexibility potential for each of the 4-hour-blocks based on the 15 min calculations, see Figure 13 for truck use case 11 as an example.
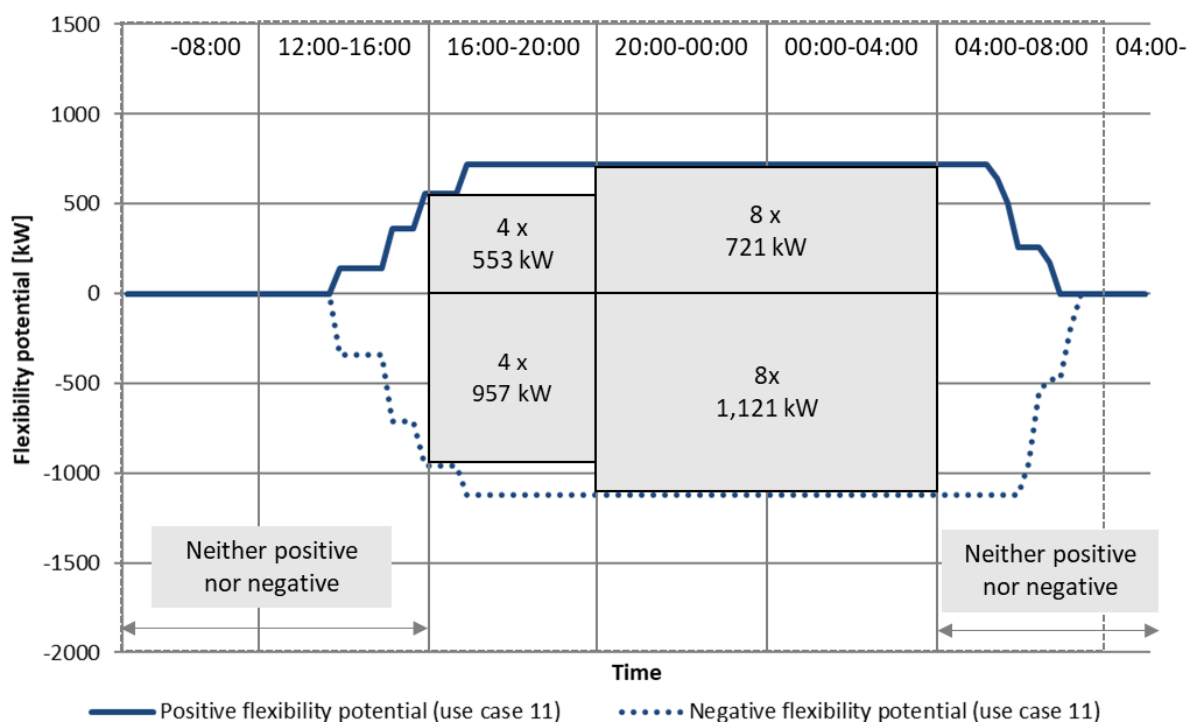
Figure 13: Illustration of maximum positive and negative flexibility potential [kW] in the six 4-hour-blocks for truck use case 11

For the truck use case 11, we find that there are three 4-hour-blocks in which both positive and negative balancing capacity can be offered: positive flexibility in the order of magnitude of 553 kW from 16:00-20:00 (i.e. for four hours a capacity of 553 kW) and 721 kW from 20:00-04:00, and negative flexibility of 957 kW from 16:00-20:00 and 1,121 kW from 20:00-04:00. From 04:00-16:00 there is no flexibility potential at all because all vehicles are on the road, i.e. the flexibility curve reaches zero at some point within these 4-hour-blocks. Note that in our simplified approach either positive or negative flexibility can be offered, i.e. the flexibility potential cannot be combined (approach for FCR later).

An overview of the positive and negative flexibility potential for the six 4-hour-blocks is provided in Table 13 for all use cases: per 4-hour-block, the upper line indicates positive flexibility potential, while the lower line indicates the negative flexibility potential. Note that there are three instances in which only positive or negative flexibility can be provided (e.g. truck use case 7 from 04:00-08:00).

Table 13: Positive (P) and negative (N) flexibility potential [kW] for aFRR

	Bus use case	Truck use cases				
		Line haul 2	Line haul 3	Retail 5	Constr. 7	Waste 11
00:00-04:00	P: 3,217	2,158	1,000	622	198	721
	N: 3,663	13,610	1,258	2,026	1,183	1,121
04:00-08:00	265	0	0	0	41	0
	568	0	0	0	0	0
08:00-12:00	95	0	0	0	0	0
	289	0	0	0	0	0
12:00-16:00	0	0	0	0	0	0
	1,013	0	0	0	0	0
16:00-20:00	0	2,158	1,000	0	92	553
	595	13,610	1,258	0	1,246	957
20:00-24:00	552	2158	1,000	315	198	721
	1,093	13,610	1,258	2,104	1,600	1,121

In the next step we consider the possible revenue opportunities of aFRR capacity provision, separately for the positive and negative products. We consider the average capacity prices [Euro/MWh] in the 4-hour-blocks in 2020 (i.e. the remuneration of 1 MW for one of the four hours). This is shown in Table 14. Note that in Section 0 the analyses are also conducted for prices of 2021.

Table 14: Average capacity prices [Euro/MW*h] for FCR and aFRR

	aFRR positive	aFRR negative
00:00-04:00	0.2	2.0
04:00-08:00	0.5	1.2
08:00-12:00	1.1	0.7
12:00-16:00	0.4	1.7
16:00-20:00	1.6	0.4
20:00-24:00	0.8	0.3

The average revenues per hour [Euro/h] in the 4-hour-blocks for positive and negative aFRR capacity provision in 2020 are stated in Table 15. Note that a "-" implies that there is no flexibility available to be offered. Considering in each cell the higher value of either positive or negative balancing capacity provision and multiplying this value with factor 1,460 (4h/day for 365 day/year), this yields the average annual revenues [Euro/a] as stated in the line "SUM" in Table 16.

Table 15: Average balancing capacity revenues [Euro/h] of
positive (P) and negative (N) aFRR provision of aFRR

	Bus use case	Truck use cases				
		Line haul 2	Line haul 3	Retail 5	Constr. 7	Waste 11
00:00-04:00	P: 0.64	0.43	0.20	0.12	0.04	0.14
	N: **7.33**	**27.22**	**2.52**	**4.05**	**2.37**	**2.24**
04:00-08:00	0.13	0.00	0.00	0.00	0.02	0.00
	0.68	0.00	0.00	0.00	0.00	0.00
08:00-12:00	0.10	0.00	0.00	0.00	0.00	0.00
	0.20	0.00	0.00	0.00	0.00	0.00
12:00-16:00	0.00	0.00	0.00	0.00	0.00	0.00
	1.72	0.00	0.00	0.00	0.00	0.00
16:00-20:00	0.00	3.45	**1.60**	0.00	0.15	**0.88**
	0.24	**5.44**	0.50	0.00	**0.50**	0.38
20:00-24:00	**0.44**	1.73	**0.80**	0.25	0.16	**0.58**
	0.33	**4.08**	0.38	**0.63**	**0.48**	0.34

Table 16: Average annual balancing capacity revenues [Euro/a] of aFRR provision

	Bus use case	Truck use cases				
		Line haul 2	Line haul 3	Retail 5	Constr. 7	Waste 11
00:00-04:00	10,696	39,741	3,673	5,916	3,454	3,273
04:00-08:00	995	0	0	0	30	0
08:00-12:00	295	0	0	0	0	0
12:00-16:00	2,514	0	0	0	0	0
16:00-20:00	347	7,948	2,336	0	728	1,292
20:00-24:00	645	5,961	1,168	922	701	842
SUM	**15,493**	**53,651**	**7,177**	**6,837**	**4,913**	**5,407**

We now consider also possible revenues from **balancing energy activation for aFRR**. Since these revenues are highly dependent on the specific use case as well as on the applied bidding strategy in balancing energy markets, we provide one illustrative example to show the order of magnitude of these revenues. The revenues of balancing energy activation depend on the position in the merit-order of balancing energy bids for two reasons: first, bids are ordered in an ascending order, i.e. a position at the front implies a lower energy bid as compared to a position at the end of the merit-order, and secondly, the probability of activation declines with an increased merit-order position. In this report, we do not consider the second part, i.e. the probability of activation explicitly. Instead we state some general figures based on historical data regarding the relationship of energy bid size and activation amounts. Please also note that predictions regarding balancing energy activation are in general attributed with a high uncertainty due to the stochastic nature of balancing.

Before we turn to that, we calculate possible revenues for 400 kWh and 1,400 kWh of positive activation and 1,000 kWh for negative activation (amounts are chosen randomly and are exemplary). We differentiate regarding the sizes of balancing energy bids: for positive balancing energy, energy bids of 50 Euro/MWh, 100 Euro/MWh and 200 Euro/MWh, and for negative balancing energy, energy bids of -50 Euro/MWh, 50 Euro/MWh, 100 Euro/MWh and 200 Euro/MWh. Note that for negative balancing energy, a negative bid indicates a payment direction "BSP to TSO", i.e. these are cost for a BSP. The rationale for generators (consumers) is that she is paid for decreasing generation (increasing consumption) at no additional cost, but, for example, conventional generators save costs for CO2 certificates and fuel (this does not apply for positive balancing energy). The resulting revenues [Euro] are stated in Table 17.

To what extent can these revenues be expected? Table 18 states some general figures regarding the relationship of energy bid size and activation amounts for 1 MW in 2020. For example, for 1 MW of positive (negative) balancing energy, the revenues of an energy bid of 100 Euro/MWh (50 Euro/MWh) with an activation amount of 574 MWh/a (542 MWh/a) result in 57,400 Euro/a (27,100 Euro/a).

Table 17: Possible revenues [Euro] of balancing energy activation for aFRR

	Positive balancing energy of 400 kWh	Positive balancing energy of 1,400 kWh	Negative balancing energy of 1,000 kWh
-50 Euro/MWh	n/a	n/a	-50
50 Euro/MWh	20	70	50
100 Euro/MWh	40	140	100
200 Euro/MWh	80	280	200

Table 18: Balancing energy bid size and activation amounts [MWh/a] of 1 MW for aFRR

	Positive balancing energy	Negative balancing energy
-50 Euro/MWh	n/a	7,302
50 Euro/MWh	5,018	542
100 Euro/MWh	574	256
200 Euro/MWh	151	85

Revenues of Frequency Containment Reserve (FCR) provision

We turn to the possible **revenue opportunities from FCR provision**, which is a symmetric product that combines the negative and positive product. We consider the average capacity prices [Euro/MWh] in the 4-hour-blocks in 2020 (i.e. the remuneration of 1 MW for one of the four hours). This is shown in Table 19. Note that in Section 0 the analyses are also conducted for prices of 2021.

Table 19: Average capacity prices [Euro/MW*h] for FCR and aFRR

	FCR
00:00-04:00	7.5
04:00-08:00	7.7
08:00-12:00	8.2
12:00-16:00	7.5
16:00-20:00	8.7
20:00-24:00	8.6

Since we assumed for aFRR that positive and negative flexibility potential cannot be combined, we need to relax this restriction for FCR to get an idea of possible FCR revenues. Thus, we introduce the following relaxation: balancing energy can only be offered if there is both positive and negative flexibility available for a 4-hour-block and the amount is the minimum of positive and negative flexibility potential. This presents an upper border for revenues and should therefore be interpreted with caution. The available flexibility potential for FCR is presented in Table 20.

Table 20: Assumed flexibility potential [kW] for FCR

	Bus use case	Truck use cases				
		Line haul 2	Line haul 3	Retail 5	Constr. 7	Waste 11
00:00-04:00	3,217	2,158	1,000	622	198	721
04:00-08:00	265	0	0	0	0	0
08:00-12:00	95	0	0	0	0	0
12:00-16:00	0	0	0	0	0	0
16:00-20:00	0	2,158	1,000	0	92	553
20:00-24:00	552	2,158	1,000	315	198	721

The average revenues per hour [Euro/h] in the 4-hour-blocks for FCR provision in 2020 are stated in Table 21. Note that a "-" implies that there is no flexibility available to be offered. Multiplying the values from Table 21 with factor 1,460 yields average annual revenues [Euro/a] as stated in the line "SUM" in Table 22.

Table 21: Average revenues [Euro/h] of FCR provision

	Bus use case	Truck use cases				
		Line haul 2	Line haul 3	Retail 5	Constr. 7	Waste 11
00:00-04:00	24.13	16.19	7.50	4.67	1.49	5.41
04:00-08:00	2.04	-	-	-	-	-
08:00-12:00	0.78	-	-	-	-	-
12:00-16:00	-	-	-	-	-	-
16:00-20:00	-	18.77	8.70	-	0.80	4.81
20:00-24:00	4.75	18.56	8.60	2.71	1.70	6.20

Table 22: Average annual revenues [Euro/a] of FCR provision

	Bus use case	Truck use cases				
		Line haul 2	Line haul 3	Retail 5	Constr. 7	Waste 11
00:00-04:00	35,226	23,630	10,950	6,811	2,168	7,895
04:00-08:00	2,979	0	0	0	0	0
08:00-12:00	1,137	0	0	0	0	0
12:00-16:00	0	0	0	0	0	0
16:00-20:00	0	27,411	12702	0	1,169	7,024
20:00-24:00	6,931	27,096	12,556	3,955	2,486	9,053
SUM	**46,274**	**78,137**	**36,208**	**10,766**	**5,823**	**23,972**

Note that for the annual revenue comparison stated in Section 5.4.3, we assume for positive balancing energy an energy bid of 100 Euro/MWh (i.e. revenues per MW of 57,400 Euro/a) and for negative balancing energy an energy bid of 50 Euro/MWh (i.e. revenues per MW of 27,100 Euro/a) and accounted these revenues with the available flexibility potential in the 4-hour-blocks and the associated marketing of either positive or negative balancing capacity.

Revenue calculations for 2021

We assume the same flexibility potential and calculation approach as for 2020 but use market data of 2021 (see Table 23). The relation between balancing energy bid size and activation amounts of 1 MW for aFRR in 2021 changed with increasing prices as well (see Table 24).

Table 23: Average capacity prices [Euro/MWh] for FCR and aFRR

	FCR	aFRR positive	aFRR negative
00:00-04:00	20.1	11.8	12.1
04:00-08:00	21.6	11.4	9.9
08:00-12:00	16.8	9.7	7.9
12:00-16:00	18.0	14.2	14.3
16:00-20:00	15.7	8.9	6.8
20:00-24:00	14.6	6.6	5.8

Table 24: Balancing energy bid size and activation amounts [MWh/a] of 1 MW for aFRR

	Positive balancing energy	Negative balancing energy
-50 Euro/MWh	n/a	5,477
50 Euro/MWh	6,750	326
100 Euro/MWh	5,049	146
200 Euro/MWh	2,256	40