Deliverable 3: Market Concepts, Economic Benefits of HDEV-based Services and TSOs' Impact

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1 Introduction

This report is dedicated to the impact of the recharging and refuelling infrastructures for Heavy Duty Electric Vehicles (HDEVs) onto the power system. The contents are organised into the following chapters:

Chapter 3 describes the **planning of the recharging and refuelling infrastructure**. First, the measures proposed in the Alternative Fuel Infrastructure Regulation (AFIR proposal from March 2022) are reviewed. The AFIR defines three separate 'locations' for the deployment of public recharging/refuelling stations for HDEV: along the TEN-T network highways, in overnight safe and secure parking areas, and in urban nodes. The target number of recharging/refueling stations are analysed following the implementation reports from major European institutions and research bodies. This chapter quantifies if the AFIR requirements are well in line with the needs of the transport sector.

Chapter 4 then describes the local **grid impact of the recharging and refuelling infrastructure.** A distinction is made between battery and fuel-cell hydrogen HDEVs because the impact on the power grid is quite different in the two cases.

- For **battery HDEVs**, the grid impact related to the expected recharging needs of electric trucks is analysed for some charging use cases, both in public and private access locations: en-route charging along motorways, opportunity charging at logistic hubs and depot charging; and
- For **fuel-cell HDEVs**, the case of refueling stations with local hydrogen production is presented as this is the most interesting in terms of fuel cell HDEV (FC-HDEV) impact on the power grid. The case of hydrogen refueling stations selling hydrogen produced from large scale electrolysers is not considered in this deliverable because it does not represent a significant impact on the local power grid where the hydrogen refilling station is installed.

Finally, Chapter 5 describes the **flexibility and financial potential of smart charging solutions for HDEV.** The goal is to clarify to what extent, and at what price, the impact of the recharging operations on the power grid can be mitigated by the adoption of smart charging solutions without altering the recharging needs of HDV freights.

2 Acronyms

ACEA	European Automobile Manufacturers' Association
AFIR	Alternative Fuels Infrastructure Regulation
aFRR	Automatic Frequency Restoration Reserve
BE-LH	Battery Electric Long Haul
BESS	Battery Electric Storage System
BET	Battery Electric Truck
EVSE	Electric Vehicle Supply Equipment
FCET	Fuel-Cell Electric Truck
FCR	Frequency Containment Reserve
GDP	Gross Domestic Product
HDEV	Heavy-Duty Electric Vehicles
HDV	Heavy-Duty Vehicles
HRS	Hydrogen Refuelling Station
HV	High-Voltage
ICCT	International Council on Clean Transportation
LDV	Light-Duty Vehicles
LV	Low Voltage
MCS	Megawatt Charging Station
MDV	Medium Duty Vehicles
mFRR	Manual Frequency Restoration Reserve
MV	Medium Voltage
MVA	Megavolt-Ampere
NCS	Overnight Charging Station
NREL	National Renewable Energy Laboratory
PSCS	Pricing Signal-based Charging Scheme
T&E	Transport & Environment
TEN-T	Trans-European Networks – Transport
TSO	Transmission System Operator
V1G	Unidirectional Smart Charging
V2B	Vehicle to Building
V2G	Vehicle to Grid
V2H	Vehicle to Home
VGI	Vehicle Grid Integration

3 Planning of recharging and refuelling infrastructure

The transition to decarbonised HDVs requires a contextual roll-out of a suitable public infrastructure, especially for long-haul operations, but at present there is only minimal publicly accessible refueling and recharging infrastructure for battery electric trucks (BETs) and hydrogen-fueled trucks.

The technical specifications and requirements of such infrastructure are quite different from those for cars, regarding:

- Location of charging and refuelling stations;
- Space requirements;
- Minimum power output levels; and
- Connection point at MV or HV level.

For this reason, the AFIR proposal [1] specifically addresses dedicated targets for HDV public recharging/refueling infrastructure. According to the AFIR proposal, to ensure a sufficient publicly accessible infrastructure coverage it is necessary to ensure a combination of:

- Distance-based targets along the **TEN-T network;**
- Targets for **overnight recharging infrastructure,** in 'secure and safe parking areas'; and
- Targets at **urban nodes.**

Regarding the charging use cases described in deliverable 1b (Table 1), no targets are defined for private access locations (in red: private depots, logistic hubs and terminals). However, it is explicitly written that *'The deployment of recharging infrastructure is equally important in private locations, such as in private depots and at logistic centres to ensure overnight and destination charging. Public authorities should take measures in the context of setting up their revised national policy frameworks to en sure that the appropriate infrastructure is provided for that overnight and destination charging'* [1].

The parallel development of private infrastructure is crucial because overnight charging and destination charging are expected to cover most of the recharging needs. As the infrastructure realisation may be challenging for private sector actors, public authorities' support will be necessary.

Table 1. Charging locations according to the charging pattern and the infrastructure access. Private access infrastructure is not considered by the AFIR proposal, whereas public access infrastructure has specific targets.

CHARGING PATTERN	INFRASTRUCTURE ACCESS	
	PRIVATE ACCESS	PUBLIC ACCESS
EN-ROUTE CHARGING	Not applicable	Along motorways
OPPORTUNITY CHARGING	Logistic hubs, terminals, depots	Urban nodes
OVERNIGHT CHARGING	Depots	Safe and secure parking areas

In the next paragraph, the current state of play for recharging and refueling infrastructure is described. AFIR targets are subsequently presented and compared to the infrastructure requirements proposed by other literature studies.

3.1 Recharging infrastructure

3.1.1 Current state of play

According to ACEA [2], in May 2021 there were fewer than ten publicly accessible charging points for BETs available in Europe. Therefore, the currently available BETs must have their private infrastructure in place for charging these short- and medium-haul vehicles.

3.1.2 Development planning

	COMMISSION PROPOSAL		
TEN-T core network	31 Dec 2025	31 Dec 2030	31 Dec 2035
Power output per recharging pool	≥1,400kW	≥3,500kW	
Number / power of recharging stations	1 x 350kW	2 x 350kW	
TEN-T comprehensive network	31 Dec 2025	31 Dec 2030	31 Dec 2035
Power output per recharging pool		≥1,400kW	≥3,500kW
Number / power of recharging stations		1 x 350kW	2 x 350kW
Safe and secure parking areas	31 Dec 2025	31 Dec 2030	31 Dec 2035
		1 x 100kW	
Urban nodes	31 Dec 2025	31 Dec 2030	31 Dec 2035
Aggregated power output	≥600kW	≥1,200kW	
Individual power output	≥150kW	≥150kW	

Figure 1. AFIR targets for HDV recharging infrastructure [3]

Figure 1 summarises the AFIR targets for HDV recharging infrastructure, which are reported in the following [1]:

- Member States shall ensure that along the **TEN-T core network**, publicly accessible recharging pools dedicated to HDVs are deployed in each direction of travel with a maximum distance of **60 km** in-between them:
    - By **31 December 2025**, each recharging pool[1] shall offer a power output of at least **1400 kW** and include at least one recharging station with an individual power output of at least **350 kW; and**
    - By **31 December 2030**, each recharging pool shall offer a power output of at least **3500 kW** and include at least two recharging stations with an individual power output of at least **350 kW**.
- Member States shall ensure that along the **TEN-T comprehensive network**, publicly accessible recharging pools dedicated to HDVs are deployed in each direction of travel with a maximum distance of **100 km** in-between them.
    - by **31 December 2030**, each recharging pool shall offer a power output of at least **1400 kW** and include at least one recharging station with an individual power output of at least **350 kW**

[1] A recharging pool consists of one or more recharging stations at a specific location, including the dedicated parking lots adjacent to them.

- by **1 December 2035**, each recharging pool shall offer a power output of at least **3500 kW** and include at least two recharging stations with an individual power output of at least **350** kW.

- By **31 December 2030**, in each **safe and secure (overnight) parking area** at least one recharging station dedicated to HDVs with a power of at least **100 kW** is installed.
- By **31 December 2025**, in each **urban node,** publicly accessible recharging points dedicated to HDVs are deployed, providing an aggregated power output of at least **600 kW**, provided by recharging stations with an individual power output of at least **150 kW**. In **2030,** the total power output should be **1200 kW**.

According to these numbers, it is possible to estimate the number of publicly accessible recharging points required by the AFIR proposal (Table 2), as indicated by [4]. The main assumption is that minimum power outputs required for at least one station is the minimum power output for all charging points at the pool.

Table 2. Number of publicly accessible recharging points based on AFIR requirements

Recharging point location	**Network length (km)**	**Number of pools**	**Minimum power output per pool in 2030 (kW)**	**Power output per recharging point (kW)**	**n° of chargers per pool**	**Minimum n° of recharging points**
Core network	35,969[2]	1199 (every 60 km)	3500	350	10	11,990
Comprehensive network	46,763[2]	975 (every 100 km)	1400	350	4	3901
Safe and secure parking areas	Not applicable	719 (every 100 km of core network)	100	100	1	719
Urban nodes	Not applicable	88[3]	1200	150	8	704

Therefore, the total estimate is **17,314** required **public access recharging points** in **2030**.

These numbers have been compared by [4] to the requirements proposed by the studies proposed by E-Laad (2020) [5], ACEA (2021) [2], Cambridge Econometrics [6] and Transport & Environment (2021) [7]. Notably, these sources (except for [2]) consider only the infrastructure for trucks and trailers, excluding coaches and buses, which are expected to rely on overnight depot charging and destination charging and therefore will not make use of the publicly accessible infrastructure.

Table 3 compares these requirements to those of the AFIR proposal in 2030, also considering the indicated power levels for different recharging options. Different numbers are due to different conditions and assumptions considered by sources. However, the breakdown of truck trip length is the main factor determining the need for charging infrastructure and its local development and distribution.

[2] https://www.cedr.eu/docs/view/60632734c6c05-en
[3] https://vitalnodes.eu/2018/01/30/vital-nodes-to-integrate-the-88-urban-nodes-of-ten-t/

Table 3. Requirements for HDV publicly accessible recharging points for 2030 proposed by AFIR [1], compared to the projections of other literature sources.

Source	Total number (2030)	En-route charging points along motorways	Opportunity charging points at urban nodes	Overnight charging points in safe and secure parking areas
AFIR proposal [1]	17,314	15,891 (350 kW)	704 (150 kW)	719 (100 kW)
ACEA [2]	50,000–85,000	30,000 (500 kW+)	15,000 (350 kW)	5000–40,000 (<350 kW)
T&E [7]	42,000	4000 (620–850 kW)	27,000 (350 kW)	11,000 (150 kW)
E-Laad [5]	Not applicable	7200 (500 kW+)	not included	10,800 (70–100 kW)
Cambridge Econometrics [6]	Not applicable	11,000 (700 kW)	not included	not included

Finally, the main conclusions that can be drawn are as follows:

- The numbers of ACEA [2] and T&E [7] are considerably higher than the estimates based on AFIR proposal, which sets minimum mandated targets. In particular, the AFIR targets for both opportunity charging points at urban nodes and overnight public charging points in parking areas seem especially low compared to these sources; and
- The minimum power output along motorways should be revised. Power output levels of 350 kW are a good start for trucks with a high number of stops and longer mandated drivers' breaks but might not be sufficient in the event of drivers' breaks being close to the legal minimum. Higher minimum levels of power output (>500 kW) might be considered in the AFIR. The sector itself is also working on higher power output levels such as 1 MW and above.

Moreover, ACEA [2] specifies that binding targets should be set per Member State and proposes a methodology which considers the share of new vehicles registrations, the national Gross Domestic Product (GDP) and average mileage. Their results are reported in Figure 2. Specific parameters should be considered to consider the role of small transit countries, such as Switzerland, Austria and Benelux as the proposed parameters are valid only for large countries with high internal HDV traffic.

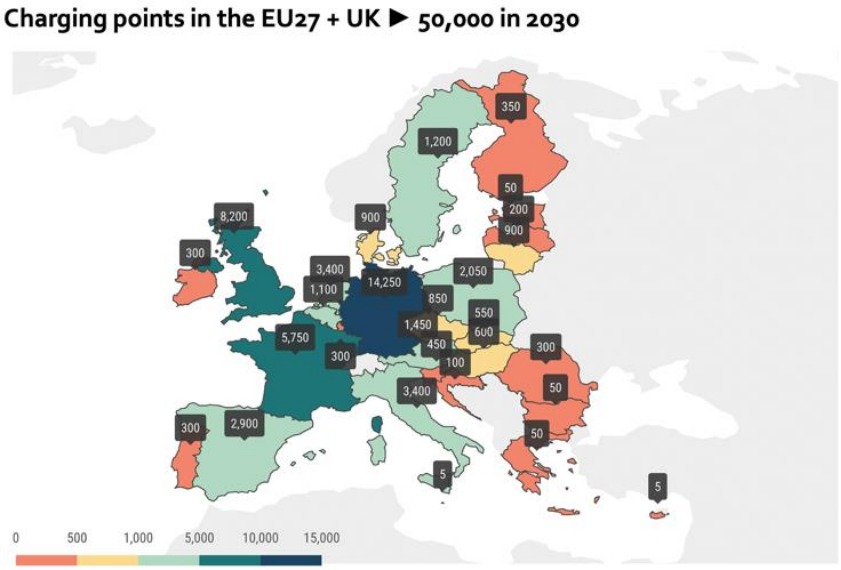

Figure 2. Binding targets per Member State for HDV recharging infrastructure in 2030 [2]

It is also relevant to report projections for private accessible recharging points, as outlined by the same literature studies. In particular, all of them express numbers for private depots overnight recharging points, whereas only [5] shows numbers for private access opportunity chargers (Table 4).

It is evident that depot charging points are expected to be dominant as this recharging option will most likely cover 80% share of total energy demand [5]. Therefore, the total number of depot charging points should be close to the total number of expected BETs.

Table 4. Requirements for HDV private accessible recharging points for 2030 proposed by different literature sources

Source	Total number (2030)	Opportunity charging points at logistic hubs	Overnight recharging points at depots
E-Laad [5]	342,000	54,000 (50 kW)	288,000 (50 kW)
ACEA [2]	270,000	not included	270,000 (50–100 kW)
Cambridge Econometrics [6]	320,000	not included	320,000 (22–90 kW)
T&E [7]	470,000	not included	470,000 (150 kW)

3.2 Hydrogen refueling infrastructure

3.2.1 Current state of play

As of 2023, **178** Hydrogen Refueling Stations (HRS) were in operation in Europe, the majority of which are located in Germany, France, Denmark, the Netherlands and Belgium [8]. These refueling stations are for passenger cars and local buses, with a set standard of compressed hydrogen refueled at 700 bar for passenger cars and 350 bar for buses [9]. Instead, technology options for hydrogen refueling stations for Medium-Duty Vehicles (MDVs) and HDVs are still under development, as illustrated in Deliverable 2.

The creation of a comprehensive network of hydrogen refueling stations is indispensable for the long-haul operations of fuel cell HDVs.

It should be noted that most of these refueling stations serve only passenger cars, with only **35 delivering 350 bar H2 to HDVs, mainly city buses**. Depending on compressor type and on-board storage pressure, these HRS might be suitable for refueling hydrogen trucks, but this is not made clear in the information provided by HRS operators [4].

According to ACEA, a hydrogen refueling station for trucks should have a minimum daily capacity of at least six tons of H2, with at least two dispensers per station.

3.2.2 Development planning

The AFIR proposal includes the following targets for the hydrogen refueling infrastructure:

- By **31 December 2030**, Member States shall ensure that publicly accessible hydrogen refueling stations with a minimum capacity of **2 t/day** and equipped with at least a **700 bars dispenser** are deployed with a maximum distance of **150 km** in-between them along the **TEN-T core** and the **TEN-T** comprehensive network in both directions or serving both directions. The station is designed to serve LDVs and HDVs:
    - This translates to a total number of **480 hydrogen refueling stations along the TEN-T network.**
- By **31 December 2030**, member states shall ensure that **at least one** publicly accessible hydrogen refueling station is deployed in each **urban node:**
    - This translates to **88 hydrogen refueling stations at urban nodes.**
- In addition, Member States must ensure that **every 450 km** on the **TEN-T network,** a hydrogen refueling station serves **liquid hydrogen** to trucks:
    - This translates to a total number of **160 liquid hydrogen refueling stations along the TEN-T network.**

Authors in [4] also found studies in the literature regarding hydrogen refilling infrastructure projections, which they compared to the AFIR proposal: ACEA (2021) [2] and Cambridge Econometrics [6]. Their projections are based on expected numbers of Fuel Cell Electric Trucks (FCETs) in 2030.

Table 5. Requirements for HDV publicly accessible hydrogen refueling points for 2030 proposed by AFIR [1], compared to the projections of other literature sources.

Source	Hydrogen refueling stations along motorways	Liquid hydrogen refueling stations along motorways
AFIR proposal [1]	728 (2 t/day)	160
ACEA [2]	1000 (6 t/day)	not included
Cambridge Econometrics [6]	250 (10 t/day) + 95 (25 t/day)	not included

The main conclusions are as follows:

- The number of stations resulting from the AFIR proposal is between the projections of [2] and [6]. However, the daily supply capacity mentioned by sources is much higher; and
- The choice for at least 700 bar hydrogen refueling points is justified as both HDVs and LDVs can utilise these refueling points [4].

- Consulted sources do not consider liquid hydrogen whereas the AFIR proposal does. According to [4], the introduction of binding targets for liquid hydrogen might be too early, given the early phase of development of liquid hydrogen technology.

Regarding the general targets about hydrogen refueling points, two discordant opinions have been found. Transport & Environment, in its reaction to the AFIR proposal [10], states that as it is not yet clear whether FCETs will be a mass phenomenon, Council and Parliament should cut back on the hydrogen refueling infrastructure ambition and focus on public funding for the mature technology of BETs. In fact, they observe that the total 2021–2050 investment in HDV recharging infrastructure will be a small percentage compared to investments for refueling infrastructure, based on AFIR proposal targets (Figure 3).

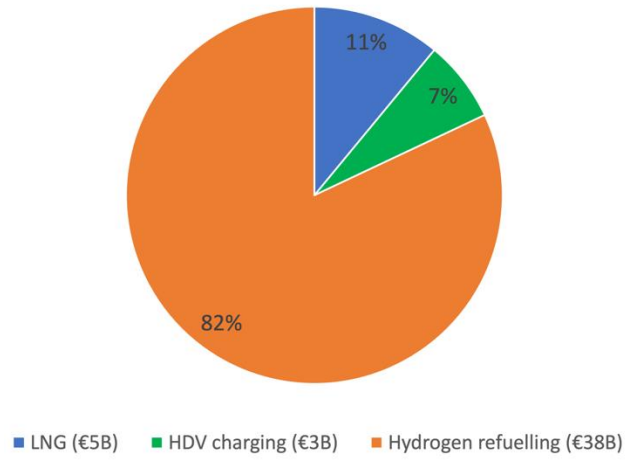

Figure 3. Total 2021–2050 investment in HDV recharging and refueling infrastructure [10]

Instead, ACEA reports that from the mid-decade, the FCETs offerings will increase significantly and be a suitable option for high payloads and long-haul operations. ACEA projections are that FCETs will mainly replace tractors. These reasons motivate their proposed targets in [2].

Finally, ACEA also sets binding targets per different Member States for HRS, which are reported in *Figure 4*.

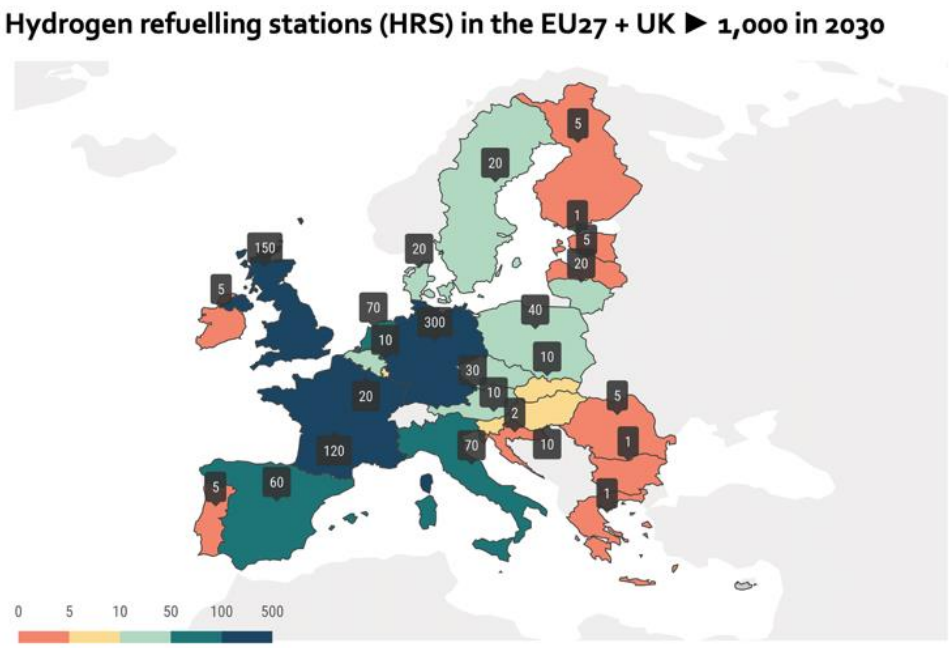

Figure 4. Binding targets per Member State for HDV refueling infrastructure in 2030 [2]

4 Grid impact of recharging and refuelling infrastructure

4.1 Recharging infrastructure

As already introduced, there are different possible recharging use cases, which imply a broad range of voltage levels and consequently different grid connection concepts. According to [11], the choice of voltage level and specific point of connection to the public power grid depends on several factors:

- Available grid capacity of the pre-existing power grid architecture;
- Cost of different connection alternatives;
- Spatial and environmental aspects;
- Available space for potential locations of substations; and
- Anticipation of future peak power developments.

Authors in [11] propose different connection approaches, based on the rated power of charging stations, which are summarised in Figure 5. The limits they consider are representative of their country grid code and should be adapted to the specific regulation.

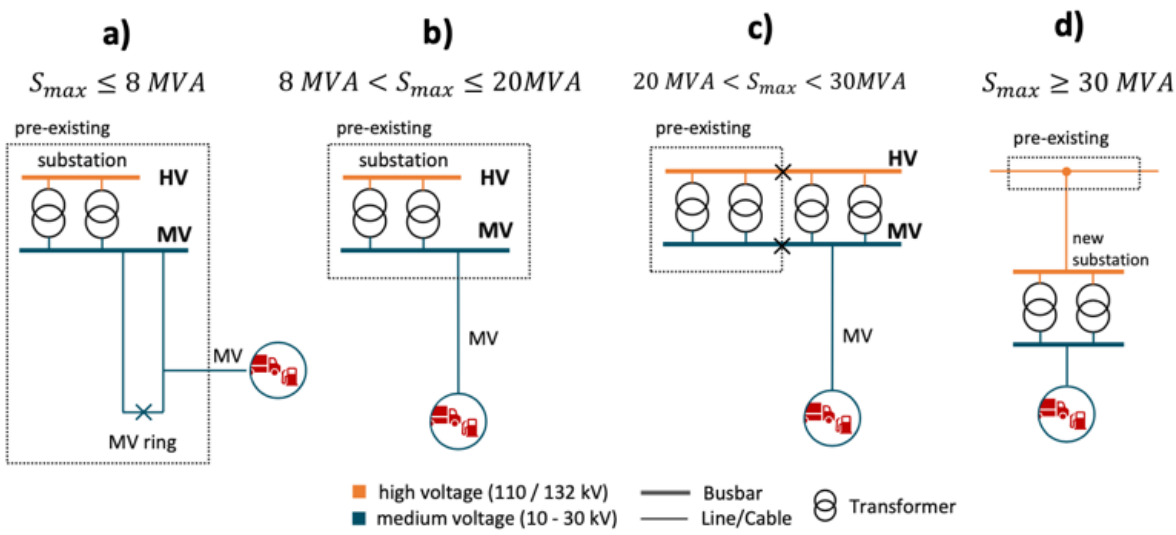

Figure 5. Grid connection concepts [11]

According to the German grid code, charging stations with rated power below 8 MVA are connected to the closed medium voltage ring (a) [11]. Above 8 MVA:

- If HV/MV transformers have sufficient spare capacity, no further investment is necessary (b). Figure 5 assumes an available capacity of 20 MVA;
- Above 20 MVA it is necessary to ensure the addition of HV/MV transformers (c); and
- Above 30 MVA the charging station is directly connected to the HV grid, involving the installation of a new substation, either near the HV grid or near the charging station.

Other innovative grid connection solutions are available, such as the one introduced by the Portuguese Transmission System Operator (TSO) REN in the context of the European project Speed-e, and already mentioned in Deliverable 2 of this project. The proposed solution is to supply EV/HDEV charging stations directly from existing transmission lines, including a tap and a special small substation that transforms

directly from Very High Voltage to Low Voltage using Power Voltage Transformers. This option enables feeding Megawatt charging stations directly from HV lines in locations where the distribution grid is absent.

As already stated in deliverable 1b, the technical and economic opportunity of integrating Battery Storage Systems (BESS) in HDEV recharging stations depends on several parameters and boundary conditions that shall be studied case by case (e.g. country regulations, local grid conditions and market structures).

According to [11], there is a connection threshold over which high battery power levels are not profitable as they would require over-sized battery capacities. Another result of [11] is that the application of a BESS in combination with Mega Charging Stations (MCS) is a better option than in combination with both MCS and Overnight Charging Stations (NCS); in fact charging stations combining Mega Chargers and overnight chargers have long-lasting peak power demands and are not ideal for economic BESS operations, whereas charging stations providing only Mega Chargers have a very different demand profile, with very short durations in peak power demands.

4.1.1 En-route charging along motorways

In the AFIR proposal [1] it is written that *'infrastructure along the TEN-T network will ensure full connectivity throughout the Union. The infrastructure should have sufficient power output to allow the recharge of the vehicle within the driver's legal break time.'*

As already mentioned, the proposal sets distance-based targets for recharging points along the TEN-T network. According to [4], TEN-T network is a relevant choice as a starting point for the roll-out of infrastructure, having a relatively high traffic intensity of long-haul trucks.

However, according to RE-xpertise [11], rolling-out the charging infrastructure only on the most important motorways will cause a 'gravity effect' as they will attract BE-LH trucks more quickly than elsewhere. Instead, motorways with low traffic intensity will experience a lower share of electric trucks. With increasing shares of BE-LH trucks, infrastructure must be rolled out across the regions and the gravity effect will become less pronounced. Moreover, even in an early stage with low fleet penetration levels, the maximum allowable distance between charging stations on the highways will need to be limited, also because of EU regulation on driving times and rest periods.

Authors in [11] present the results of a simulation analysis, which considers traffic flows along motorways to find the required MCS and NCS and their related grid capacities. **Error! Reference source not found.** Table 6 reports different scenarios which, based on traffic flows (high or low) and station densities, express the required numbers of MCS and NCS with the associated grid capacity.

The authors consider a steep increase of the share of battery-electric long-Haul trucks from 2035 to 2040: in the case of high traffic volume, the increase is from 50% to 70%, whereas in the case of low traffic volume it is from 7% to 60%. In combination with this ramp-up scenario, the two prototypes cover different ranges of possible customer MCS volumes, based on the station density.

Table 6. Required grid capacity of public charging stations [11]

proto-type	scenario	year	station density	MCS	NCS	grid capacity 1 dir.	grid capacity 2 dir.
#	#	-	km	#	#	MVA	MVA
high traffic volume	1	2027	100	3	41	3.8	7.6
	2		200	5	81	6.3	12.6
	3	2030	50	4	54	5.1	10.2
	4		100	7	108	8.8	17.6
	5	2035	50	8	136	10.1	20.2
	6	2040	50	13	217	16.4	32.8
low traffic volume	7	2027	100	1	4	1.3	2.6
	8		200	2	8	2.5	5.0
	9	2030	50	2	5	2.5	5.0
	10		100	2	10	2.5	5.0
	11	2040	50	3	43	3.8	7.6

Already in 2030, the required grid connection power is in the range 2.5 – 18 MVA depending on the traffic volume and charging station densities. Following the expected growth of the BE-LH truck fleet, the required grid connection increases significantly, reaching 33 MVA in the 2040 scenario with high traffic flows (Figure 6).

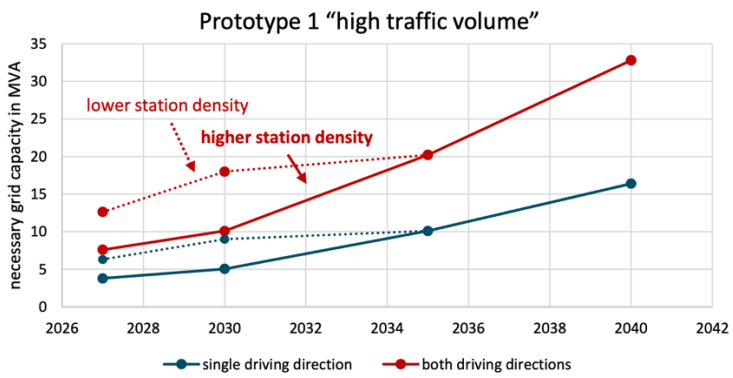

Figure 6. Required grid capacity of public charging stations with high traffic volumes [11]

Finally, charging stations along motorways may require strong network reinforcements depending on the expected traffic volume and the high voltage connection level in the specific country. Based on Figure 5, a charging capacity of 33 MVA requires a connection at medium voltage level or high voltage level beyond 2035.

The high predictability of LH trucks electrification favours step-by-step planning measures of the grid connection, but the related construction costs may be significant.

There is the possibility that HDEV recharging stations along motorways will be placed at already existing petrol stations. However, another approach may be to place megawatt recharging stations where the connection to the HV network is more convenient. For example, the plans of the Slovenian TSO (ELES) are to build completely new HDEV megawatt recharging stations from the green field, and to identify optimal locations considering the intersections between highways and HV lines.

4.1.2 Opportunity charging at logistic hubs

Authors in [11] also simulated the grid capacity required for opportunity charging at logistic hubs, whereby trucks regularly stay for loading or unloading goods. The typical duration of stay in such locations is similar

for lighter and heavy trucks, with a significant share of all trucks leaving within the first two hours after arrival (Figure 7).

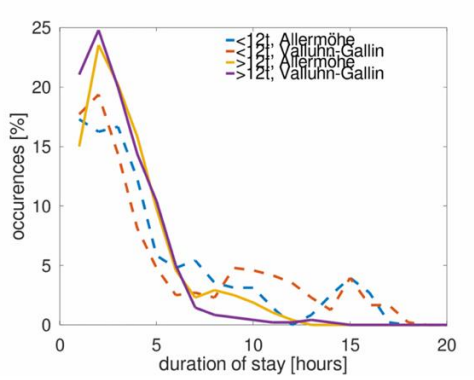

Figure 7. Duration of stay distribution for two examples of logistic hubs in Germany [11]

Instead, times of arrival and departure are very diverse: heavy trucks arrive during all times of the day, whereas lighter trucks arrive or departure the area during night-time only to a limited extent (Figure 8). Most lighter trucks do not operate during night-hours and hence stay at the site during night hours for more than 5 hours.

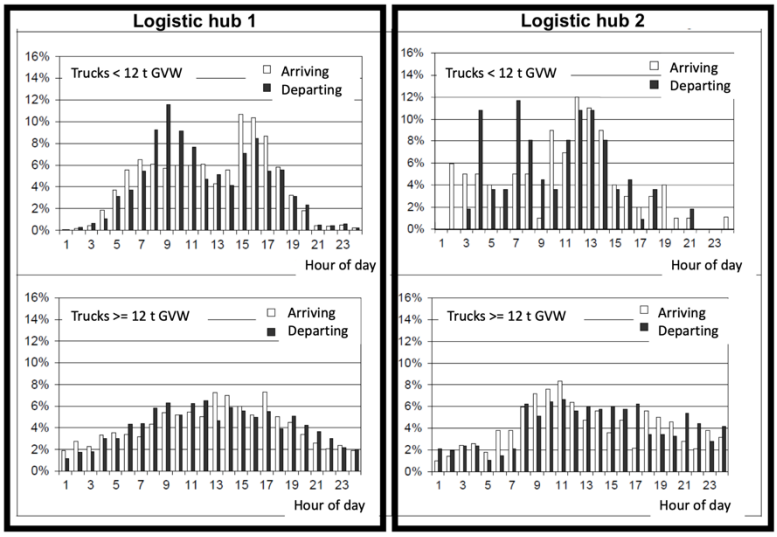

Figure 8. Arrival and departure of trucks at two different logistics hubs in the Hamburg area, Germany; top: trucks < 12 T GVW (Gross Vehicle Weight); bottom: trucks > 12 T GVW (Gross Vehicle Weight) [11]

Authors then report interesting considerations about the surface occupied by logistic hubs, which are here briefly summarised:

- Current **peak load levels** of logistics areas are approximately **40 kW/ha;**
- Based on their simulations, they found an increase of the peak load of around 10 kW/ha in 2040 because of the introduction of BE-SH and -LH trucks and their charging infrastructure: it would mean **50 kW/ha;**
- Business areas can range from some ha to several hundred ha (e.g. the sites included in the European Freight Village Ranking have an average size of 200 ha). Considering a business area of **125 ha**, the required grid capacity would be approximately **60 MW** in **2040;**
- Therefore, a **dedicated HV substation** would be needed.

As the planning, permitting and construction of substations and HV lines usually takes several years, it is necessary to start the preparation and arrangement of business areas as soon as possible, with a complete redesign and implementation of new network connections. Strong HV-distribution networks in the vicinity of logistics hubs will therefore become an important factor for site development. However, in most cases, large business areas are located close to urban agglomerations, and distances to the transmission network are reasonably short.

4.1.3 Depot charging

There is general consensus that depot charging will play a major role in the recharging of electric trucks and buses [4] [5] [12]. The grid impact of depot charging for HDEVs can be significant in relation to the larger volumes and numbers of vehicles served. T&E estimates that, for trucks coming back to the depot**, approximately 80% of the energy recharged by electric trucks will be delivered while charging at the depot**, whereas destination charging[4] covers 15% of the total energy, and public charging approximately 5%.

T&E recommends that depot charging should be prioritised, especially in **urban nodes[5].** They are hotspots for freight activity: trips coming to or from the urban nodes compose half of the total EU freight activity (tkm[6]) and 39% of trips. On average, in each urban node, the energy demand from electric trucks would increase up to approximately **86 GWh** in the EV-Leaders scenario (15% electric truck share sale) and to **166 GWh** (30% electric truck share sale) in the Road-2-Zero scenario in **2030** [7], or up to 50 TWh in total at EU level (or 1.6% of the current total electricity generation). It is very likely that these energy withdrawals will be concentrated in industrial/logistic area where the depots are normally located.

An interesting result regarding the impact on the grid of depot charging is produced by the National Renewable Energy Laboratory (NREL) based on the US case study [13]. The study developed depot charging **load profiles for heavy-duty trucks from real-world operating schedules**, applying these load profiles to **36 distribution real-world substations**. They found that short-haul operations (≤322 km) represent ~50% of heavy-duty and ~60% of total truck energy use and greenhouse gas emissions in the United States [13]. The long and predictable off-shift dwell periods (usually overnight) at a central location, such as a depot, means that these vehicles are expected to perform all charging at their depots, where it is convenient, inexpensive and easily controlled. The analysis on vehicle usage first reveals that at depot **charging requirements are met at 100 kW** power rates per vehicle, which is used as the reference power to assess the impact on the grid.

The study was conducted for three types of fleets (Fleet 1, beverage delivery; Fleet 2, warehouse delivery; Fleet 3, food delivery), with different representative sizes (10, 50 and 100 HDEVs), modelling three charging strategies. The first strategy is referred to as '100 kW immediate' with uncoordinated 100 kW per vehicle charging beginning once a shift ends and continuing until either the battery is fully recharged or a subsequent shift begins. The second is '100 kW delayed', which demonstrates the extent to which charging loads can be

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[4] Destination charging occurs during a working cycle at a specific destination where the vehicle spends an extended period of time. In case of light duty vehicles, it can be a restaurant, a shopping center or an attraction. In the case of a truck, the destination could be a distribution center where the vehicle is directed to load and unload freight. Depot charging occurs at central locations at the end of the vehicle's daily route or during off-hours when the vehicle is not in use.

[5] A combination of the existing 88 urban nodes defined in the TEN-T Regulation are considered, plus additional 85 nodes which are the remaining areas with the most urban and regional truck activity across Europe.

[6] tkm stands for tonne-kilometre, a unit of measure of freight transport which represents the transport of one tonne of goods (including packaging and tare weights of intermodal transport units) by a given transport mode (road, rail, air, sea, inland waterways, pipeline etc.) over a distance of one kilometre. Only the distance on the national territory of the reporting country is considered for national, international and transit transport.

postponed to fully recharge the vehicle's battery prior to a subsequent shift. The final strategy is 'constant minimum power', which leverages the entire off-shift period to charge at the minimum power required to fully recharge the vehicle's battery prior to a subsequent shift.

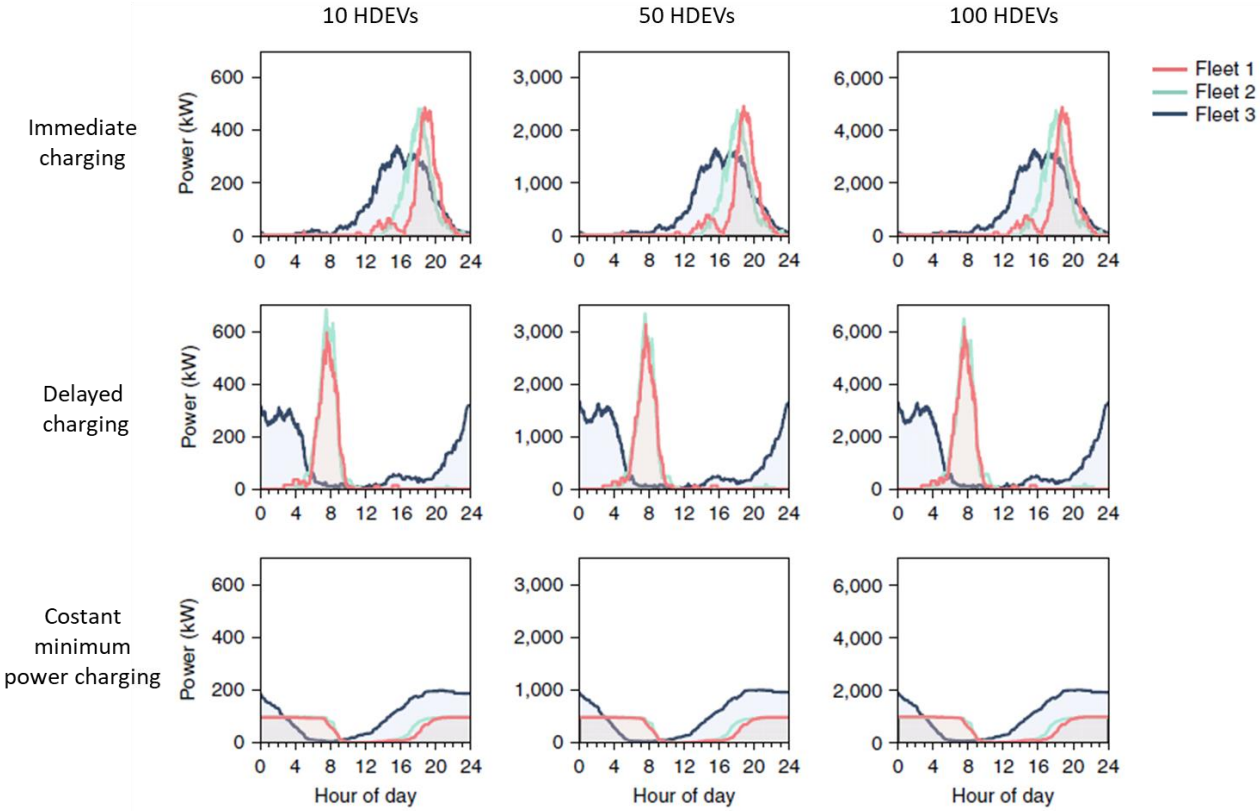

Figure 9. Average daily depot load profiles for multiple scenarios. Each scenario represents a combination of fleet, fleet size (10, 50 and 100 EVs charging [left, centre and right columns, respectively]) and charging strategy (100 kW immediate, 100 kW delayed and constant minimum power [top, middle and bottom rows, respectively]). Fleet 1 is beverage delivery. Fleet 2 is warehouse delivery. Fleet 3 is food delivery.

The shape and magnitude of the load profiles for Fleets 1 and 2 are very comparable due to their consistent operating schedules which led to high peak loads (472–654 kW for 10 EVs) because most vehicles charge concurrently. If charging is not managed (100 kW immediate), peak load coincides with the typical system-level peak period, which adds load when the system is most stressed. The delay strategy shifts the peak load into the early morning (6:00–10:00); however the roughly three-hour duration of the fleet's peak demand period can move anywhere between the apexes of these two profiles (that is, 18:00–7:00). The constant minimum power strategy effectively flattens the fleets' load profiles, which produces a >80% reduction in the peak demand. This is accomplished by charging at substantially lower power levels (maximum 15.3 kW per vehicle for Fleet 1 and 22.8 kW per vehicle for Fleet 2). Fleet 3's load profiles differ due to earlier start times and more variable operating schedules. Despite the higher vehicle energy requirements, staggered shifts produce lower aggregate peak because fewer vehicles are likely to be at the depot at any time.

Finally, a load integration case study was performed for 36 substations to determine the likelihood that heavy-duty depot charging necessitate upgrades to distribution substations (HV/MV). Given local variabilities in grid conditions and operations, some upgrades are difficult to avoid. Figure 10 shows the likelihood that heavy-duty electric truck depot charging requires specific upgrades to real-world distribution substations, including new feeder breakers, transformer upgrades, new transformers or new substations. It was found that charging 10 EVs at 100 kW per vehicle (peak load ~700–900 kW) requires upgrades to ~6% of substations and one new substation installation. However, the majority (78–86%) of the substations studied can supply

100 BETs with 100 kW per vehicle charging without upgrades. Up to 89–92% substation can handle 100 trucks charging under the constant minimum power strategy.

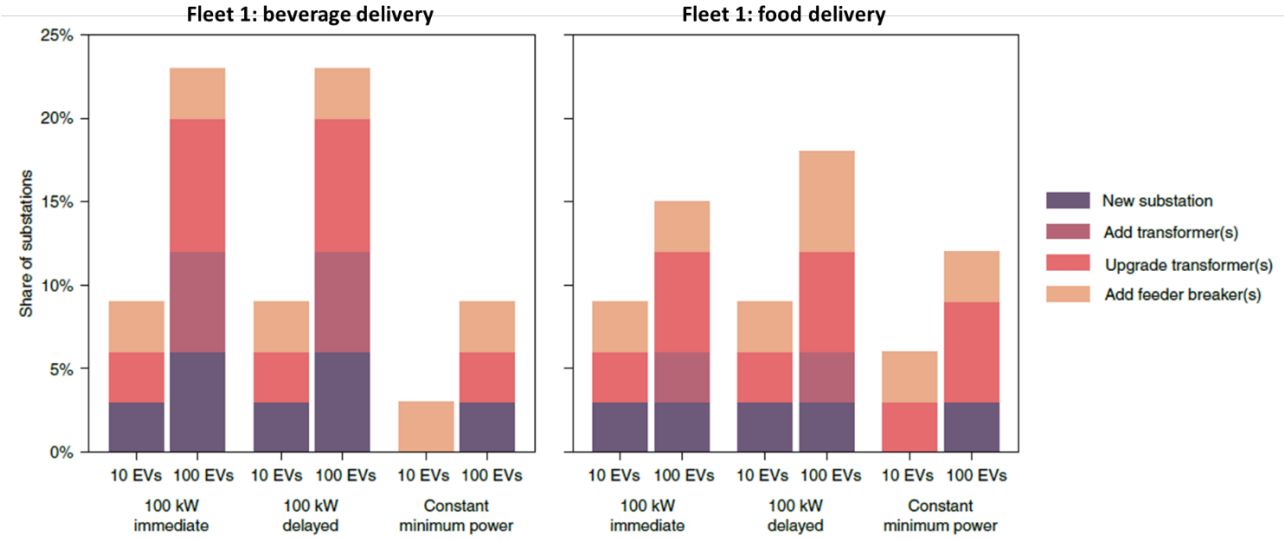

Figure 10. Share of substation that requires upgrades for the peak day profile. The peak day load profiles for Fleet 1 (left) and Fleet 3 (right) are added to each substation transformer's respective 2019 single-day peak demand profile for combinations of fleet size (10 and 100 EVs charging) and charging strategy (100 kW immediate, 100 kW delayed and constant minimum power)

Another study related to depot charging grid impact is [14]. The authors state that, in depots, **82%** of the charging demand is at night, between **20:00 and 08:00,** opting for a form of smart charging to spread out the power demand over the night and limit the charging costs. Their study focuses on the charging infrastructure requested for electric trucks and buses in city logistics, in **2030 in the city of Amsterdam**. The total expected recharge demand is shown in Figure 11. This distribution would lead to a maximum power demand of **2600 kW in a single logistic location**.

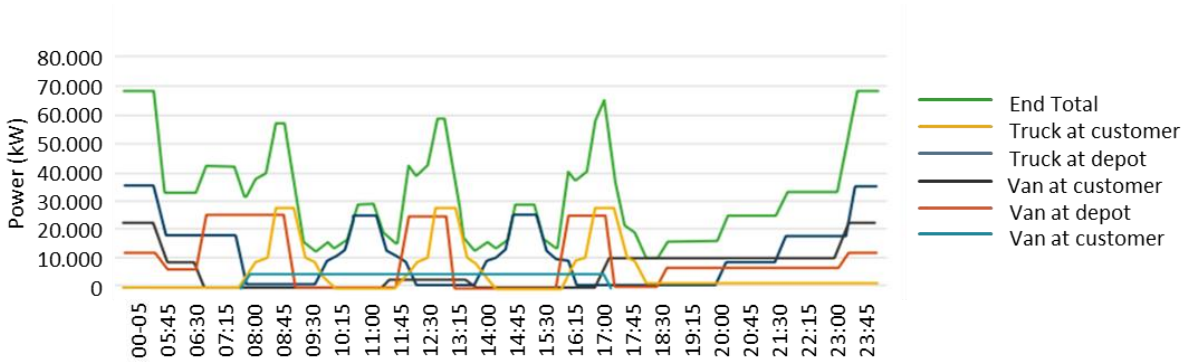

Figure 11. Recharge demand for the electric trucks and vans in the city of Amsterdam in 2030 [14]

An analysis for the **bus depot** is provided based on the fleet in operation in the area of Milan. Thirty percent of the urban bus fleet is already running on electricity. The electric buses are equipped with 216 – 316 kWh battery and rely both on overnight charging (between 60 kW and 120 kW, with power balance reduction at 50 kW) and opportunity charging at 200 kW [15]. The renovation fleet plan intends to turn the whole fleet, composed of 1200 buses, into battery electric by 2030.

Table 7 details a possible scenario of recharge demand from the electrified fleet in 2030. As shown, assuming a simultaneous charging factor of 80%, the total overnight recharge demand would reach **48 MW,** which represents approximately 3% of the maximum annual peak of the city [16]. Despite the observation that the

increase in total electric power demand is not significant, a **peak in the power demand**, both geographically and over time, can have major consequences **locally**.

Table 7. Expected recharge demand for a fleet of full electric buses in the City of Milan in 2030

Fleet size	Recharge power	Estimated contemporary factor	Total recharge demand overnight	Percentage of the peak power (1.64 GW)
1200	50 kW	80%	48 MW	3%

A detailed study conducted by Tennet and Daimler [17], illustrated in Section 5.1, shows the possible recharging process of a fleet of approximately **150 bus** (Figure 12). The maximum battery capacity in the buses is 350 kWh. The assumed charging system can provide a maximum of 80 kW per bus, with one charging point per bus. From around 06:30 to 20:30, most buses operate and are not connected to the grid, thus during the day grid load is lower compared to the late-night hours. During night nearly all buses are connected to the grid, and with uncontrolled charged the load appears flat with maximum power slightly **above 4 MW**.

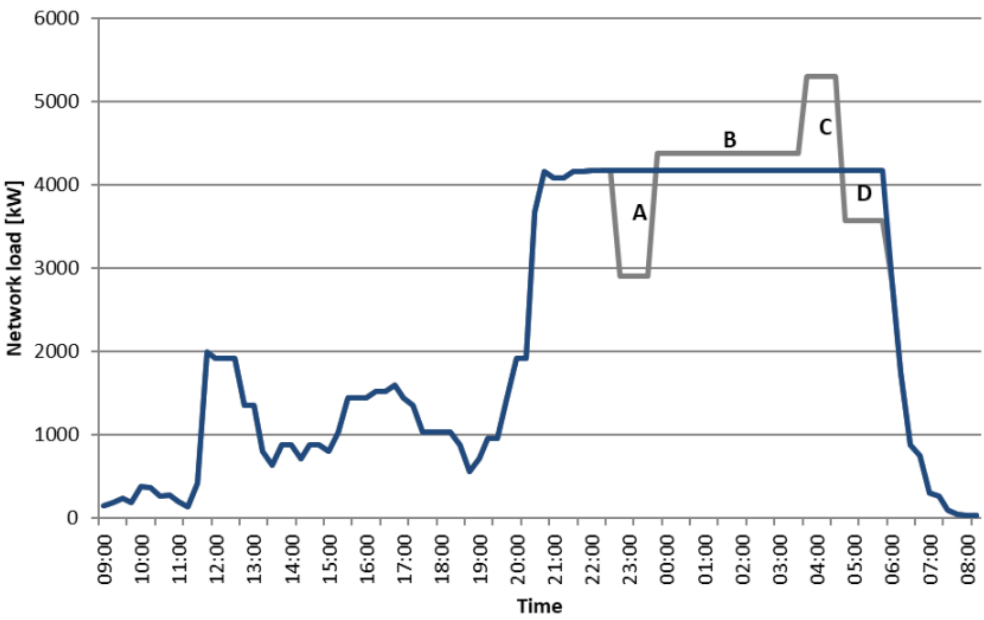

Figure 12. Network load for the bus use case (blue) and exemplary balancing power activation (grey) [17]

Another relevant segment that will recharge at the depot is the **garbage collection and street cleaning** vehicles. The charging scenario suitable for waste vehicles is almost exclusively depot charging [17]. For this category, RSE has elaborated a profile of the recharging demand based on the Milan use case [18]. An electric fleet composed of steer sweeper, dump lorry, compactor and lift car will require for the recharge a daily

energy of **40 MWh per million inhabitants**. The power profile for the recharges normalised per million inhabitants is shown in Figure 13. Notably, the power levels remain **below 3 MW per million inhabitants**.

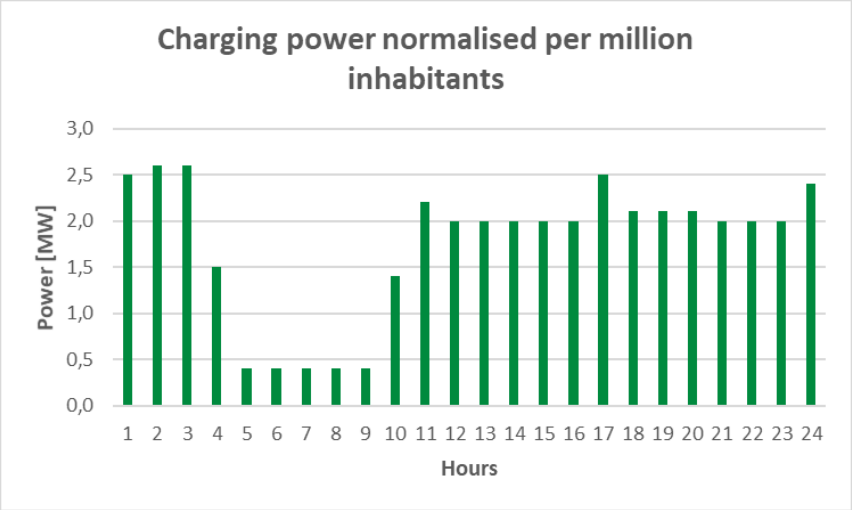

Figure 13. Charging power normalised per million inhabitants for garbage collection and steer vehicle recharge (based on RSE's own simulations)

In the context of depot, network upgrades might encounter land use restrictions, especially if depots are located in **dense urban areas**. **Coordinated planning for grids and depots** are essential to anticipate potential land use issues from grid extension [19].

4.2 Refuelling infrastructure

As highlighted in the previous deliverable, hydrogen for supplying fuel cell HDEVs can be produced at the site of the refueling station or can be produced centrally in combination with a distribution system that transports hydrogen from the production site to the refueling station.

Centralised production is intended for large hydrogen production that supplies a large variety of industrial processes and final use, including the refuelling of fuel cell HDEVs. The production of hydrogen from large scale electrolysers has no significant impact on the local power grid where the hydrogen refilling station is installed. Thus, this configuration is not considered in the present study, which focuses on the impact of road transport on the grid.

For the purpose of this study, it is of interest the configuration where the electrolyser is located at the same site of the refueling station, thus requiring a connection to the electricity grid. HRS with local hydrogen production also avoids the need of transporting hydrogen to the refueling station, which may improve both system and cost efficiency. An example is reported by authors in [20], who examine the cost of centralised and decentralised electrolysis-based hydrogen production systems that HRS for heavy transport, in different European regions. Their results show that **decentralised grid-connected hydrogen** supply system is **more convenient** than a centralised grid-connected system in all the studied regions. Although slightly lower costs[7] for hydrogen production and storage can be achieved in the centralised system, the additional cost for hydrogen transport to the refueling station resulted in a higher total cost. Thus, according to the study, the higher cost for hydrogen transport offsets the advantage of having access to large-scale hydrogen storage. It is important to remark that the comparison should include electric grid cost, including the reinforcement, which are not introduced in reference [20]. The overall convenience of each solution will depend on various

[7] Some cost indications can be drawn from the study. Lowest costs for delivering hydrogen reach 2.2–3.3€/kgH2 in the case of on-site production. A centralised hydrogen supply system involves a higher cost of 3.7–4.8€/kgH2.

factors such as infrastructure development, electricity cost, and policies, which can vary significantly depending on the case study and require a case-by-case analysis.

Authors at [21] have investigated the interplay of HRS for heavy duty trucks with the power system in Germany. Assuming a **100% market uptake of fuel cell HDVs until 2050**, the study identifies an optimum of **137 HRS along the highways** to serve all the vehicles. Of these 137 stations, 96 stations reach the maximum capacity of 30 tons per day, and the average capacity of all stations built is around 28 tons.

The study considers two scenarios which are compared with the basic situation without HRS. Scenario 1 involves optimising the investment in hydrogen refueling stations before optimising the electricity system. The variable cost of electricity is not affected by the station configuration, which is determined by locally minimising the upfront investments at the local level.
In Scenario 2, both the investment for stations and the electricity system are optimised simultaneously. The optimal station configuration depends on the varying costs of electricity supply. In addition, the hydrogen station operator receives a price signal incentivising a schedule conducive to cost-efficient electricity system operation.

As shown in Figure 14 and Figure 15, the total electrification of the transport sector using hydrogen can lead to significant implications for the power system both for demand and generation respectively. The total installed **generation capacity increases by ca. 37 GW (equaling +11%),** whereas the total **electricity demand increases by approximately 60 TWh (+12%).**

		Without HRS	Scenario 1	Scenario 2	Unit
Demand	Total annual demand	509	570	570	TWh_{el}
	Annual electricity demand	509	509	509	TWh_{el}
	Hydrogen refueling demand	0	61	61	TWh_{el}
HRS	HRS electrolyzers capacity factors		76.00	32.00	%
	LCOH		5.36	4.83	euro/kg_{H2}
	- CAPEX share		*18.8*	*28.8*	*%*
	HRS electrolyzers		8.6	20.1	GW
	HRS hydrogen storage		134.0	134.0	GWh
Power system	Total annual system costs (relative)	79.0	88.9	80.2	euro/MWh
	Total annual system costs (absolute)	44.68	56.76	50.17	bn euro/a
	- HRS Electrolyzers	*0.00*	*0.43*	*0.99*	*bn euro/a*
	- HRS storage	*0.00*	*0.26*	*0.26*	*bn euro/a*
	- Other storage (battery, hydro & hydrogen)	*9.0*	*14.4*	*9.3*	*bn euro/a*
	Transmission network expansion cost (absolute)	*0.48*	*0.70*	*0.56*	*bn euro/a*
	Volume of transmission network expansion (relative)	26.1	38.3	30.9	%
	Volume of transmission network expansion (absolute)	12.5	18.3	14.8	TWkm
	Curtailment of renewable generators	10.85	5.46	10.83	%

Figure 14. Summary of annual demand, HRS parameters and power system parameters for the German power system without HRS, for scenario 1 and for scenario 2 [21]

	Without HRS			Scenario 1			Scenario 2		
	Capacity [GW]	Energy [TWh]	Energy [%]	Capacity [GW]	Energy [TWh]	Energy [%]	Capacity [GW]	Energy [TWh]	Energy [%]
OCGT	23	40	7.0	23	40	6.2	22	40	6.4
Offshore wind (AC-connected)	20	77	13.6	21	81	12.7	21	82	13.1
Offshore wind (DC-connected)	34	154	27.3	29	132	20.6	35	160	25.6
Onshore wind	55	135	23.8	81	183	28.6	64	155	24.8
Run-of-river	3	18	3.2	3	18	2.8	3	18	2.9
Solar	183	142	25.0	240	185	29.0	220	170	27.2
Total	**328**	**565**	**100**	**397**	**639**	**100**	**365**	**626**	**100**

Figure 15. Overview of capacities and energy demand per source of renewable energy for the German power system without HRS, for scenario 1 and for scenario 2 [21]

Transmission networks require expansion in both absolute and relative terms compared to today's transmission system volume. Even without HRS, we have observed a considerable line expansion of approximately 12.5% of today's volume. Adding HRS increases the necessary grid expansion to more than 18.3% in scenario 1 and 14.8% in scenario 2, whereby HRS electrolysers can be designed to be operated flexibly.

The final network loading levels are only marginally different across the considered scenarios, as shown in Figure 16. However, adding HRS requires additional network expansion to maintain such loading levels and avoid overloading network capacities.

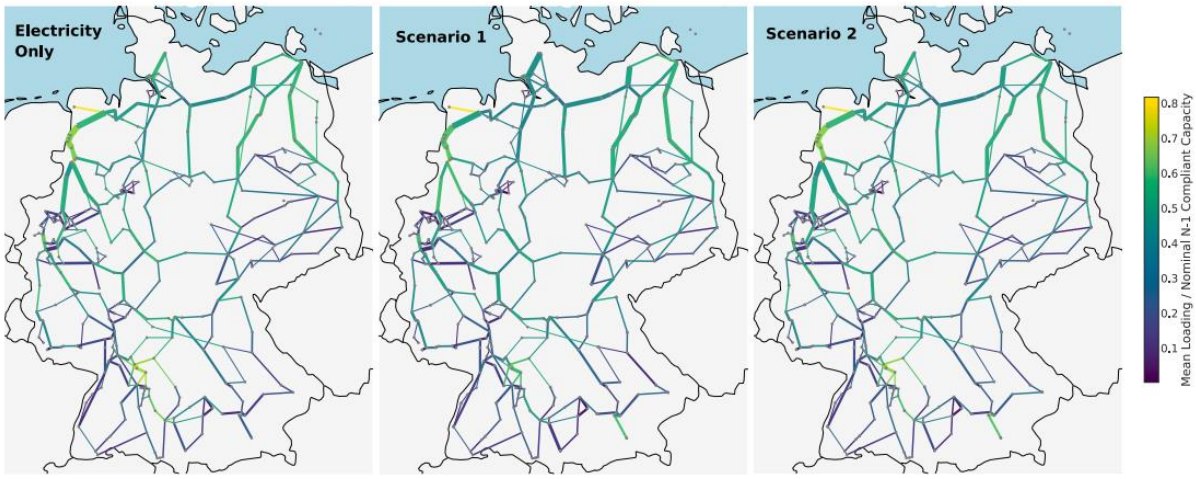

Figure 16. Mean networking loading for scenario without HRS (left), scenario 1 (middle) and scenario 2 (right) [21]

The relative costs of electricity are also more expensive. This is because the most productive sites for renewable energy generation have already been exploited for decarbonising the power sector, and additional demand must be covered by generation at less favorable locations.

Although the assumptions made in this study are very ambitious regarding the market penetration of fuel cell heavy-duty trucks, some interesting trends can be identified:

- A **system-aware planning** that considers both the electricity system and HRS network can save total system **costs; and**
- Even the resulting very limited number of approximately 140 potential new HRS needed to supply the national fleet results in additional **installed generation capacity and network expansion**.

5 Flexibility and financial potential of smart charging and vehicle-to-grid

The significant energy and power demand from HDEVs charging raises challenges regarding their impact on the electricity grids that requires addressing. HDEVs present more predictable patterns compared to cars, especially buses and urban/regional trucks that travel on fixed predefined routes with return to-base operation. This facilitates the prediction of the charging behaviour; in addition, the larger battery size and the higher charging power required by HDEVs might suggest significant potential for flexibility. However, it should be noted that HDEVs are subject to more stringent operational requirements than cars (more limited parking time). Thus, the assessment of the flexibility potential shall always be contrasted against the use mode operation of HDEVs, the cost opportunity from providing flexibility and battery degradation in the event of bidirectional charging.

The ICCT study [22] on the grid impact of BETs in Germany and the United States shows that in 2040, BET energy needs will represent 6% of Germany's electricity production and 3% of the United States'. This does not imply that a 6% and 3% increase in grid capacity will be required as the existing infrastructure can be **leveraged through demand management**.

Generally, the actual charging time is significantly shorter than the actual rest period of 9 to 11 hours as mandated in EU Regulation (EC) No 561/2006. This results in a high potential for charging management for overnight chargers. Figure 17 demonstrates this effect: the maximum charging time of all overnight charging processes is less than 5.5 hours, leaving at a minimum **3.5 hours for charging management**.

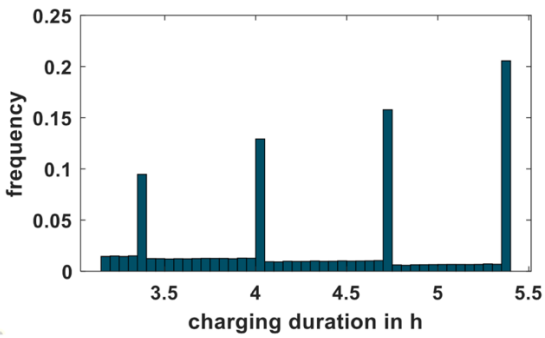

Figure 17. Distribution of charging duration of overnight charging at 150 kW [11]

The management of the charging process can be handled by means of different types of control, which differ for technological requirement and complexity. The simplest form of management consists of time-of-use pricing without automated control, which encourages consumers to defer the charging from peak to off-peak periods. It has relatively low technical requirements for implementation and proves to be relatively effective at delaying EV charging until off-peak hours at low EV penetration levels. More advanced approaches, such as direct control mechanisms, will be necessary as a long-term solution at higher penetration levels. Such mechanisms range from simply switching on and off the charging, to unidirectional control of vehicles (V1G) that allows the charging rate to be increased or decreased, and to the technically challenging bidirectional vehicle-to-grid (V2G), which allows the EV to provide power to the grid in the discharge mode. In addition, vehicle-to-home (V2H) and vehicle to-building (V2B) are forms of bidirectional charging whereby EVs are used for increasing self-consumption of RES on-site or as a residential back-up power supply during periods of high power prices or power outage. Finally, dynamic pricing with automated control better reflects the real-time cost of energy and the grid at hourly or even smaller time intervals. Within this mechanism of control, automated solutions on the consumer side, such as embedded meters and close-to-real-time communication between vehicle, Electric Vehicle Supply Equipment (EVSE) and the grid, are required.

With smart management, the charging process can be adapted to both the conditions of the power system and the needs of HDEV operators, facilitating their integration into the grid. A fleet of HDEVs handles large energy volumes that may act as a potential resource for providing flexibility services to the power system. In general, flexibility services can be distinguished into three main segments in which HDEV fleet can provide their support:

- **Wholesale market**: The cost for electricity purchased by the logistics depot is based on the commercial electricity tariff charged by the energy supplier. If that tariff is time varying or dynamic, it will change over the course of the day, depending on the spot market price on the electricity wholesale market. Consequently, the price reflects how much cheap energy is available on the grid for a given period. These price signals offer incentives to customers to exercise their flexibility, for example, by shifting the timing of EV charging to minimise cost. Varying pricing from spot market can drive the charging process, flattening the peak demand and filling the 'valley' of demand by incentivising late morning/afternoon charging in systems with large penetration of solar, and nighttime charging following for example wind production. Early evening charging that may otherwise increase peak demand would be deferred in this manner.
- **System balancing**: A fleet of HDEVs can adjust their charging levels to provide upward regulation and downward regulation to support the real-time balancing of grids. This can be achieved through both V1G and V2G. With V1G, the charging power can be reduced to provide upward regulation or increased for downward regulation. V2G, in addiction to charging modulation, can provide upward and downward regulation by increasing or decreasing the amount of power supplied to the grid. As an opportunity to provide flexibility, the HDEV could start to charge at a lower value and then provide downward regulation by increasing your consumption profile. The potential for this type of flexibility is addressed in the following section.
- **Congestion management**: A fleet of HDEVs can also provide flexibility at local level by managing their power consumption and eventually increasing their rates of renewable power integration. In this case the physical location of the asset, for example a HDEV depot, is crucial for solving spatial bottlenecks in the electricity network. An attractive market for congestion management solutions is necessary to enable voluntary participation.

Table 8 summarises the possible charging management mechanism, highlighting the type of control and possible uses for flexibility services. These approaches are derived in general for electric vehicles and, from a conceptual perspective, can also be relevant for HDEVs.

Table 8. Type of smart charging approaches from electric vehicles [20]

Type of application	Smart control over charging power	Possible uses	Maturity
Uncontrolled but with time-of-use tariffs	Not applicable	Peak shaving with implicit demand response; long-term grid capacity management (both transmission and distribution system operators)	High (based on changes in charging behaviour only)
Basic control	On/Off	Grid congestion management	High (partial market deployment)
V1G	Increase and decrease in real time the rate of charging	Ancillary services, frequency control	High (partial market deployment), load following
Bidirectional V2G and G2V	Instant reaction to grid conditions; requires hardware adjustments to most vehicles and EVSE	Ancillary services including frequency control and voltage control, load following and short-duration integration of renewable energy	Medium (advanced testing)
Bidirectional vehicle-to-X (e.g. V2H/V2B)	Integration between V2G and home/building management systems	Micro-grid optimisation	Medium (advanced testing)
Dynamic pricing with EVs (controlled)	EVSE-embedded meters and close-to-real-time communication between vehicle, EVSE and the grid	Load following and short duration integration of renewable energy	Low

Even though the research on the HDEVs' impact on the grid is still in its infancy, some authors have started investigating the potential for HDEV smart charging. Table 11 in Annex summarises the key assumptions and key messages from the most recent literature related to charging management and smart charging. From the literature review, some main trends can be identified:

- **The HDEV impact on the grid can be reduced through mitigation strategies**, most of which consist of flattening the peak demand and pricing schemes that encourage off-peak charging;
- **Depot charging**, especially overnight, is the best candidate for implementing **smart charging** strategies, due to the long rest periods;
- Smart pricing for electricity and network use is crucial to creating a cost-efficient and grid-optimal environment. The more prices reflect actual cost, the more transport operators are incentivised to integrate their HDEVs and other flexible resources into the grid in a manner beneficial for all. **Time-varying network tariffs better reflect the actual cost of grid use and thus incentivise smart charging behavior; and**
- Smart charging can offer **financial benefit for fleet operators.**

More research and demonstration with final users are necessary to understand the charging opportunities, costs and framework conditions for enabling flexibility services from HDEV depot charging. In this context, TSOs, in collaboration with fleet operators can play a crucial role, for example, by introducing pilots to gather experience on grid impacts, customer acceptance of time-varying tariff and to assess real flexibility potential.

5.1 Feasibility study by Daimler and TenneT TSO: Flexibility market utilisation options for HDEVs

In the context of flexibility, it is worth mentioning the recent study from Daimler and TenneT [17] (TSO in the Netherlands and large parts of Germany) which investigated the flexibility potential for unidirectional charging of electric trucks (line haul, retail, construction and waste) and buses. The focus is on balancing power[8] services in Germany.

An example of network load with exemplary deliveries of balancing power for the bus use case (149 vehicles) is reported in Figure 12 (grey curve). From 22:45 until 23:45, the delivery of positive balancing energy in the amount of 1280 kWh ('A' in the figure) is illustrated, whereas from 03:45 until 04:45 the delivery of negative balancing energy in the amount of 1120 kWh (C) is shown. 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 delivery of negative balancing energy in C, less energy is required 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 5300 kW (compared to 4180 kW without the delivery of balancing power). The derived flexibility potential is illustrated in Figure 18. The area below (above) the solid (dotted) curve is the maximum available energy that can be offered as positive (negative) flexibility potential. In practice, this amount will not be offered to the market entirely because of uncertainty. If balancing power must 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. Notably, the flexibility potential is highest, up to 6 MW, in the early morning hours, when many buses are connected to the grid and are not fully charged.

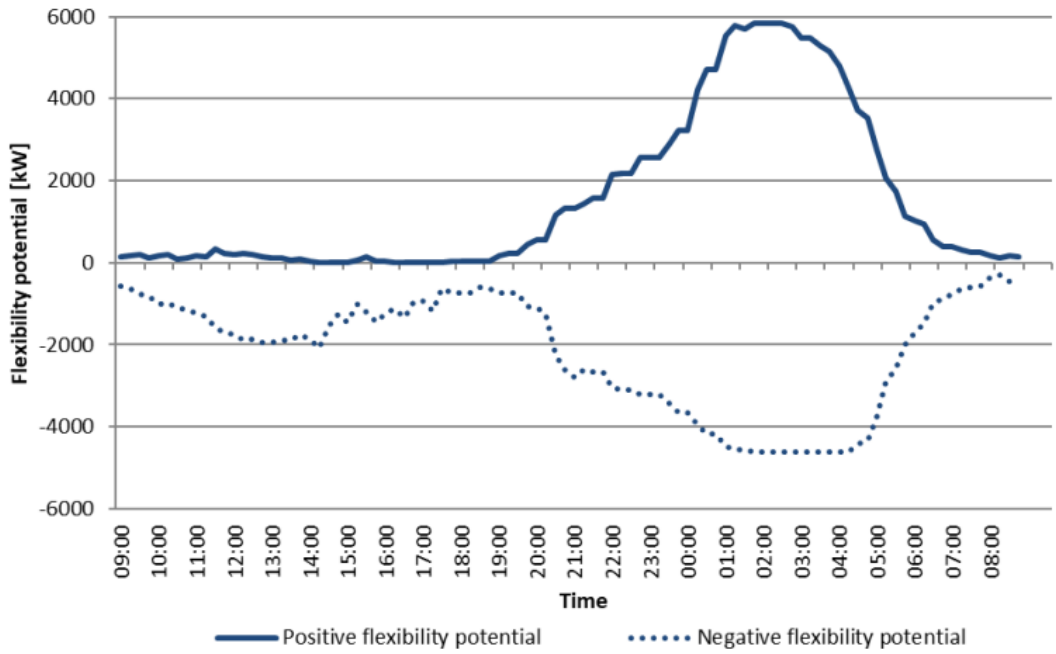

Figure 18. Flexibility potential for the bus use case (149 vehicles) [17]. The reference load in shown in Figure 12

Technically, trucks and buses can participate in all three balancing types: Frequency Containment Reserve (FCR), Automatic Frequency Restoration Reserve (aFRR) and Manual Frequency Restoration Reserve (mFRR). However, FCR and aFRR are most suitable because the charging of batteries can be adjusted quickly, and they have sufficient capacity that can be shifted. The potential for revenues is of paramount importance for the

[8] 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, storage and consumption and, thus, maintain a stable operation of the system.

businesses of operators, which will not use electrified vehicles if there is no positive business case. In practice, depot operators may have electricity contracts with flexibility aggregators who grant remuneration or rebate on electricity price in exchange for provided flexibility.

Figure 19 illustrates the reduction potential for the total cost of ownership [EURct/kWh] for Daimler Truck's customer through revenue from aFRR and FCR provision. The revenue potential is larger for the aFRR market, and the largest revenue results from truck line haul and waste, whereas the bus use case and truck use case retail have the lowest potential. For aFRR, the revenue potential can be very significant given average electricity prices for German industry at approximately 20 EURct/kWh. If transport companies could facilitate flexibility marketing reliably, significant rebates on their electricity costs would be possible.

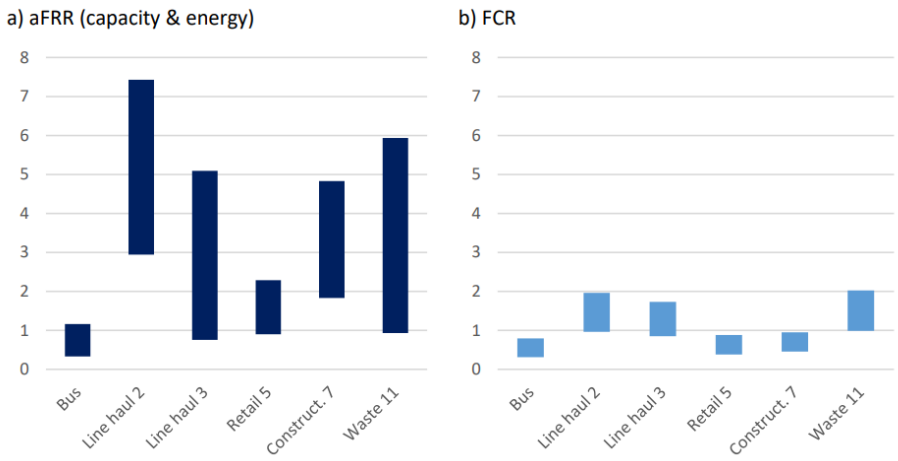

Figure 19. Range of maximum possible revenue per consumed kWh from flexibility segments, in EURct/kWh

The study finally assessed the aggregate flexibility potential for the selected bus and truck use case-specific depots. The flexibility potential (expressed in MW) for TenneT's grid operation is quantified as positive[9] and negative[10]. Table 9 illustrates the aggregated flexibility potentials for 2025, 2030 and 2040, whereas Table 10 offers a more detailed picture of flexibility potential for in 2040. From both tables it can be deduced that typical hours of participation could range between 4 pm to 4 am.

Table 9. Maximum positive (+) and negative (-) flexibility potential for Germany in 2025, 2030 and 2040 [MW] [17]

	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

[9] Positive flexibility potential increases when charging processes can be delayed or slowed down because scheduled charging occurs at a higher power level and there is still sufficient time to fill the battery at a later point in time.
[10] Negative flexibility potential increases when charging processes can be shifted forward or accelerated because scheduled charging occurs at a lower power level than technically possible.

Table 10. Maximum positive (+) and negative (-) flexibility potential for Germany in 2040 [MW] [17]

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**

Focusing on Table 10, **it emerges that the flexibility potential is substantial for the line haul and retail trucks**. Furthermore, **large bus depots could play a substantial role**, especially in the early morning hours. From 16:00-04:00, a theoretical flexibility potential of over 4 GW of positive and 16 GW of negative is assessed. The potential peaks at over 23 GW of negative flexibility between 20:00–24:00 and at over 7 GW of positive flexibility in 00:00–04:00.

Comparing these results with the 2022 demand for 7.1 GW positive and negative balancing power in Germany, all examined use cases combined could have a significant impact on the provision of flexibility services to the grid, considering the expected growing demand.

5.2 Bidirectional charging potential

Bidirectional charging, known as Vehicle 2 grid (V2G), allows for more flexibility potential to the grid. The V2G technology also enables fleet operators to optimise the energy use and saving. However, despite these benefits, the advantages of **V2G technology depend on the use cases**, especially regarding HDEVs.

V2G technology is cost-effective for vehicles with short operating schedules and that can **be parked and connected to the charger for a long period of time during a day** [23]. This can be the example of school bus fleets, which have few transportation tasks. Furthermore, commercial heavy-duty fleets can be another example in which the V2G can be beneficial as they have predefined timetables and routes and are usually parked for long periods at a centralised depot.

Interesting results have been provided by the **California E-Bus to Grid Integration Project** [24] that quantified the costs and benefits of diverse vehicle-grid-integration (VGI) for an urban bus fleet. It emerged that the **use case** and charging requirements of the analysed bus fleet **are incompatible with V2G.** The electric buses charge during **nighttime** hours when grid congestion is **low** and prices are less volatile**.** On the other hand, it was observed that fleets with lower annual use rates present more opportunities for V2G services, especially if behind-the-meter resources are permitted to provide a wholesale market service.

V2G technology is still in its **early stage** of development, **even for passenger EVs**. A step toward V2G has been accomplished with the release of the ISO 15118-20 standard, which defines the communication protocol for bidirectional power transfer between EVs and EVSEs. However, additional actions are necessary to foster the rollout of V2G technology. There is still a need for additional standardisation efforts at a Europe-wide and worldwide level from regulatory committees. Especially in the field of market design and regulation,

new efficient market features are required to proactively involve EV and HDEV owners in V2G solutions. Considering all these factors, it is expected that the utilisation of bidirectional chargers with V2G technology in HDEVs will start at a **slow pace in mid-2024 and reach a mature market by end of 2030** [23]. **One key recommendation is that operators should institute smart charging framework before attempting additional VGI services** [24].

6 Annex A

Table 11. Summary of findings from the literature review on HDEV charging management and smart charging

Study	Key assumption	Key findings
[25]	• Fleet: **10 trucks** operating in urban environments • Charging strategy: at depot • Two charging scenario: ○ Scenario 1: Overnight charging starting at 10:00 p.m., with 22 kW of power, supported by opportunity charging ○ Scenario 2: Overnight charging starting at midnight, with 43 kW of power. The higher power is necessary to compensate for the absence of opportunity charging and the later starting time.	• Cheaper energy prices are not necessarily a reliable basis for cost-optimisation. • Capacity-based **Network charges are the largest cost driver for a typical depot's total cost,** accounting for 42% to 53% of overall charging costs in both scenarios. • **Depots can save up to 15,000 euros per year** in Scenario 1 by extending the trucks' **charging time overnight at lower capacity** and allowing for opportunity charging during the day.
[5]	• Fleet: trucks and vans in Netherlands • Charging strategy: 90% of the energy demand is recharged at overnight depot charging, the rest on the go • Charging scenario: smart charging spreads the required power as much as possible during the night before truck departure. Smart Charging is used as standard at depots, and in safe and secure parking areas.	• An additional 16.7 TWh of electricity will be needed to accommodate the electric van and truck fleets by 2050 (15% of the current national consumption). This raise concerns in more than 500 industrial sites (15% of the total) that are already experiencing congestions or have given advance notices. • **Smart charging could reduce trucks' overnight peak load demand by up to 50% on an average day.**
[26]	• Fleet: up to 40 vehicles of medium-duty (60%) and heavy-duty (40%) • Charging strategy: at commercial facility • Charging scenario: ○ Pricing signal-based charging scheme (PCSC): the charging starts at the off-peak period when energy prices are low, until the required energy is met ○ Smart Charging System determining the optimal charging or discharging rate with the objective of minimising the peak demand of the aggregate load profile at the facility.	• **PSCS shifts** the charging load to off-peak periods, reducing the increase of load in the peak demand. However, the PSCS still introduces significant increases in peak demand. • **Monthly saving in demand charge of up to 54% compared to uncontrolled charging schemes.** • **400 kW reduction in peak demand compared to uncontrolled charging.**
[27]	• Two fleets are modeled: ○ Low: 10 BET ○ High: 100 BET • Charging strategy: at depot overnight • Three charging scenarios: ○ '100 kW immediate' uncoordinated charging ○ '100 kW delayed' allow postponed charging ○ 'Constant minimum power' fleets charge during off-shift periods at minimum power.	• When charging 10 EVs at 100 kW, approximately 94% of the 36-substation modelled do not require upgrades during peak day profile in the immediate and delayed scenarios. This increases to 94%–97 % when the fleet is allowed to charge at minimum power. • When charging 100 EVs at 100 kW, approximately 78%–86% of the substations can satisfy the demand without any upgrades in the immediate and delayed scenarios. This increases to 89%–92 % when the fleet is allowed to charge at minimum power.
[28]	• Fleet: 23 buses • Charging strategy: Overnight at depots or en-route via a pantograph • Two scenarios: ○ 'Uncoordinated charging': e-buses charge until full maximum power allowed ○ 'Coordinated charging': smart charging to shave the load.	• Under the 'coordinated charging', the peaks and valleys of the voltage profile curve are eliminated and the voltages on the bus bars are supported. • Under the 'coordinated charging', the peak power demand is almost halved.

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