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Electric Vehicles Management for carbon neutrality in Europe

Deliverable D2.6
Control strategies for the optimal operation of electrified road freight and public transport

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Disclaimer

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[1] https://ev4eu.eu/

Executive Summary

This deliverable D2.6 "*Control Strategies for the Optimal Operation of Electrified Road Freight and Public Transport*" presents a threefold analysis: First, the status of fleet electrification in Europe is reviewed with a specific focus on the four countries involved in the EV4EU project: Denmark, Greece, Portugal and Slovenia. Second, this deliverable investigates the driving and charging patterns of early electrification pilot projects for fleets in both Denmark and Slovenia, analysing the driving demand and flexibility potential of buses and garbage refuse trucks. Third, the deliverable presents an innovative framework for managing charging and discharging operations in electrified freight and public transport systems using smart charging and planning technologies. The deliverable addresses the complex requirements of fleet operators by developing smart control strategies that optimize energy usage, prioritize operational needs, and leverage renewable energy integration while providing services targeted at grid stability.

The proposed methodology incorporates data-driven insights from EV charging profiles, including user behaviour, vehicle specifications, and charging station capabilities. By integrating real-time data with advanced optimization algorithms, the methodology accounts for diverse fleet scenarios such as variable arrival states-of-charge, travel schedules, parking and idle conditions. The control strategies have been validated through simulation studies based on real data from Denmark, analysing scenarios with and without the availability of V2X functionalities. Results demonstrate the robustness of the methodology in managing fleet priorities, ensuring optimal states-of-charge (SoC) and balancing the energy needs. In scenarios involving garbage refuse trucks, the methodology addresses specific challenges such as depot parking rules, extended travel needs, and regulatory frameworks in the country of investigation. V2X capabilities enable bidirectional energy flows, allowing for strategic discharging of the trucks' batteries to support the grid during peak demand or when renewable energy is abundant. This ensures that energy flexibility is maximized without compromising the SoC requirements of critical vehicles.

The proposed optimization model features a rolling-horizon procedure for limiting the operational foresight in the operational planning. By doing so, the modelling outcomes provide a realistic picture of the potential cost reductions that bidirectional charging capability may bring, either by adapting to price variations or renewable energy availability. Additionally, the methodology ensures that critical operational constraints are respected, even in cases where V2X discharging is employed.

In conclusion, the deliverable highlights the potential of bidirectional smart charging technologies to help operators manage electrified freight and public transport fleets, considering both price arbitrage and ancillary service provision. The proposed modelling framework provides a scalable and adaptable solution that aligns with the operational realities and energy transition goals of fleet operators.

Table of Contents

List of Figures

List of Tables

Acronyms

ARC	Amager Resource Centre
BSP	Balance service provider
CCS	Combined charging standard
ct.	Cents
DSO	Distribution system operator
EV	Electric vehicle
FCR-D	Frequency containment reserve for disturbance operation
FEC	Full equivalent cycle
HDV	Heavy-duty vehicle
MCS	Megawatt charging standard
NECP	National Energy and Climate Plan in Greece
PA	Price arbitrage
PCC	Point of common coupling
PES	Production electricity supplier
PV	Photovoltaic
RAP	Regulatory assistance project
SOC	State-of-charge
SOH	State of health
ToU	Time of use
tsd.	Thousand
TSO	Transmission system operator
V2G	Vehicle-to-grid
V2X	Vehicle-to-everything

1 Introduction

To achieve a fully sustainable transition to a carbon-free transportation sector, there is a strong necessity to shift from fossil-based internal combustion engines to electric mobility [1]. Not only passenger electric vehicles, which experience a steep increase in sales over the last years, play a role in this transition, but especially commercial freight and public transport as they are responsible for a large share of emissions in the transport sector. According to the European Commission, over a quarter of carbon emissions originate from heavy-duty vehicles (HDV), while only constituting 2.5% of the road fleet [2][3]. The European Commission set ambitious targets to lower the carbon intensity for heavy-duty vehicles [4], aiming at a 45% reduction in 2030 and a 90% reduction in 2040, compared to the levels of 2019. Electric trucks and buses will hence over time become a necessary asset for complying with European regulation.

For managing the upcoming increase in electric HDV deployment and showcasing the potential benefits to involved stakeholders, necessary control strategies need to be in place for securing an optimal operation of electrified road freight and public transport. In this deliverable D2.6, we assess the state-of-the-art of the HDV electrification in Europe, present insights from electric trucks and buses already in operation in the demonstration countries of EV4EU, as well as provide a methodology for an optimal operation of electric HDV.

1.1 Scope and Objectives

Deliverable D2.6 focuses on HDV electrification and fleets management, addressing electric buses and freight transport. It aims to develop realistic and innovative solutions that optimize charging and discharging operations while balancing the needs of fleet operators, employees, and users. Central to the task is the design and deployment of next-generation electrified HDV with minimal impact to user experience and to the electric grid. The possibility of planning and modulating the charge of electric vehicles, V1G, and the potential of V2X will reduce infrastructure costs, integrate renewable energy sources, and adapt to grid constraints.

By leveraging user behaviour analysis and operational data, the deliverable aligns EV charging management with travel patterns and parking or idle conditions. An example is a co-simulation environment that combines electric buses, power distribution networks, and charging management strategies to evaluate and refine decision-making processes. This holistic approach supports both the technical and operational integration of smart charging in urban and corporate ecosystems, fostering efficient and sustainable mobility.

The primary objective is to create a comprehensive framework for managing EV fleets through innovative algorithms and decision-support tools. These solutions will optimize shared charging services for company fleets and external users, incorporating driving behaviour patterns such as arrival state-of-charge, travel schedules, and battery characteristics. By integrating these insights, the deliverable aims to design tools that address diverse operational contexts, including passenger transport and freight logistics.

A core focus is on developing charging management strategies that enhance grid stability, minimize energy costs, and extend battery life, while maintaining user satisfaction and operational flexibility. This includes creating systemic designs that treat the specific traffic region and vehicles as a shared resource where electrification is a central point.

The deliverable also emphasizes the simulation and validation of strategies in a co-simulation environment. This environment will model traffic flow, grid operations, and recharging infrastructure, ensuring the scalability and adaptability of proposed solutions. Finally, the project will evaluate sustainable business models that improve user experience and operational efficiency, contributing to the goal of sustainable mobility.

1.2 Structure

The deliverable is structured as follows. In Chapter 2, we present the state-of-the-art progress of the road freight and public transport electrification in Europe. Recent datasets are summarised and analysed in Chapter 3. A new methodology for the optimal operation of electric trucks in the context of vehicle-to-grid are described in Chapter 4 including numerical results. Chapter 5 concludes this deliverable.

1.3 Relationship with other deliverables

The present work builds up on the previous deliverables of WP1 and WP2. The EV charging profiles used as input data in the proposed electric vehicle management algorithm were developed in the *D1.2 of the EV4EU project: Impact of V2X in energy and power systems* [5]. The EVs and charging station (CSs) power limitation used as input data in the proposed energy community management was adapted from the D2.1 of the EV4EU project: Control Strategies for V2X Integration in Houses [6] and from *Smart Electric Vehicle Management vs. Battery Storage for Energy Communities: A Case Study from Denmark* [7]. The company demand data was adapted and expanded from the one used in the *D2.2 of the EV4EU project*: *Control Strategies for V2X Integration in Buildings* [8]. The information of a parking lot cluster and V2X potentials were taken from *D2.3 Optimal management of V2X in parking lots* [9].

2 State-of-the-art of fleet electrification in Europe

Out of the 336 million vehicles in Europe, around 90 million belong to the group of commercial vehicle fleets. These split into passenger cars (50%), light commercial vehicles (41%), buses (8%) and heavy-duty vehicles (1%). By 2030, the overall stock of commercial vehicles is expected to increase to over 100 million. On EU roads, heavy vehicles weighing more than 12 tons account for the largest share of greenhouse gas emissions, constituting more than 25% even though the vehicle stock is relatively small. This is one reason for the European Commission to recently introduce stricter CO_2 emission standards for heavy-duty vehicles, aiming for a reduction of 45% by 2030 and 90% by 2040, compared to 2019 levels. The road transport has over the last years steadily increased its importance in terms of ton-kilometres for freight transport in Europe, reaching approximately 25% in 2022 [10]. In 2021, 13.65 billion tons of goods were transported in the 27 EU states [11].

In terms of fleet electrification, passenger cars and buses are generally leading the progress. Electric vehicles (EVs) are making up 35% of new passenger car registrations and 21% of bus sales in 2022 on a European level. Light commercial vehicles are following this trend with 12% of new sales being electric . Yet, the electrification of heavy-duty commercial vehicles is lagging significantly. Only 1% of new vehicles sales have been electric in 2022 in Europe. This slow adoption to e-mobility is due to high upfront costs, limited commercial options although they become more available, and operational complexities. Fleet electrification still represents only about 1.4% of the total commercial fleet, with only 0.1% of trucks being electric by the end of 2022 [12].

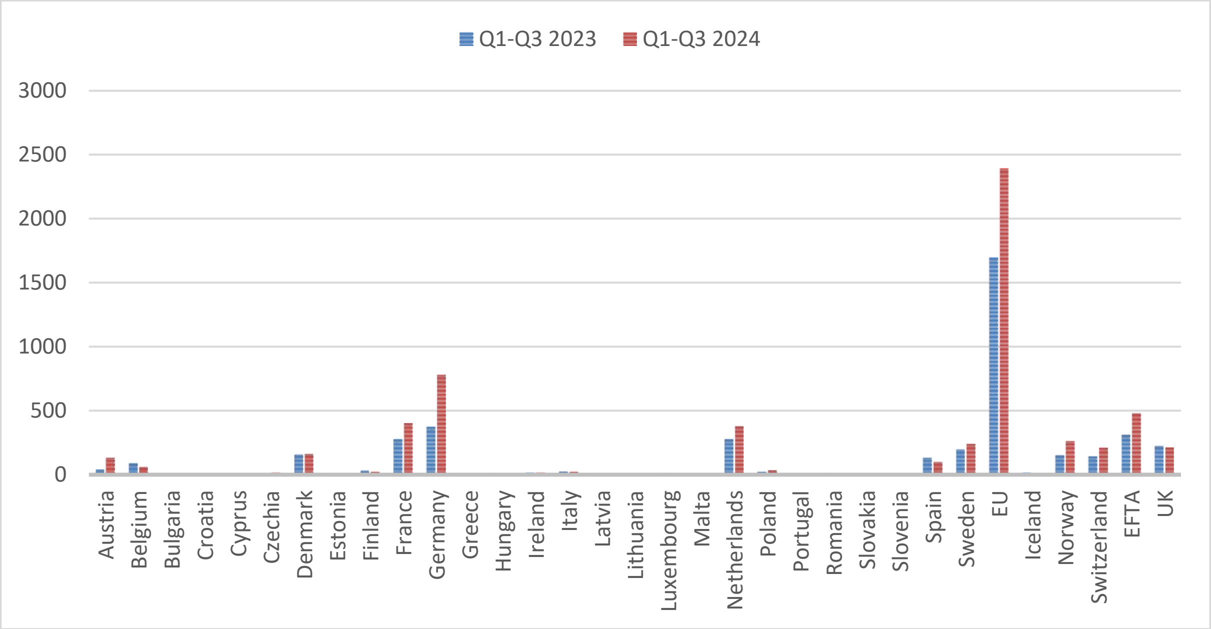


Figure 1: New heavy-duty truck registrations in Q1-Q3 2023 and 2024 across European countries including battery electric and plug-in hybrids.

Figure 1 details the current progression of heavy-duty truck registrations in 2023 and 2024, showing an increasing trend in new electric truck registrations, yet at small increments for most countries with a change of 20-50 % compared to the previous year. Exceptions being Germany and Norway that are almost doubling their numbers, and Austria with three-fold increase of registrations, see Figure 2.

A similar picture can be drawn for medium-duty trucks between 3.5 and 16 tons, with overall more registrations and some opposing trends. France, for instance, recorded a steep decrease in electric truck registrations of these sizes, as did the Netherlands, as can be seen in Figure 3.

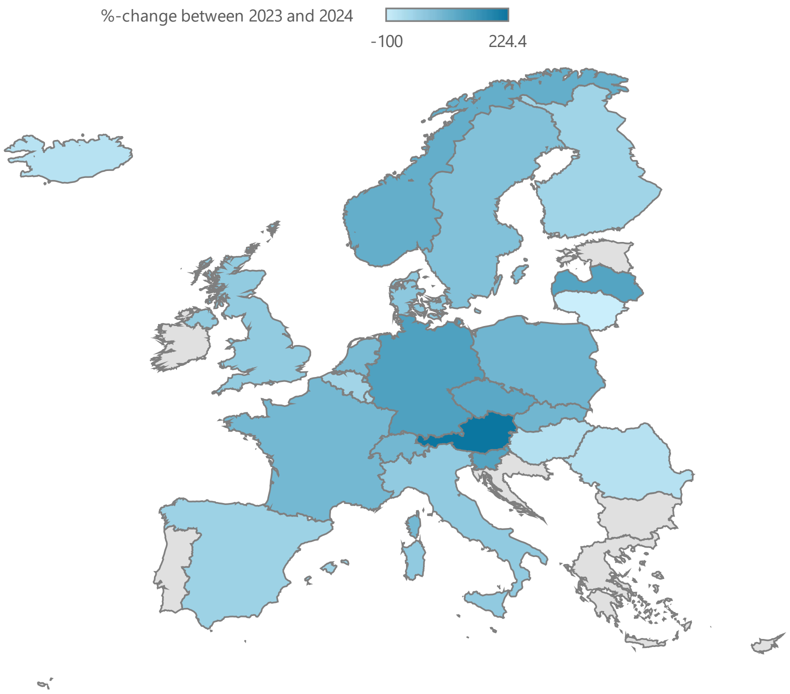


Figure 2: Percentage change between heavy-duty truck registrations in 2023 and 2024 in European countries. A value of -100 % means that there were no registrations in 2024, while some in 2023. Austria increased their electric truck registrations by 224% compared to 2023.

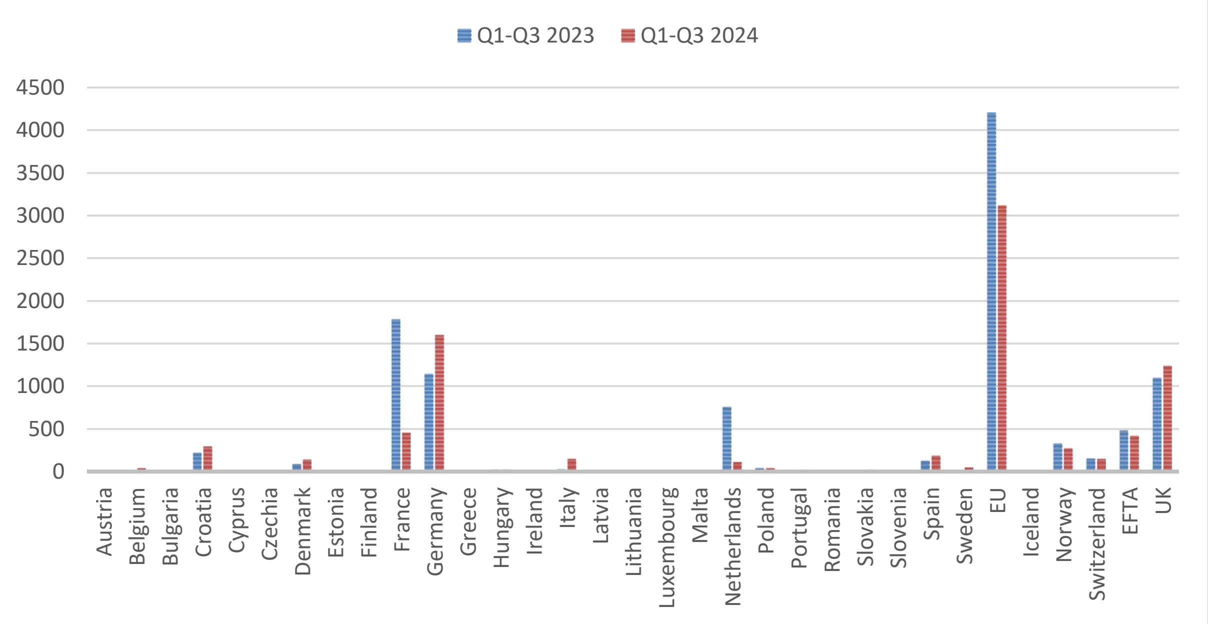


Figure 3: New medium-duty truck registrations in Q1-Q3 2023 and 2024 across European countries including battery electric and plug-in hybrids.

The targets for the fleet electrification in Europe are ambitious, and they require a huge upscaling of both technology development, research and infrastructure rollout. By 2030 on a European level, fleet electrification is envisioned to cover 50% of the total EV energy demand. To meet EU net-zero targets, a drastic scale-up in the electrification efforts is required. This entails electrifying 4.4 million light-duty commercial vehicles, as well as 0.3 million trucks and buses. Considering the status in different European countries, these targets are difficult to achieve, and a strong coordinated effort across the continent is needed [12].

The ICCT-commissioned study [14] finds that battery-electric and fuel-cell trucks could feasibly decarbonize Europe's road freight sector by 2050 with the right policy support and infrastructure investment. Although CO2 emissions from freight are growing rapidly and current policies for heavy-duty vehicles lag those for passenger cars, the report highlights a path to reduce emissions by up to 90%. Battery-electric trucks are ideal for short-haul city deliveries, while the study suggests that fuel-cell trucks are better suited for long-haul routes. However, new infrastructure could make battery options viable for longer distances as well and looking at recent industry developments, purely electric trucks seem to win the upper hand.

The EV charging industry is ramping up to meet this growing demand by developing ultra-fast chargers and the upcoming megawatt charging standard (MCS), expected to be industry-ready by 2025. Infrastructure initiatives, such as *Milence*'s goal of installing 1,700 heavy-duty charging points across Europe, aim to ease fleet managers' concerns over charging access. While the high initial costs of electric trucks may deter some, subsidies, toll fee reductions, and lower total cost of ownership by 2025 are creating strong incentives for electrification, setting the stage for a zero-emission heavy-duty future in the EU [15][16].

Cost projections show that zero-emission trucks, while currently more expensive than diesel, could reach cost parity by 2030 due to fuel savings. The study suggests that if alternative vehicles, including electric and fuel-cell trucks, could handle 90% of the EU's freight ton-kilometres by 2050, emissions from truck transport would decrease by 90%, aligning with long-term climate goals [14].

The further sections of this chapter provide the state-of-the-art overview of the fleet electrification in the respective countries involved in the EV4EU project: Denmark, Portugal, Greece and Slovenia.

2.1 Status in Denmark

The electrification of the heavy transport has started but is to date still in its initial stages. Today, there are about 43,000 trucks and 375,000 commercial vehicles on Danish roads [17]. Diesel is still the predominant fuel for both commercial vehicles and trucks, and the latter account for around a quarter of all carbon emissions on Danish roads [18]. Smaller lorries tend to drive short distances with goods in and around the big cities, while larger lorries tend to drive longer distances and often motorway journeys. For example, trucks weighing 40 tonnes or more make up only a third of the total truck fleet in terms of numbers but over 60% of CO2 emissions.

While the shift to electric vehicles in passenger transportation already demonstrates exponential growth [13], the figure is less bright for electric trucks. As of May 2024, electric trucks make up around 1% of the total truck fleet in Denmark. Semi-trailer trucks with a weight more than 12 tons and one trailer attached, transporting goods within Denmark, constitute around 33 per cent of trucks in Denmark, but account for about 67 per cent of the kilometres driven. The major driver for the transition is among others on charging infrastructure, specifically the possibility to fast charge, the regulatory framework including taxes and duties and incentives for the industry to go through with the transition. Denmark invests around 700 DKK million in a roll-out plan for 25 charging parks with 175 fast-charging stations, which are envisioned to be in operation by 2030 [19].

In the first quarter of 2023, the number of electric trucks sold more than quintupled compared to the first quarter of 2022, while the number of newly registered electric commercial vehicles has increased from 355 units in 2022 to 615 units in 2023, constituting a market share of around 10% in sales. With respect to trucks, there was a growth of 6.3% in March 2023 compared to the same month the year before. While this is only a small increase, the development continues in the right direction [20].

In the first quarter of 2023, diesel is still accounting for a market share of 89.1%. Yet, this market share has decreased by 9.3 percentage points compared to the first quarter of 2022 [20], due to the accelerated electrification of trucks. In the first quarter of 2023, 85 new electric trucks were registered, bringing the market share of electric truck sales to 6.5%. In total, as of September 2024, around 600 trucks are running on electricity, of which the most are moving trucks with local distances.

With respect to the project's demonstrator, the island of Bornholm where electrification for electric vehicles is already well underway, heavy-road transport (lorries, tractors, etc.) is experiencing some more uncertainty. The market is not mature enough to indicate the necessary investments and specifically their costs. Establish a forum to facilitate the transition of heavy transport by promoting access to knowledge and networks. The forum's objective is to support alignment among key stakeholders on Bornholm. Additionally, it is under consideration to form collaborations across municipalities, potentially under the leadership of *Gate21*. The initiative will be led by the Centre for Regional Development, IT, and Secretariat (Development) in collaboration with the Centre for Properties and Operations. Bornholm Energy and Forsyning (BEOF) are also invited to participate. Bornholm has the goal to become completely carbon-neutral in 2040. In 2019, Bornholm emitted around 120,000 tons of CO_2 of which around 30,000 tons are originating from commercial vehicles, lorries and tractors. The municipality's goal is to transition the commercial vehicles by 2030 and lorries and tractors by 2040 to fossil-free fuels [21].

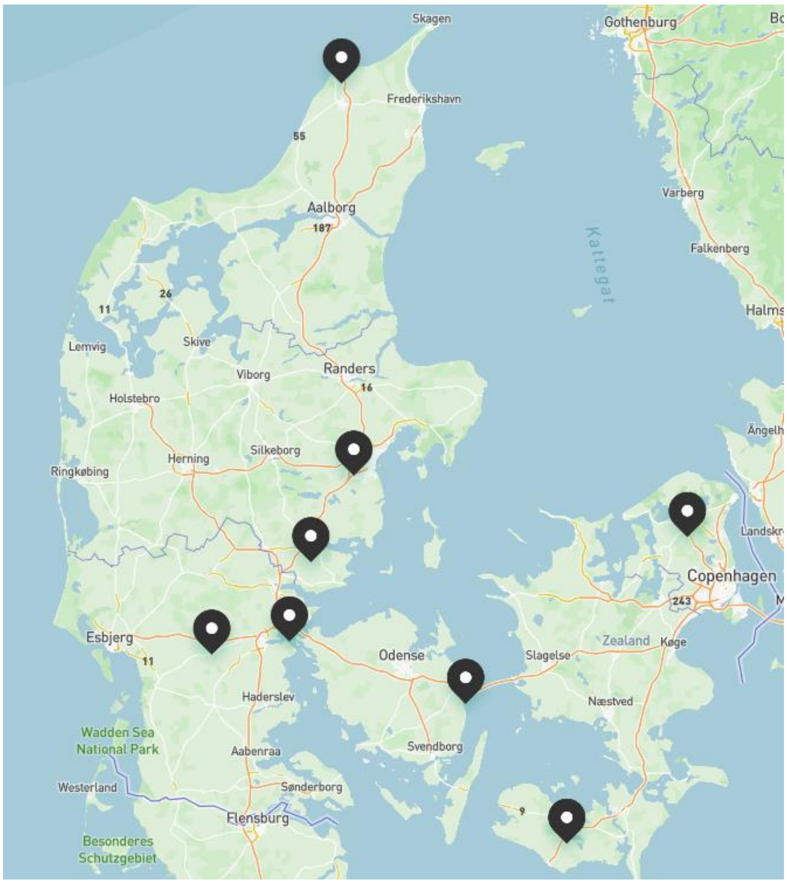


Figure 4: Charging points in Denmark which are suitable for heavy-duty trucks [22]. In total 34 charging outlets with charging power between 180 – 400 kW.

2.2 Status in Portugal

Portugal has made gradual but promising progress in adopting HDVs, focusing on public transportation fleets such as buses and trucks. With environmental concerns and EU policies driving efforts to reduce carbon emissions, the shift toward electric HDVs is aligned with broader goals for carbon neutrality by 2050.

Public transportation, especially electric buses, has led Portugal’s HDV electrification efforts. In 2018, Portugal began integrating electric buses, with 51 vehicles in operation, and several cities have since expanded their fleets. Lisbon’s public transport operator, Carris, aims to reach over 100 electric buses by 2025, setting an example for other municipalities. By 2024, electric buses represented over 8% of new bus sales in Portugal, although this accounts for only about 4% of the total bus fleet, slightly below the European average of 12.7% [23].

The adoption of electric trucks has been slower. In 2018, there were only 10 electric HDVs registered, growing to 30 by the end of 2023, representing less than 2% of new HDV sales and a very small share of the total fleet. Challenges such as high purchase and maintenance costs, limited charging infrastructure, and the downtime required for charging have hindered widespread adoption, particularly for long-haul logistics. Charging points are still largely limited to specific strategic corridors, which can disrupt logistics schedules and pose operational inefficiencies.

Government support through financial incentives and infrastructure development is expected to accelerate HDV electrification. Subsidies for vehicle purchases and grants for charging stations aim to ease the financial burden on businesses, while investments in charging infrastructure along key transportation corridors may address operational challenges for electric trucks.

Portugal’s ongoing efforts, despite current limitations, mark a shift toward a more sustainable transportation future. Public and private support is key to overcoming existing challenges, and the continued development of electric HDV infrastructure will be essential for Portugal to meet EU decarbonization targets and contribute to global efforts against climate change. The electrification of HDVs is motivated by both environmental goals and the potential for long-term economic benefits, as Portugal seeks to improve air quality, reduce fossil fuel dependency, and stimulate green technology growth [24][25].

2.3 Status in Greece

The Ministry of Environment and Energy in Greece recently unveiled the updated National Energy and Climate Plan (NECP), laying out the nation’s strategic goals for energy efficiency and emissions reduction [26]. This roadmap aligns with the broader European objective of reaching climate neutrality by 2050, with a significant benchmark in 2030. The NECP sets forth ambitious targets, particularly in the transportation sector, which is currently the second-largest source of greenhouse gas emissions in Greece.

Despite progress toward fleet electrification, Greece faces notable challenges in meeting the NECP’s stringent 2030 and 2050 targets, particularly given the country’s current vehicle demographics. With passenger cars and trucks averaging 17 and 23 years old, respectively, well above the EU averages, the efficiency and emissions profile of Greece’s fleet remains problematic. The limited adoption of electric vehicles in medium and heavy-duty truck segments is also telling; only two electric heavy-duty trucks (> 16 t) were registered out of 425 new units last year, and none were registered in the medium-duty category [27]. This lag can be attributed to the high upfront costs of electric heavy vehicles, alongside infrastructure limitations that hinder deployment, especially in areas with extensive logistics needs.

The NECP acknowledges these gaps and outlines a series of corrective measures, including expansion of charging infrastructure, financial incentives for vehicle replacement, and the introduction of electric buses. The deployment of 250 Yutong electric buses in Athens and Thessaloniki since summer 2024 is expected to significantly enhance the share of electric public transit and could serve as a pilot for broader fleet upgrades across urban centres. Meanwhile, a gradual increase in plug-in electric light vans, which constituted 9.8% of new light van registrations in 2023 [27], indicates a shift in the urban logistics sector towards lower emissions. The NECP introduced a target for light trucks, aiming for 40% of new registrations to be electric by 2030, and includes efforts to increase electrification in public transit. These goals would result in a dramatic increase in EVs, projecting a rise from 30,000 electric vehicles currently on the roads to over 460,000 by 2030. However, achieving widespread adoption in heavier-duty transport will require substantial advancements in battery technology, along with policy support to address cost barriers.

The NECP thus represents a foundational shift, emphasizing decarbonization across transport and other high-emission sectors to meet climate neutrality goals. Success in this effort will hinge on continuous investment in both technological infrastructure and supportive policy frameworks to facilitate a systemic shift toward low-emission mobility. Additionally, meeting the NECP's targets will require enhanced collaboration across public and private sectors, as well as public awareness initiatives to drive behavioural shifts in vehicle ownership and usage. Though Greece's pathway to climate neutrality presents significant logistical and economic challenges, the NECP sets a clear trajectory for advancing transport sustainability and aligns the country with broader EU climate directives.

2.4 Status in Slovenia

In Slovenia, the transition to electric heavy-duty vehicles and public transportation is still in early stages. Overall, Slovenia has approx. between 2000 – 3000 buses, coaches, minibuses and trolley buses [28]. Of this stock, there are approx. 700 city buses while the remaining are intercity and mini buses. The main activity in the electrification process are several pilot projects to investigate the use of electric buses for designated routes. As of 2024, Slovenia has 2-3 projects ongoing or completed that involve the deployment of electric buses with 10-12 meters and some more with smaller buses up to 8 meters.

One of the key projects is in the city of Maribor with the acquisition of two 12-meter electric buses featuring "panto down" charging technology. In early 2024, Maribor expanded this project by adding two more 12-meter electric buses with the same technology. Meanwhile, the Municipality of Kranj has introduced eight 12-meter electric buses into its public transport network. In TD Gorje, two 9-meter electric buses are now in operation, primarily serving local transportation needs. Other small-scale projects have brought additional mini electric buses, typically up to 8 meters in length, into regional and local transit systems. Altogether, these efforts mean that Slovenia currently operates a fleet of 14 electric buses for city and longer-distance transport, along with approximately 10 mini electric buses dedicated to local routes or specialized services.

Moving forward, Slovenia has set ambitious goals to expand its electric HDV fleet over the next two years. These include bringing in eight more electric buses with panto down charging technology, along with 25 electric buses for wider city use.

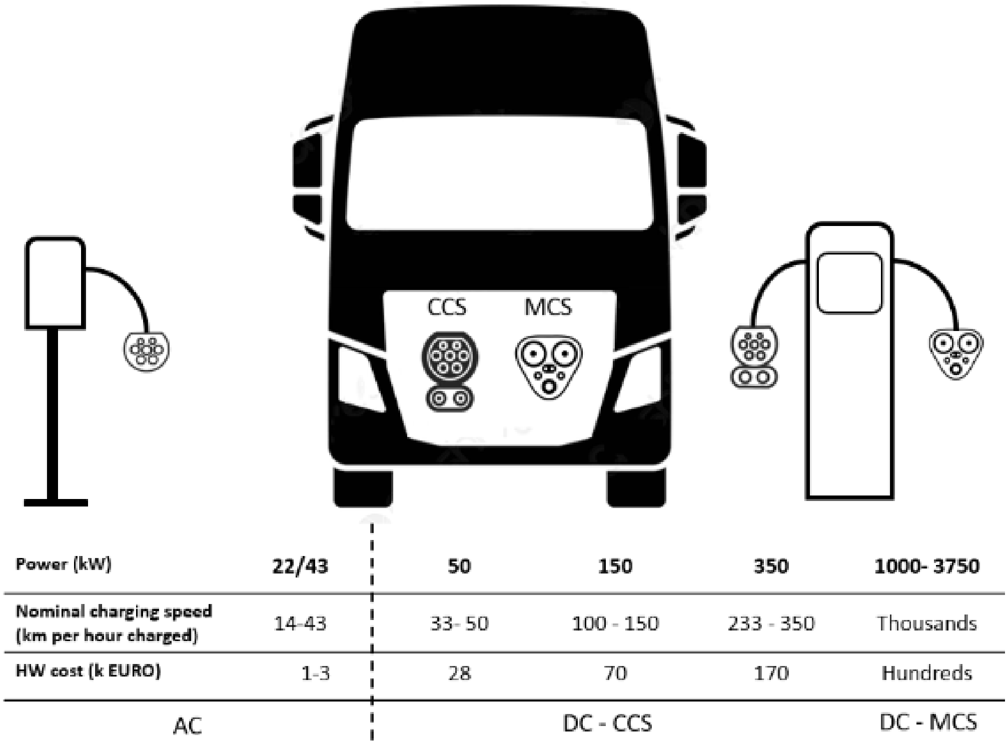
In contrast to public buses, Slovenia's adoption of electric trucks remains limited. As of 2023, there are approximately 10 electric trucks in operation across the country which represents only an insignificant fraction of the total number of trucks (>100,000) in the country. However, Slovenia's long-term forecasts, as outlined in the 2019 NIR report [29], suggest a significant increase in alternative fuel usage in both buses and HDVs by 2030. The report anticipates that the share of alternatively fueled buses will reach 41.25% of the total bus fleet, while alternative fuel HDVs are projected to comprise 28.1% of the HDV fleet by the same year. These targets underscore Slovenia's commitment to reducing greenhouse gas emissions and aligning with broader European Union goals for cleaner transportation.

To support these transitions, Slovenia has begun investing in the necessary infrastructure for electric heavy-duty vehicles. Currently, charging infrastructure is typically installed at the time of vehicle delivery to ensure fleet owners have secure and dedicated charging access. Slovenia's first major public project for large-scale HDV charging is being led by ELES, which aims to develop mega-charging hubs near highway corridors. These hubs are designed to provide 20–40 MW of available charging capacity per location and are funded in part by the EU's IPE *GreenSwitch* project [30], with a demonstration site planned.

2.5 Charging technology and capabilities

To support the electrification of long-haul trucking in Europe, policymakers must address the challenges of establishing high-capacity charging infrastructure along major highways, starting in 2025 under the EU's Alternative Fuels Infrastructure Regulation [31]. Generally, the charging technologies can be separated into AC charging with lower charging power values up to 43 kW, 22 kW being the standard, which is likely to be solely feasible for light-duty commercial vehicles, to DC charging with either CCS (Combined Charging System) or MCS (Megawatt Charging System). The CCS, and specifically the CCS Type 2, is an established standard that can reach 700 kW peak power and possibly reach a maximum of 1MW, but due to the size limitation of the cable and of the plug, it needs a specific cooling system for delivering power from about 350 kW (800 V and 437 A) and above or it will require 2 different inlet for reaching the highest charging power. The MCS is a new standard for HDV and it can support up to 1250V and 3000A, with a much bigger plug and cable size, resulting in a peak power of 3750 KW [32] and it is still under development.

Most depot charging for electric trucks currently uses CCS Type 2 inlet, following the IEC 62196 standard, allowing compatibility with both AC and DC chargers [16]. To meet the heavy transport sector's higher power needs, especially for long-haul trucking with short layover times, a new MCS standard is being developed, aiming to provide the high-speed, high-power charging essential for long-distance routes and quick turnaround at destinations. Charging power, speed, and cost can vary widely, with maximum speeds typically lower than nominal values, especially at higher power levels, as shown by ACEA estimates in Figure 5 taken from [16].



Power (kW)	22/43	50	150	350	1000- 3750
Nominal charging speed (km per hour charged)	14-43	33- 50	100 - 150	233 - 350	Thousands
HW cost (k EURO)	1-3	28	70	170	Hundreds
AC			DC - CCS		DC - MCS

Figure 5: Illustration of AC and DC charging for heavy-duty vehicles using CCS and MCS inlet. Charging speeds are based on an assumed consumption of 1-1.5 kWh per km, the maximum/nominal charging power and cost provided by [33]. The figure is taken from [16].

RAP's analysis [31] reveals significant cross-border cost disparities in charging due to varying national grid regulations and taxation, which could lead to "charging tourism," where fleet operators seek out cheaper charging sites. This behaviour may strain local grids in low-cost areas while leaving high-cost regions underutilized, raising overall electricity system costs that burden consumers. To prevent such inefficiencies, RAP recommends policies that coordinate network pricing, taxes, and levies across EU Member States to ensure an even distribution of megawatt charging infrastructure.

When it comes to the chargers' costs, ABB provided a list of prices for their DC charging products according to the required power level. Starting with the ABB Terra DC Wallbox 24 kW CCS2, this model is designed for settings that benefit from moderate DC output, priced at approximately €6,000 (+/- €1,000), excluding VAT. The Terra Wallbox is optimized for environments where space and power capacity are limited, yet DC fast charging remains essential. This could for example be the case in depot for rather light-duty commercial vehicles or vans.

For installations that require higher energy throughput, the ABB All-in-One DC Chargers provide scalable options across several power levels. The 50 kW model, priced at €18,000 (+/- €1,000), offers increased output suitable for moderate-demand locations, while the 90 kW and 100 kW models (priced at €40,000 and €50,000 with a variance of +/- €3,000) are ideal for sites where a faster energy transfer rate is beneficial. These models allow for faster charging by delivering more power within shorter time frames, balancing performance with operational cost.

For high-demand environments, ABB also offers a 180 kW model at €60,000 (+/- €3,000) and a 350 kW model at €80,000 (+/- €5,000). These units are designed for rapid energy transfer, supporting applications where minimizing charging downtime is critical, e.g., along highways where drivers need to stop to adhere to mandatory breaks in long-haul services. Notably, the 1 MW charger is currently only in pilot testing and is not yet commercially available. This ultra-high-power option aims to support the rapid scaling of high-capacity electric vehicle or truck infrastructure as demand evolves.

3 Fleet data

In this section of the deliverable, we summarize the results of our data collection and analysis from different heavy-duty road freight and public transportation fleets in the project's demonstrators. More specifically, we present data insights for Danish electric buses that operate in the Danish region Zealand originating from an extensive data set from Movia in Section 3.1. Afterwards, we present data from Danish electric garbage refuse trucks that operate in the Copenhagen area in Section 3.2. In Section 3.3, an extensive data set from a Slovenian pilot project for electric buses is analysed with respect to indicating how far smart operational strategies may be deployed.

3.1 Bus data (DK)

Movia is a public company that works for increased mobility across the region of Zealand in Denmark. Movia's objective is to be fossil-free by 2030, with 50% of its fleet, comprising approximately 1,300 buses, to be electric. As a public transport authority, Movia neither owns nor operates these buses but is responsible for handling tenders for bus operations for private operators. In the tender conditions, Movia establishes the requirements for bus equipment and operations. The data presented here belong to tenders completed up to the year 2023. This section of the deliverable aims at characterizing the public electric buses in Denmark and the range of flexibility that can be leveraged by their chargers.

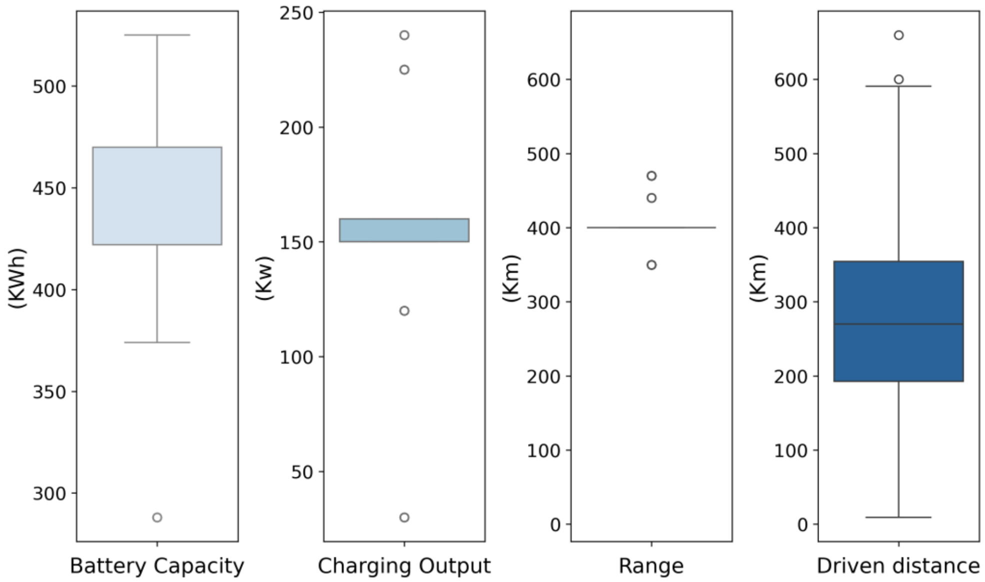


Figure 6: Denmark's public bus fleet characteristics.

By the end of 2023 the number of operational electric buses was 404. Here, operational refers to the number of buses required for service. Figure 6 provides an overview of the fleet's features, including data from 380 buses identified as operational on a typical weekday. As illustrated, the average battery capacity across the fleet is 430 kWh per bus, with minimum and maximum capacities recorded at 288 kWh and 525 kWh, respectively. Two thirds of these buses utilize lithium iron phosphate battery chemistry, while 23% are equipped with nickel manganese cobalt batteries and the remainder have nickel cobalt aluminium chemistry. The average charging power output for the fleet is 150 kW, with low variability indicating consistency across charging capabilities.

Tender requirements specify all charging must take place at the operator's garage facility. Only one exception allows for opportunity charging for buses equipped with the smallest available battery capacities. On an average weekday, buses are required to cover approximately 277 km to fulfil public transport demands of their routes. This range falls within the fleet's maximum range capability of 400 km under optimal conditions, such as new battery and moderate external temperatures. Nevertheless, some routes demand distances up to almost 600 km. In these cases, backup buses are deployed to complete operations.

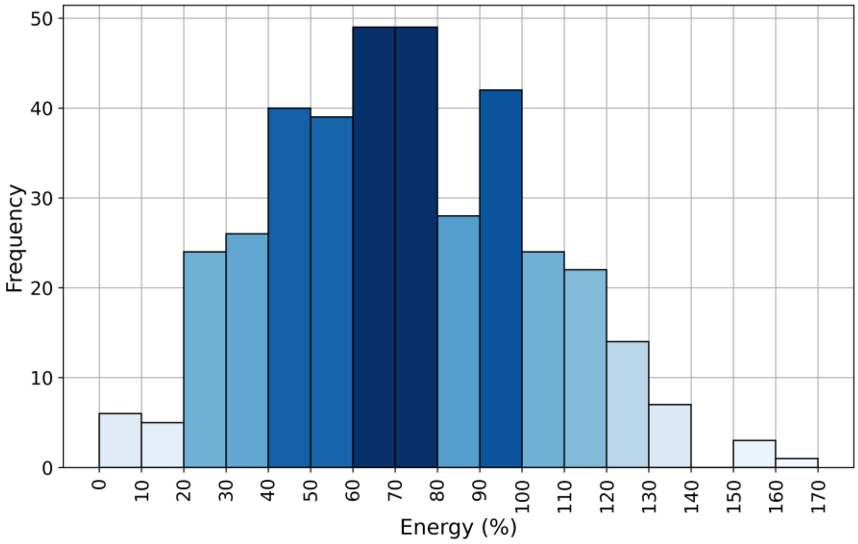


Figure 7: Energy usage as a percentage of nominal battery capacity per bus during a weekday.

Figure 7 presents the histogram with the distribution of energy requirements as a percentage of nominal battery capacity per fleet bus during a weekday. The average driving consumption of the fleet is 1.1 kWh/km excluding an estimated 12% due to losses during the charging process. This energy use estimate considers 292 electric buses who were operating at the beginning of the year, since the rest began operations in late October and December. On the other hand, the distance considered is based on service trips, meaning not empty trips.

The graph indicates that most buses require between 60% and 70% of their nominal battery capacity during a typical weekday. However, a significant portion of buses operate at higher levels of capacity utilization, between 80% and 120% of their nominal capacity. This distribution implies that, under typical operational conditions, the energy requirements for most buses approach or exceed their nominal capacity, possibly requiring to recharge during operation. This highlights potential limitations in operational flexibility, as the buses operate close to their maximum capacity.

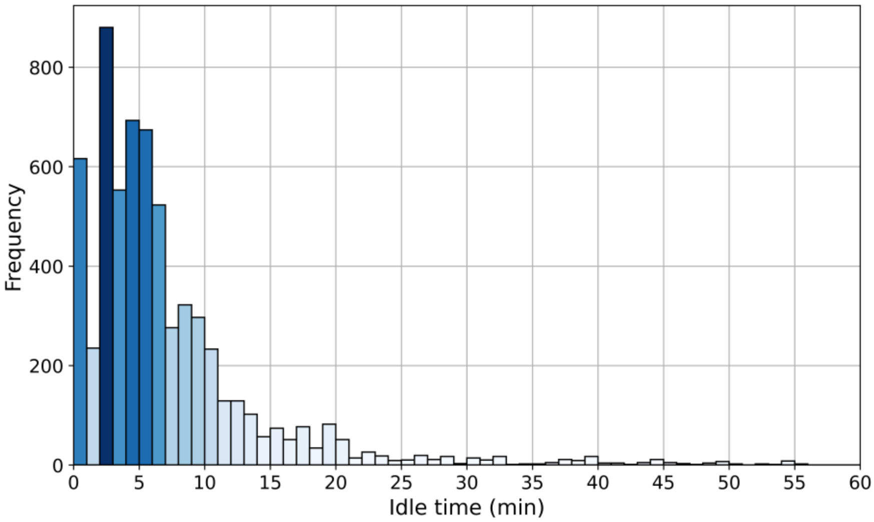


Figure 8: Idle times at bus stops on a weekday.

The potential range of flexibility available in the public bus fleet can be estimated by examining fleet availability in relation to its primary usage and the occupancy rate of bus stations. For instance, the distribution of weekday bus idle times at stops, measured in minutes and derived from the operational plans specified in the tenders, is shown in Figure 8. There is a highly right-skewed distribution, with most idle times concentrated in the lower range. The peak happens at around 2 to 5 minutes of idle time, likely corresponding to brief stops for passenger on- and offboarding. The top 25% of idle times occur past 9 minutes, with only very few instances exceeding 21 minutes. It is rare for idle times to extend beyond 60 minutes during operation.

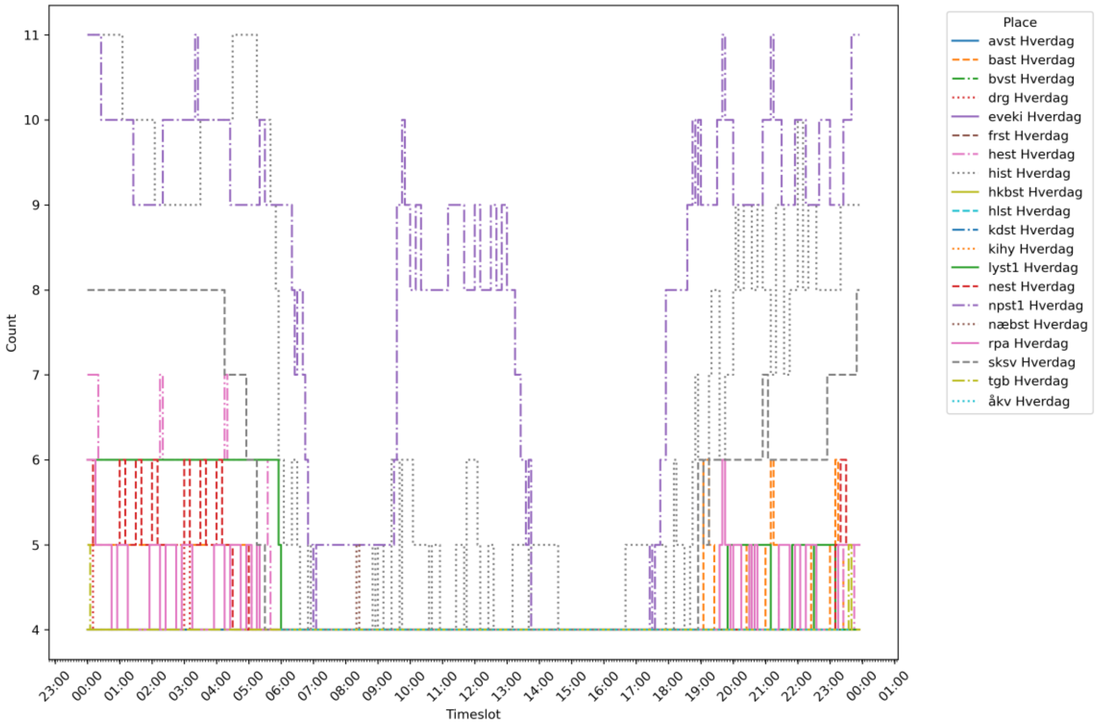


Figure 9: Occupancy rate of bus stations on a weekday.

Additionally, the routes of a normal weekday were summarized by 5-minute periods on timetables. The timetables indicate the place and time of trips between bus stops or stations and if the bus either runs or stays still. For the analysis only 229 out of the 380 buses were considered. Operations with inconsistencies between initial and final destinations or initial and final time overlaps were left out. These inconsistencies are explained by the practice of swapping out operational buses for back-up buses, which unfortunately is not visible from the data. Figure 9 illustrates the top bus stations with more than 4 buses at any given period.

From 23:00 to 6:00 there are plenty of stations with several idle buses ranging from 4 to 10 buses. After 6:00 and up until 17:30 most stations do not harbor buses, this is the main period of service where the buses run. However, during this period between 9:30 to 13:30, stations 'hist' and 'npst1' harbor 5 and 9 buses, respectively. Then, towards late afternoon at 17:30 the occupancy of the stations increases again.

3.2 Garbage refuse trucks (DK)

Amager Resource Centre (ARC) is a joint municipality company who operates several municipal waste services that involve waste collection, recycling services and energy. Particularly, since 2022 waste collection in the Copenhagen Municipality is done with electric garbage trucks where driving, lifting and compacting of waste are electrically powered [37]. The data presented here about their electric refuse trucks fleet originates from an e-mail interview conducted with ARC.

Figure 10: One of ARC's electric garbage refuse trucks in operation. Picture taken from [34].

ARC's fleet consists of 100 trucks each with 300 kWh of battery capacity c, most of which are SCANIA trucks. ARC's charging station consists of 100 ABB CCS Combo 2 plugs with a charging capacity P^{char} of 100 kW and 25 kW. ARC's waste collection operations run from 6 am until 5 pm. Each truck covers 75 km consuming 170 kWh daily.

3.3 Bus data (SI)

The data for the country of Slovenia are belonging to a pilot project in the city of Maribor. With the help of ABB, the municipality established two pantograph down chargers for public buses. One is located in the city center at Mlinska station with a nominal charging power of 300 kW and one at the other end of the bus route no. 6 at Vzpenjača in the south-west of the city with a charging power of 150 kW. The project started with two 12m electric buses operating on the ~10km long route. In the beginning of 2024, two more buses were added to this project. This part of the present deliverable aims at analysing the operational data of this project, gathered over the last year.

Figure 11 depicts the distribution of energy delivered per charging session and bus. Each subplot represents the vehicle-specific charged energy. It is interesting to note that the delivered energy per session mostly lies in the range of 5-20 kWh, suggesting that the buses are frequently charged with smaller amounts during operation. For buses, a charged energy translates only to a minor change in SOC of around 1.5 – 6 %. Indeed, the route is fairly short, and the estimated amount of energy needed for the full 10 km route is around 11 – 15 kWh, depending on the season.

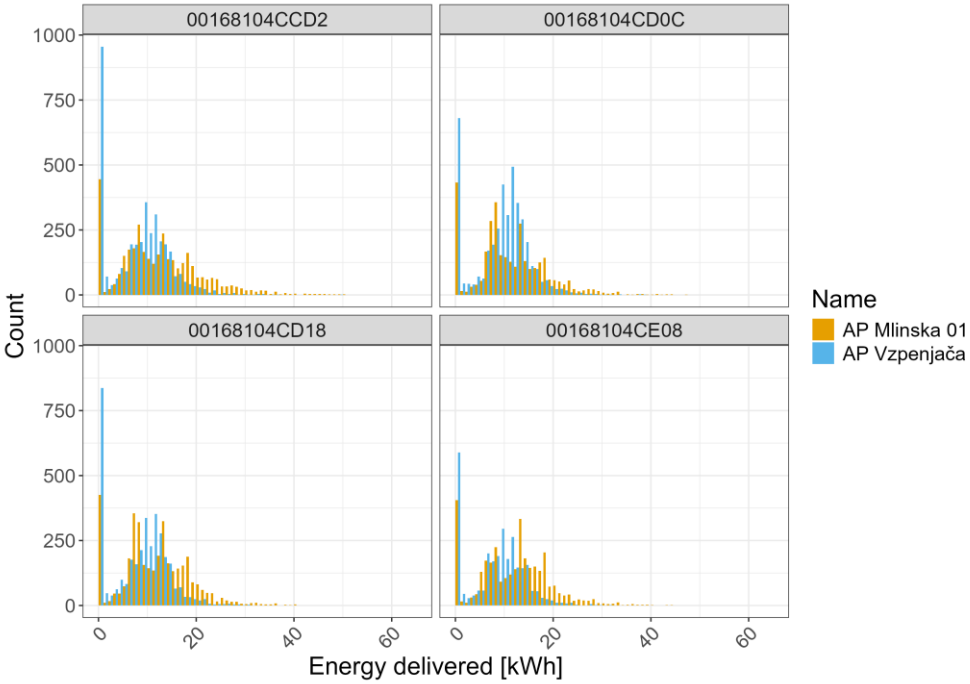


Figure 11: Distribution of energy delivered per charging session and bus (denoted by the vehicle ID).

Figure 12 records the measured average power per charging session at the two locations. The colours refer to the different vehicle IDs represented the four buses. While Mlinska has a nominal charging power of 300 kW, this is in practice seldomly reached and most of the charging takes place at an average charging power of 200-250 kW. On the contrary, the charging at Vzpenjača typically occurs at nominal level.

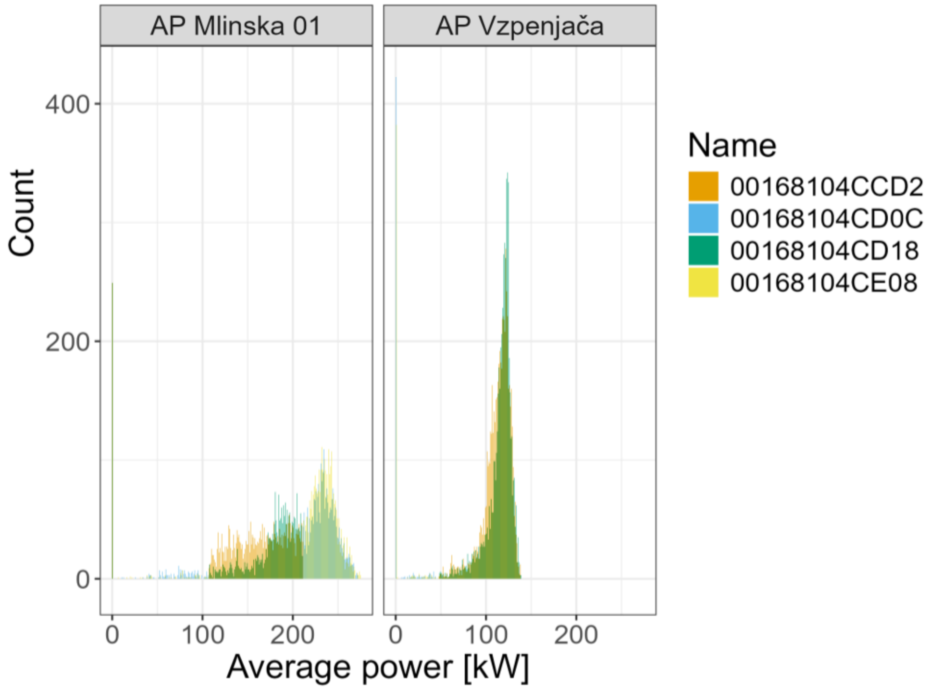


Figure 12: Distribution of the average power recorded per charging station.

Figure 13 plots the daily charged energy per bus. The black lines show the monthly average suggesting that the energy consumption in winter is around 10-20% higher than in summer due to extended requirements for cabin heating and other weather-related conditions. On some days, the daily energy charge is zero as only two buses operate on the route on weekends. In addition, the data suggests that there must be other charging stations which the buses can use which are not part of the data and which are unknown. Hence, these daily energy requirements only provide an estimate for the four buses. In winter, the buses need approximately 300 – 350 kWh, meaning that they drive back and forth between the two stations around 10-15 times per day. In summer, the energy requirement falls to around 250 kWh.

The charging pattern of one of the four buses is depicted in Figure 14 for the month of April 2024. This pattern suggests that the buses are charged regularly, with only a limited amount of energy which is due to the driving schedule of the buses. In the breaks at the end points of the routes the buses are charged repeatedly for around 5-15 minutes. The state-of-charge of the buses is kept strictly to 60-80%. The depicted bus has not been in schedule for the first two Sundays of the months, and neither for the latter two Saturdays. Most of the charging takes place during the day integrated into the driving schedule of the buses.

Figure 13: Daily charged energy per bus.

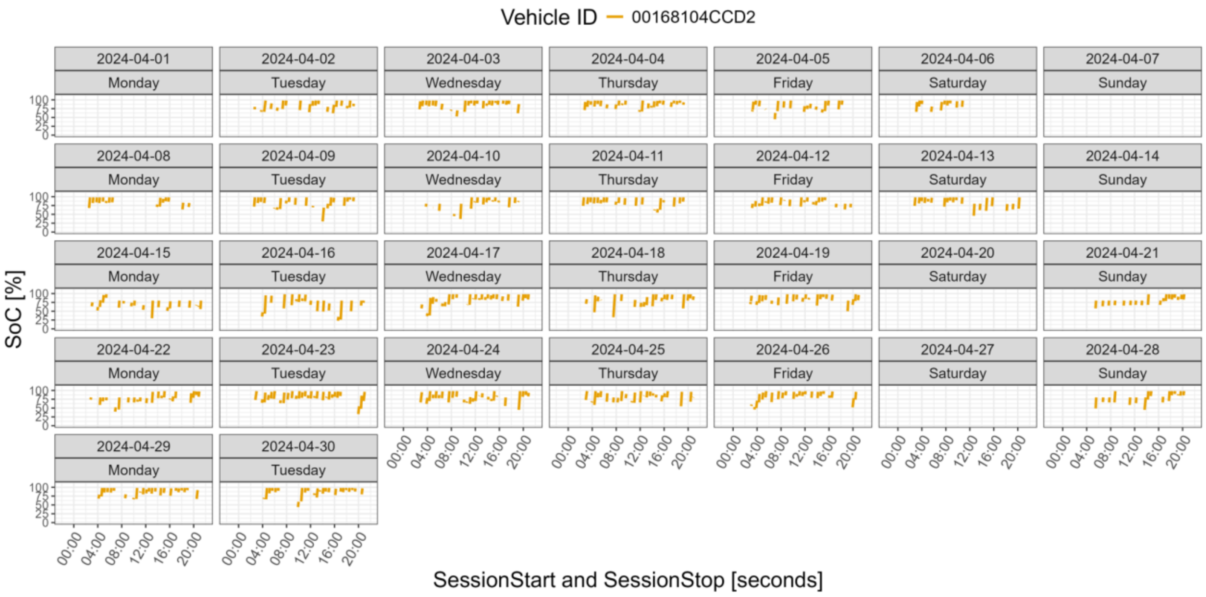


Figure 14: Daily state-of-charge evolution while charging for each day in April.

4 Optimal operation and charging strategies

In this section, operational and charging strategies for heavy-duty fleets are presented to assess the bidirectional charging potential of commercial fleets for providing grid services. Therefore, the primary goal is to reduce overall electricity costs, either by achieving cost savings or generating revenue. Hereby, it must always be ensured the fleet still satisfies its driving demands.

Latest research highlights the potential of fleets in providing regulation services and participating in energy trading through bidirectional charging. In this context, cost savings are possible through electricity price differences by charging EVs during hours of low prices and/or discharging at times of high prices, formally known as price arbitrage (PA). Another option is providing regulation services by reserving capacity to activate it during substantial frequency deviations of the power system [35]. These two vehicle-to-everything (V2X) services will be evaluated using mathematical optimization models.

The reminder of the section is structured as follows. Section 4.1 describes the techno-economic mixed-integer linear optimization implemented to simulate the operational and charging strategies discussed. Section 4.2 presents the use case for the fleet data presented in 3.2, where selected data contextualizes it within a real-life setting. Finally, section 4.3 analyses and discusses the modelling results. A more thorough explanation will be published in paper [36].

4.1 Methodology

This section explains the logic for evaluating the techno-economic impact of the operational and charging strategies of heavy-duty fleets. First, it illustrates the general framework of these strategies, in other words, their elements and interactions. Afterwards, the section continues by mapping out the requirements and expected results of the mathematical modelling and the general model set-up. Lastly, it explains the implemented objective functions and constraints that conform the optimization problem. A detailed nomenclature can be found in APPENDIX A: Nomenclature of the modelling variables.

The provision of these services requires different assets and interactions between agents. Figure 15 describes the components and their dynamics for two cases: Fleet Vehicle-to-grid (V2G), in a), and Fleet V2G + frequency containment reserve for disturbance operation (FCR-D), in b). These elements and their interplay serve as a framework for developing optimal operational strategies.

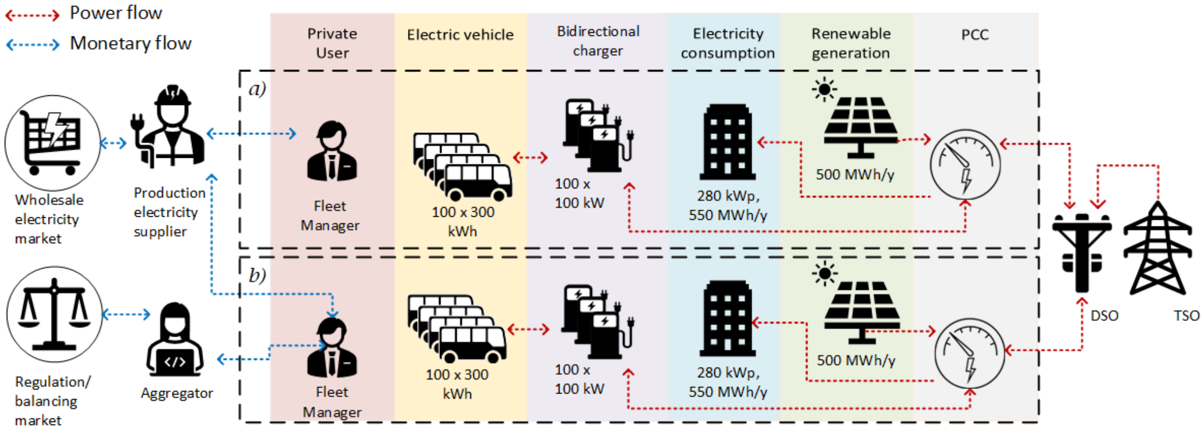


Figure 15: Overview of power and monetary flows in frameworks: a) Fleet V2G, b) Fleet V2G + FCR-D.

Fleet V2G alludes to the PA done by an EV fleet connected by bidirectional chargers to a Point of common coupling (PCC), enabling grid connection, as shown in a) of Figure 15. The PCC connects Photovoltaic (PV) panels, a commercial building and the EV depot. The EV fleet manager is responsible for all these assets. The fleet parked at the depot can charge or discharge to cover building consumption or use the PV production. Otherwise, surplus energy from the EV fleet or PV production can be fed into the grid to generate revenue from market trading. The operation strategy decides when to draw or inject energy depending on varying time of use (ToU) tariffs, consisting of low, high and peak price periods, as well as spot price variations. A production electricity supplier (PES) is assumed to handle the electricity market transactions. The cost for electricity consumption is equivalent to the hourly spot price plus components arising from transmission system operator (TSO) tariffs, distribution system operator (DSO) tariffs and state taxes. The selling price of the energy fed back into the grid is the spot price minus additional fees from the PES services, TSO producer tariffs and DSO producer tariffs.

The Fleet V2G plus FCR-D is an extension of the Fleet V2G where the EV fleet additionally offers FCR-D up reserves in the regulating market. As seen in b) of Figure 15, access to this market is considered through an aggregator as the balance service provider (BSP), who disposes of specific target consumption/production to provide the service. In the case of FCR-D up the fleet is discharged, thus enough energy must be available in the EVs' batteries. Reserved capacity is paid as bid but there is no payment for the delivered energy. All other costs mentioned for Fleet V2G apply plus the aggregator-imposed service fees.

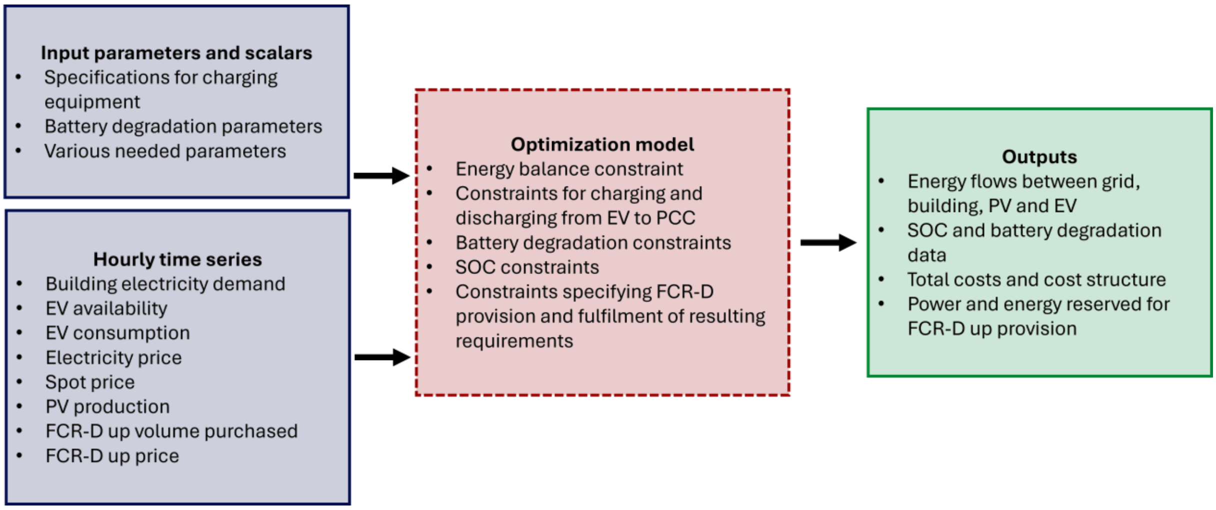


Figure 16: Optimization model diagram for operational and charging strategies.

The previous frameworks guide the mathematical optimization models to represent the operating strategies. The optimizations have the objective to minimize overall costs while satisfying their system boundaries. For instance, the model needs to assure the energy balance corresponds to the power flows defined in Figure 15. Moreover, the behaviour of the elements needs to be simulated. For example, the performance of the charging and discharging processes is dependent on the efficiency of the bidirectional charger. Additionally, the battery's modelling must include the tracking of its state-of-charge (SOC) and its degradation [37]. Finally, regulations from the electricity markets should also be followed. Figure 16 illustrates the optimization model with the previously mentioned constraints, plus its inputs and outputs. The inputs are mainly prices, costs and parameters required to model the constraints, see section 4.2. The outputs will be used to evaluate the tecno-economic impact of the operational strategies and are analysed in section 4.3.

4.1.1 Model set-up

The overall set-up of the models as well as the implemented objective functions and constraints are described in the following.

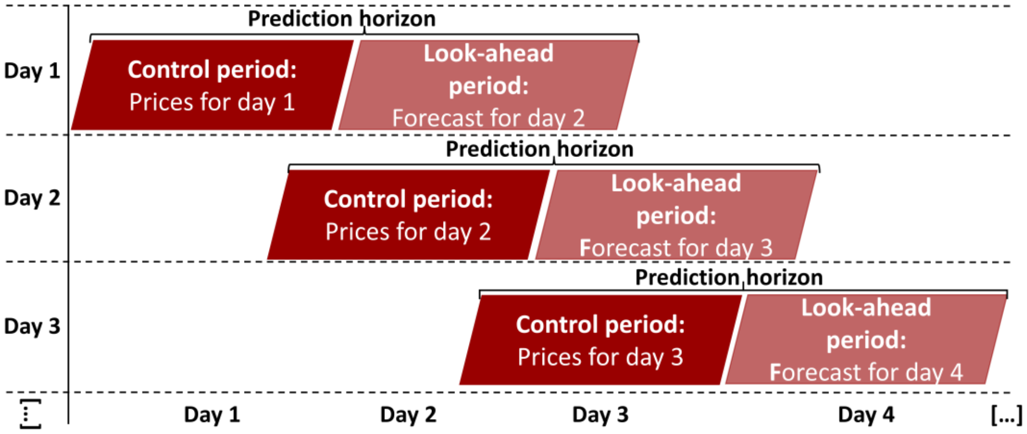


Figure 17: Principle of the rolling horizon with persistence forecast for price

The model considers a full year but runs day by day in a rolling-horizon fashion to limit its foresight, as illustrated in Figure 17. For example, on the initial date, called the *control period*, the optimization uses its respective historical prices. The corresponding consecutive day, called the *look-ahead period*, applies a persistence forecast which predicts the prices to be the same as the *control period*'s prices. The model then executes the objective function and sets the decision variables for the first and second day, using the actual and predicted information for these days. The values of the decision variables are saved when the optimization for the first day is finished. Then, the model moves on to the second day and gets the actual data for the second and the predicted data for the third day. The optimization is executed based on the new information, running in a loop for each day of the year. However, only the values of the *control period* are later considered for the results. Only the price and FCR-D parameters are implemented with the persistence forecast. The foresight for the other parameters, e.g. building consumption, is also restricted to two days using the rolling horizon. Yet, the actual values are used for the *control* and the *look-ahead period*.

4.1.2 Mathematical description for Fleet V2G

The objective function of the optimization for fleet V2G is divided in five summations, as seen in the equation below. The first one represents the cost for electricity consumption from the grid E^{grid}_{t}, considering the consumer electricity price $\pi^{el}_{d,t}$. The next two terms are added to consider grid feed-in. First, the revenue generated from selling electricity to the grid is deducted from the cost. Therefore, the spot price $\pi^{spot}_{d,t}$ is multiplied with E^{feedin}_{t}. Second, the costs arising for each kWh fed into the grid add to the objective function. They are represented by multiplying E^{feedin}_{t} with all arising tariffs, τ^{TSO}, τ^{PES} and τ^{DSO}. The last summations determine costs resulting from cycle and calendar battery degradation for the set of vehicles v comprising the fleet.

$$\min_{E_t^{grid}, E_t^{feedin}, E_{t,v}^{char}, E_{t,v}^{dis}, \delta_{t,v}^{cal}} \underbrace{\sum_{t\in T} E_t^{grid} \cdot \pi_{d,t}^{el}}_{\text{Electricity cost}} - \underbrace{\sum_{t\in T} E_t^{feedin} \cdot \pi_{d,t}^{spot}}_{\text{Feed-in revenue}}$$

$$+ \underbrace{\sum_{t\in T} E_t^{feedin} \cdot (\tau^{TSO} + \tau^{PES} + \tau^{DSO})}_{\text{Feed-in cost}} + \underbrace{\sum_{v\in V} \frac{\sum_{t\in T} E_{t,v}^{char} + E_{t,v}^{dis} + \kappa_{d,t}}{2 \cdot c} \cdot \alpha^{cyc}}_{\text{Cycle degradation cost}}$$

$$+ \underbrace{\sum_{t\in T, v\in V} \delta_{t,v}^{cal} \cdot \alpha^{cal}}_{\text{Calendar degradation cost}}$$

The following constraints define the system boundaries. The following equation implements the energy balance at the PCC. The difference of E^{grid}_t and E^{feedin}_t needs to satisfy the demand $\gamma_{d,t}$ and the sum of all charging $E^{char\_pcc}_{t,v}$. Following load convention, $PV_{d,t}$ is deducted from all demands, as well as the sum of all discharging $E^{dis\_pcc}_{t,v}$.

$$E_t^{grid} - E_t^{feedin} \geq \gamma_{d,t} - PV_{d,t} + \sum_{v\in V} \left(E_{t,v}^{char\_pcc} - E_{t,v}^{dis\_pcc}\right) \quad \forall\, t \in T$$

The following four constraints regard the charging and discharging of the EV. The equation displayed directly below associates the possible charging steps P^{char}_p with an efficiency η^{char}_p. The variable $\beta^{char}_{t,p,v}$ ensures the charging and discharging granularity are independent of time steps dictated by input parameters, e.g. spot prices. The scalar ω defines the number of charging slots in an hour. The lowest equation below applies the same logic to the discharging process.

$$E_{t,v}^{char} = \sum_{p\in P^{sc}} P_p^{char} \cdot \eta_p^{char} \cdot \frac{\beta_{t,p,v}^{char}}{\omega} \quad \forall\, t \in T, v \in V$$

$$E_{t,v}^{dis} = \sum_{p\in P^{sd}} P_p^{dis} \cdot \eta_p^{dis} \cdot \frac{\beta_{t,p,v}^{dis}}{\omega} \quad \forall\, t \in T, v \in V$$

In the same way, the following two equations represent the charging and discharging energy at the PCC.

$$E_{t,v}^{char\_pcc} = \sum_{p\in P^{sc}} P_p^{char} \cdot \frac{\beta_{t,p,v}^{char}}{\omega} \quad \forall\, t \in T, v \in V$$

$$E_{t,v}^{dis\_pcc} = \sum_{p\in P^{sd}} P_p^{dis} \cdot \frac{\beta_{t,p,v}^{dis}}{\omega} \quad \forall\, t \in T, v \in V$$

To ensure that the EV can only be charged or discharged within an hour, $\rho^{char}_{t,v}$ and $\rho^{dis}_{t,v}$ are established, where the binary variable $\theta_{d,t,v}$ specifies if the EV is available at the depot.

$$\rho_{t,v}^{char} + \rho_{t,v}^{dis} \leq \theta_{d,t,v} \quad \forall\, t \in T, v \in V$$

The next equation ensures that the sum over all charging steps p of $\beta^{char}_{t,p,v}$ can take the maximum value of ω, meaning that all charging windows are covered by the charging process $\rho^{char}_{t,v}$. The equation after the next equation has the same function for the discharging process $\rho^{dis}_{t,v}$.

$$\sum_{p \in P^{sc}} \beta^{char}_{t,p,v} \leq \omega \cdot \rho^{char}_{t,v} \quad \forall\, t \in T, v \in V$$

$$\sum_{p \in P^{sd}} \beta^{dis}_{t,p,v} \leq \omega \cdot \rho^{dis}_{t,v} \quad \forall\, t \in T, v \in V$$

The next equations set the minimum and maximum boundaries of the SOC. For the upper limit, the decision variable $y_{d,t,v}$ allows to operate below SOC^{max} or up until the battery's capacity c .

$$SOC^{min} \leq SOC_{d,t,v} \quad \forall\; t \in T, v \in V$$

$$SOC_{d,t,v} \leq c \cdot y_{d,t,v} + SOC^{max} \cdot \left(1 - y_{d,t,v}\right) \quad \forall\; t \in T, v \in V$$

The subsequent equations specify the incurred calendar degradation $\delta^{cal}_{d,t,v}$. Hereby, seasonal variations in degradation are considered and base and additional battery degradation are distinguished. The latter results from exceeding SOC^{max}.

$$\delta^{cal}_{d,t,v} \geq \delta^{cal}_{ba,s} + \delta^{cal}_{ad,s} \cdot y_{d,t,v} \quad \forall\; t \in T, v \in V,\; d \in S$$

$$\delta^{cal}_{d,t,v} \geq \delta^{cal}_{ba,w} + \delta^{cal}_{ad,w} \cdot y_{d,t,v} \quad \forall\; t \in T, v \in V,\; d \in W$$

At last, the following equation computes the SOC for each hour t and EV v. The if-statements ensure the last SOC of the previous hour is considered. Then, the charged and discharged energy $E^{char}_{t,v}$ and $E^{dis}_{t,v}$, respectively, are added or subtracted to the previous SOC. Furthermore, $\kappa_{d,t,v}$ is deducted to consider the driving consumption of the EV. Thus, $SOC_{d,t,v}$ represents the energy content of the battery at the end of each hour t.

$$\begin{aligned} SOC_{d,t,v} = & \begin{cases} SOC_{d-1,24,v}\,, & if d \geq 2 \wedge t = 1 \\ 0\,, & if\ d < 2 \wedge\ t > 1 \end{cases} + \begin{cases} SOC^{min}, & if\ d = 1 \wedge t = 1 \\ 0, & if\ d > 1 \wedge t > 1 \end{cases} \\ & + \begin{cases} SOC_{d,t-1,v}\,, & if\ t \geq 2 \\ 0, & if\ t < 2 \end{cases} + E^{char}_{t,v} - E^{dis}_{t,v} - \kappa_{d,t,v} \quad \forall\, t \in T, v \in V \end{aligned}$$

4.1.3 Mathematical description for Fleet V2G + FCR-D

In the case of offering FCR-D up reserves in the model Fleet V2G + FCR-D, the objective function includes the revenue from the FCR-D up provision, which reduces overall costs.

$$
\begin{aligned}
min_{E_t^{grid}, E_t^{feedin}, E_{t,v}^{char}, E_{t,v}^{dis}, \delta_{t,v}^{cal}} & \underbrace{\sum_{t \in T} E_t^{grid} \cdot \pi_{d,t}^{el}}_{\text{Electricity cost}} - \underbrace{\sum_{t \in T} E_t^{feedin} \cdot \pi_{d,t}^{spot}}_{\text{Feed-in revenue}} - \underbrace{\sum_{t \in T} P_t^{res} \cdot \pi_{d,t}^{FCR-D}}_{\text{FCR-D revenue}} \\
& + \underbrace{\sum_{t \in T} E_t^{feedin} \cdot (\tau^{TSO} + \tau^{PES} + \tau^{DSO})}_{\text{Feed-in cost}} + \underbrace{\sum_{v \in V} \frac{\sum_{t \in T} E_{t,v}^{char} + E_{t,v}^{dis} + \kappa_{d,t}}{2 \cdot c} \cdot \alpha^{cyc}}_{\text{Cycle degradation cost}} \\
& + \underbrace{\sum_{t \in T, v \in V} \delta_{t,v}^{cal} \cdot \alpha^{cal}}_{\text{Calendar degradation cost}}
\end{aligned}
$$

Besides all constraints used in the model of Fleet V2G, additional constraints are needed to implement FCR-D up provision. The next equation calculates the total discharging power P^{res}_t, that can be offered as FCR-D up reserves. The binary $res^{up}_{t,p,v}$ indicates the individually selected discharging step for each EV v in case of activation. Furthermore, the subsequent equation constraints $res^{up}_{t,p,v}$ to one step for each vehicle v for each hour.

$$
P_t^{res} \leq \sum_{v \in V, p \in P^{sd}} \frac{P_p^{dis} \cdot res_{t,p,v}^{up}}{\eta_p^{dis}} \quad \forall\, t \in T
$$

$$
\sum_{p \in P^{sd}} res_{t,p,v}^{up} \leq 1 \quad \forall\ t \in T, v \in V
$$

In the equation listed below, the volume $vol^{FCR-D}_{d,t}$ is multiplied by the binary availability variable $\theta_{d,t,v}$, which assumes the value of 1 when the EVs are present at the depot. Furthermore, the market share χ represents a limit to the attainable FCR-D up regulation through competitive market bidding by the fleet.

$$
P_t^{res} \leq \theta_{d,t} \cdot vol_{d,t}^{FCR-D} \cdot \chi \quad \forall\ t \in T
$$

Due to market regulation the energy reserve E^{res}_t, needed for an hour in which FCR-D provision is considered, is calculated as shown in the following equation.

$$
E_t^{res} \geq P_t^{res} \cdot \frac{1}{3} \quad \forall\, t \in T
$$

The last equation relates the needed energy reserve to the storage of the EV fleet. It ensures that the EV fleet keeps the defined minimum SOC and stores enough energy to fulfil the FCR-D requirement.

$$
\sum_{v \in V} SOC_{d,t,v} \geq E_t^{res} + \sum_{v \in V} SOC^{min} \quad \forall\ \in T
$$

4.2 Case description

For the optimization models, several inputs and parameters are selected to characterize the components outlined in the frameworks for developing optimal operational strategies. The EV fleet to consider originates from an e-mail interview conducted with ARC. Hereby, a theoretical EV fleet possessing identical attributes to the actual fleet is studied. For the case study, the chargers are assumed to have 100 kW bidirectional capability. The availability $\theta_{d,t,v}$ and driving consumption $\kappa_{d,t,v}$ of the fleet come from the refuse trucks' schedule. There is no difference between the vehicles, but the consumption varies in summer and winter. Winter and summer are defined from the ToU tariffs, October-March and April-September, respectively. Dost et al. Furthermore, nominal consumption differs by season, it is 29% lower in summer and 18% higher in winter.

To incorporate the cost of battery degradation, the battery cost of 180 €/kWh is assumed with a lifetime for vehicular application determined by the point at which it experiences a 20% to 30% state-of-health (SOH) loss and needs replacement. In this regard, c^{useful} is set to 70% of the nominal capacity. Then, battery degradation costs α^{cyc} and α^{cal} can be determined. SOH specifies the state of the capacity with respect to its original amount, so 100% is assumed as the initial value. A 3% SOH loss for each 1,000 full equivalent cycle (FECs) is considered for cycle degradation. Moreover, 65% is set up as the SOC^{max} in accordance with calendar degradation plateau regions. A detailed explanation on the degradation modelling is offered in [36] . Meanwhile, 30% is established as SOC^{min} to address user concerns of inconvenience and range anxiety.

Besides the previously described inputs, time series data from the year 2023 are considered for the spot price and building demand. The spot prices for the bidding zone DK2 $\pi^{spot}_{d,t}$ are taken from Nordpool for every hour of the year. The electricity price $\pi^{el}_{d,t}$ is derived from spot prices plus additional tariffs. The TSO tariffs τ^{TSO} are defined by Energinet for 2023 and the DSO tariffs τ^{DSO} are those applicable as of October 2023 for customers in category A-low (connection at 10 kV side of a substation), according to DSO Cerius. For V2G operation, the PES tariff τ^{PES} 0.0054 €/kWh is taken from Nettøpower, a registered PES in Denmark. Although there are financial incentives for EVs in Denmark, these do not apply to the considered frameworks.

At last, time series for FCR-D prices $\pi^{FCR\text{-}D}_{d,t}$ and volumes $vol^{FCR\text{-}D}_{d,t}$ in 2023 are retrieved from the data hub of the TSO Energinet. From the volume sold, a hypothetical market share χ of 5% is assumed to account for a potential prospective contribution from flexible resources. This share is comparable to the contribution of batteries and flexible resources to the added FCR-D upregulation capacity in 2023.

The time series determining the PV production $PV_{d,t}$ and demand $\gamma_{d,t}$ of a potential office building, have their origin in the data from Campus Bornholm from the projects of EV4EU and INSULAE. The dataset from 2018 is adjusted to align with 2023. The building has a peak demand of 276 kW and a yearly consumption of 550 MWh. Moreover, the PV generation, from a 61 kWp system, is scaled up to 450 kWp to accommodate the estimated depot area suitable for a PV installation. For further details on the case study, refer to [36].

4.3 Numerical results

Within this section, results common to both frameworks are discussed before moving on to relevant individual results. To put the results in perspective, a unidirectional case was created. Hereby, the objective, agents and assets involved remain the same as described in the frameworks, except that the EVs do not have the ability to discharge power.

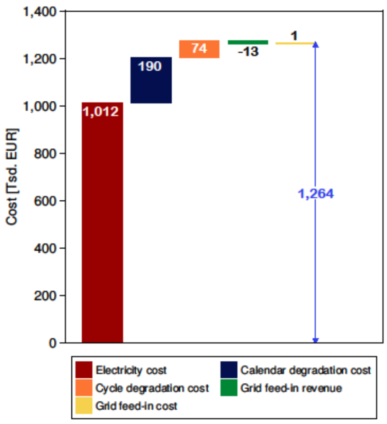


Figure 18: Structure of yearly costs: unidirectional case

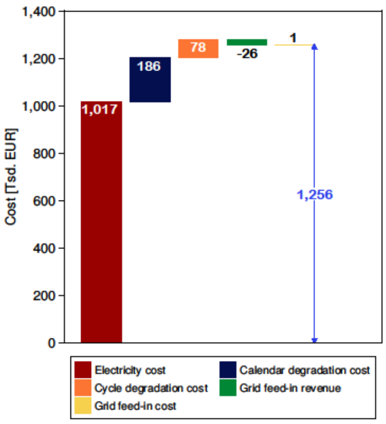


Figure 19: Structure of yearly costs: Fleet V2G

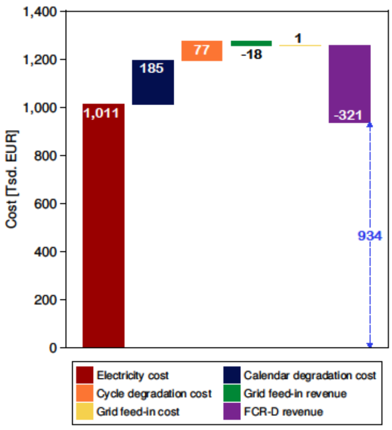


Figure 20: Structure of yearly costs: Fleet V2G + FCR-D

The yearly results from the optimization models are illustrated in Figure 18, Figure 19 and Figure 20; breaking down the different components of the net profit. Compared to the unidirectional case, Fleet V2G and V2G plus FCR-D result in cost savings. Notably, V2G plus FCR-D achieves cost savings of 330 thousand € (tsd. €), or 26% relative to the unidirectional case. On the other hand, Fleet V2G yields savings of 8 tsd. €, which represents only 0.63% cost savings compared to the unidirectional case.

Table 1: Yearly results of cases

		Unidirectional	Fleet V2G	Fleet V2G + FCR-D
Net Profit	[tsd. €]	-1,264	-1,256	-934
	[%] vs. uni		0.6%	26%
Feed-in profit	[tsd. €]	12	25	17
	[%] vs. uni		108%	42%
FCR-D profit	[tsd. €]	-	-	321
	[%] vs. uni			
E^{grid}	[tsd. €]	4,496	4,548	4,494
	[%] vs. uni		1.2%	-0.1%
E^{grid_feedin}	[tsd. €]	195	221	191
	[%] vs. uni		12%	-2.1%
E^{char_pcc}	[tsd. €]	4,221	4,412	4,348
	[%] vs. uni		4.5%	3%
E^{dis_pcc}	[tsd. €]	-	155	114
	[%] vs. uni			
Self-sufficiency	[tsd. €]	5.8%	5.7%	6.4%
	[%] vs. uni			
SOH loss	[tsd. €]	2.86	2.86	2.84
	[%] vs. uni		0%	-0.7%

Furthermore, the transition to bidirectional operation does not result in a noticeable increase in electricity consumption, as seen in Table 1. Similarly, the overall battery degradation costs remain unchanged. While there is a slight increase in cycle costs brought on by a higher EV fleet utilization, it is countered by a slight reduction in calendar costs enabled by the flexibility in SOC management of bidirectional operations. Indeed, the yearly SOH loss of 2.8% is the same in all cases. To explain this, Figure 21 compares the SOC operation for weekdays in winter between V2G plus FCR-D and the unidirectional baseline.

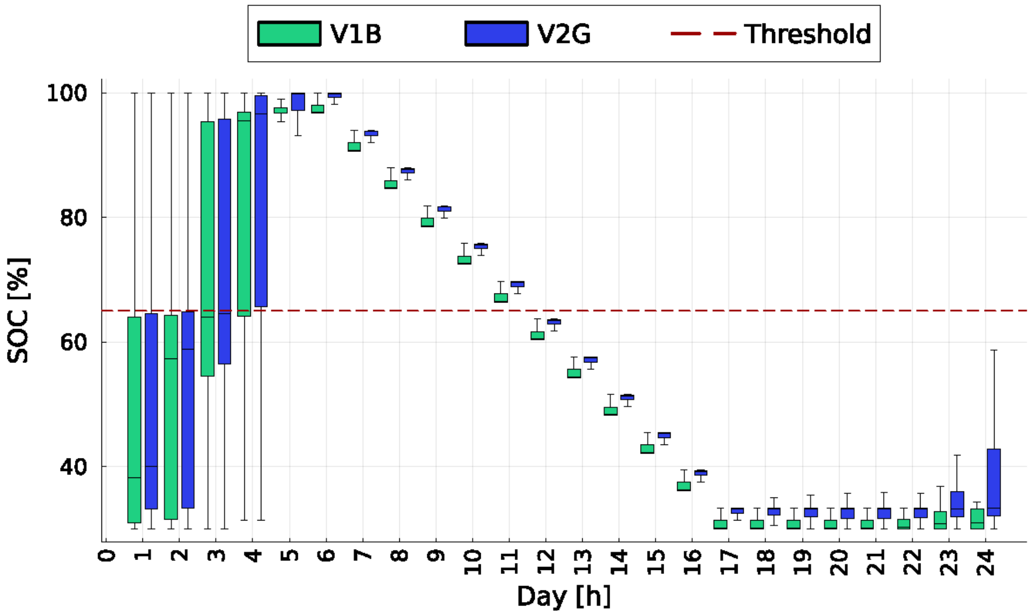


Figure 21: State of Charge of the fleet on weekdays in winter

The SOC exceeds the maximum SOC threshold and even rises to near 100% for both operations. V2G plus FCR-D seems to keep a slightly higher SOC at some hours of the day compared to the unidirectional operation, but the SOC is kept in the same side of the threshold. Capacity fade increases only when the threshold is trespassed. The optimization schedules charging towards the end of the period at the depot, close to 6am, where high SOC levels happen for both operations. This way it avoids that the EVs maintain a high SOC for a longer time and thus avoids increased calendar degradation. In comparison, summer's SOC is lower, around 70%, due to lower driving demand. Still, the threshold is surpassed the same number of hours in a day as in winter. On weekends, when there is no driving demand, the SOC is kept below the threshold. Thus, low electricity prices on weekends do not outweigh additional calendar degradation costs.

After 5pm the fleet is available at the depot to perform a bidirectional service, but the SOC is near the minimum limit at 30%. In the case of Fleet V2G, if the fleet would charge after returning to the depot, the charging would occur during the peak price hours. Consequently, the EV fleet cannot satisfy building demand during these hours. Therefore, PA is rarely performed and thus self-sufficiency is low, similar to the unidirectional case. Likewise, the spot prices are not high enough during the available time slots to encourage grid feed-in. E^{grid_feedin} only differs from the unidirectional case by only 12%, still feed-in profit doubles. Bidirectional operation enables grid feed-in at higher prices, which before was limited by the occurrence of PV production. In fact, most of the PV production cannot be used by the EV fleet during working days because it occurs during midday.

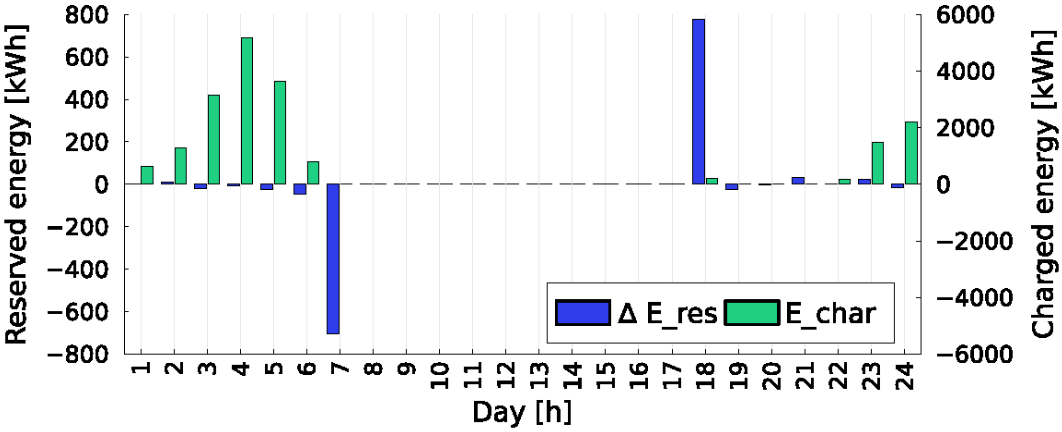


Figure 22: Average FCR-D up provision on weekdays in winter

In contrast, after the driving demand in V2G plus FCR-D there are small charging sessions occurring at 6pm on weekdays to store energy, E^{res} and offer FCR-D up reserve with it, as illustrated in Figure 22. As seen, E^{res} is kept until 6am when it is taken back. This short charging session at 6pm is close to the daily peak, where the electricity price around 0.29 €/kWh. However, the service is still beneficial since SOC can be kept for several hours because only a small amount of energy is ever discharged. Thus, the offered reserve P^{res} can span for consecutive hours. The sum of the offered reserves amounts to 8,917 MW, two thirds of the volume allowed to offer for the full year.

The investment required for V2G plus FCR-D is the price change of the bidirectional chargers with respect to unidirectional. There is no publicly known information for bidirectional chargers with a power output of 100 kW. However, the estimated price for the bidirectional model would range between 74,062 € and 120,000 €. The simple payback period of V2G plus FCR-D is 3 to 17 years.

Notably, the FCR-D profit demonstrates its capacity to offset the increase in all other incurred costs when an EV fleet transitions from unidirectional to bidirectional operation. V2G operation does not entail a big change in the charging and discharging patterns of an EV fleet, as the additional energy stored is low. Furthermore, V2G operation offering the FCR-D up-regulating service is suitable for the high levels of SOC and the schedule imposed by the driving demand of the EV fleet. Regardless of the electricity price, V2G plus FCR-D proves to be beneficial if it can be offered in consecutive hours.

In conclusion, the operational patterns of EV fleets significantly impact the feasibility of V2G services. For example, while the FCR-D price is lower than peak demand charging price, the fleet's rigid schedule enables the provision of reserves profitably over consecutive hours. In contrast, Fleet V2G operations, despite feeding into the grid at higher prices, is constrained by insufficiently high spot prices during the available time windows, making the service less attractive. Additionally, PV support for both services is minimal due to misalignment with the fleet's schedule. From a battery SOH perspective, calendar degradation dominates. Therefore, the optimization strategy minimizes calendar degradation by scheduling charging sessions immediately before driving, thereby maintaining high SOC only for brief durations.

5 Conclusions

For achieving a fully sustainable transportation sector, the electrification of heavy-duty road freight and passenger transportation is one of the most important yet challenging tasks. Being responsible for 25% of exhaust carbon emissions while only accounting for 1% of the vehicle stock, heavy-duty freight and passenger transportation requires the build-up of new infrastructure and innovative operational solutions that align with their rigid schedules and high energy demand. In this deliverable D2.6 “Control strategies for the optimal operation of electrified road freight and public transport”, the analysis is threefold: First, the status of fleet electrification in Europe is reviewed with a specific focus on the four countries involved in the EV4EU project: Denmark, Greece, Portugal and Slovenia. Second, this deliverable investigates the driving and charging patterns of early electrification pilot projects for fleets in both Denmark and Slovenia, analysing the driving demand and flexibility potential of buses and garbage refuse trucks. Third, the deliverable presents a new methodology for assessing the profitability of fleet operators to use their fleets in V2G applications. In particular, the focus is set on exploiting price variability through arbitrage and providing frequency containment reserve services.

The review of the electrification demonstrates that the electrification of heavy-duty vehicles is in very early stages, but the evolution over the past two to three years is promising. Overall, in Europe, there has been an increase in new electric heavy-duty truck registrations of about 40% in Q1-Q3 2024 compared to Q1-Q3 2023. Individual countries, e.g. Austria, Germany or Norway, have more than doubled their registrations for the same period. The demonstrator countries of the EV4EU project report progress in the electrification efforts through different pilot projects, while the massive infrastructure built-out and transition is yet to come. A range of documents points out that the high upfront investment costs for both trucks and charging infrastructure are currently one of the major barriers for the transition.

The conducted analysis of driving and charging patterns for two electric bus projects and garbage refuse trucks indicate that the electrification is definitively possible with limited to no impact on the driving schedule. However, the potential solutions differentiate significantly between the projects and solutions must be case-specific to a certain extent. While garbage refuse trucks are at the depot throughout the evening and night with only one larger charging session, buses might require several smaller charging sessions within their driving schedule at relatively high power. The requirements that a truck or bus fleet needs must be clearly defined at an initial stage. The flexibility potential in terms of grid services or price arbitrage operations that can provide additional revenue streams to fleet operators depend on this.

When it comes to operational and charging strategies for heavy-duty fleets, a new methodology is presented for assessing the profitability of bidirectional charging of commercial HDV fleets. Investigating both price arbitrage and grid services such as frequency containment reserve for disturbance operation, the primary goal is to reduce overall electricity costs that fleet operators face, either through avoiding costs by shifting the charging to times with low spot prices or actively discharging the batteries of the vehicles for generating revenue. The framework provides a realistic picture of the potential cost reductions that bidirectional charging capability may bring. Similar to the point raised before, the operational patterns of EV fleets significantly influence their range of action for participating in V2G services. A fleet’s rigid schedule (like the one for garbage refuse trucks) opens for providing frequency reserves over consecutive hours (e.g., at night), yet the low spot price spread in times of availability lead to insignificant cost savings. Having a renewable energy source such as PV on the depots’ rooftop (as it is envisioned in many charging stations) only brings a minimal support for these services and offsetting grid consumption due to low coincidence between availability and local production. The analysis shows that battery degradation is mainly caused by “unavoidable” calendar degradation, as the investigated services are of low energy intensity. The optimal operational strategy for minimizing calendar degradation is to schedule charging sessions immediately before driving, thereby avoiding times of high SOC as far as possible.

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APPENDIX A: Nomenclature of the modelling variables

Table 2: List of sets, variables, parameters, and scalars

	Value	Unit	Description
Sets			
t	$\in T$	h	Time steps of the optimization
u	$\in U$	-	Users regarded in the optimization
d	$\in D$	-	Used for implementing rolling horizon
s	$\in S$	-	Days in summer
w	$\in W$	-	Days in winter
p	$\in P$	-	Power steps in charging or discharging mode
v	$\in V$	-	Vehicles in the regarded EV fleet
Decision Variables			
E^{grid}_{t}	$\in \mathbb{R}^{+}_{0}$	kWh	Energy drawn from the grid
$E^{dis}_{t,v}$	$\in \mathbb{R}^{+}_{0}$	kWh	Energy discharged from EV, seen from EV side
$E^{char}_{t,v}$	$\in \mathbb{R}^{+}_{0}$	kWh	Energy charged to EV, seen from EV side
$E^{dis\_pcc}_{t,v}$	$\in \mathbb{R}^{+}_{0}$	kWh	Energy discharged from EV, seen from grid side
$E^{char\_pcc}_{t,v}$	$\in \mathbb{R}^{+}_{0}$	kWh	Energy charged to EV, seen from grid side
$\delta^{cal}_{d,t,v}$	$\in \mathbb{R}^{+}_{0}$	$\%^{SOH}$/h	Calendar capacity loss
$SOC_{d,t,v}$	$\in \mathbb{R}^{+}_{0}$	kWh	Energy stored in EV
$\gamma_{d,t,v}$	$\in \{0,1\}$	-	Implies going beyond the operating threshold of SOC
$\rho^{char}_{t,v}$	$\in \{0,1\}$	-	Ensures the EV can only be charged within an hour
$\rho^{dis}_{t,v}$	$\in \{0,1\}$	-	Ensures the EV can only be discharged within an hour
$\beta^{char}_{t,p,v}$	$\in \mathbb{Z}^{+}_{0}$	-	Number of charging windows in an hour for charging
$\beta^{dis}_{t,p,v}$	$\in \mathbb{Z}^{+}_{0}$	-	Number of charging windows in an hour for discharging
E^{feedin}_{t}	$\in \mathbb{R}^{+}_{0}$	kWh	Energy fed into the grid by the household
P^{res}_{t}	$\in \mathbb{R}^{+}_{0}$	kW	Power for FCR-D up reserve
E^{res}_{t}	$\in \mathbb{R}^{+}_{0}$	kWh	Energy for FCR-D up reserve
$res^{up}_{t,p,v}$	$\in \{0,1\}$	-	Power step for FCR-D up reserve
Parameters			
P^{char}_{p}	-	kW	Maximum power of each charging power step
P^{dis}_{p}	-	kW	Maximum power of each discharging power step
η^{char}_{p}	-	-	Efficiency of each charging power step
η^{dis}_{p}	-	-	Efficiency of each discharging power step
$\gamma_{d,t}$	-	kWh	Household demand
$\theta_{d,t,v}$	-	-	Binary indicating if EV is available (1 = available, 0 = unavailable)
$\kappa_{d,t,v}$	-	kWh/h	Driving consumption of EV
$\pi^{el}_{d,t}$	-	€/kWh	Electricity price for household consumers

$\pi^{spot}_{d,t}$	-	€/kWh	Day ahead spot price for the bidding zone DK2
$PV_{d,t}$	-	kWh	Energy generated by PV panels at EV fleet depot
$\pi^{FCR\text{-}D}_{d,t}$	-	€/kW	Price for reserved FCR-D upregulation capacity
$vol^{FCR\text{-}D}_{d,t}$	-	kW	Total volume of FCR-D up purchased
Scalar			
c	300	kWh	Capacity of the fleet vehicle
SOC^{min}	30%	kWh	Minimum SOC for EV battery
SOC^{max}	65%	kWh	SOC threshold for higher calendar degradation of EV battery
ω	6	-	Number of charging windows in an hour
$\delta^{cal}_{ba,s}$	1.14E-04	$\%^{SOH}/h$	Base calendar capacity loss per hour at 20°C
$\delta^{cal}_{ad,s}$	3.26E-05	$\%^{SOH}/h$	Additional calendar capacity loss per hour for high SOC at 20°C
$\delta^{cal}_{ba,w}$	8.97E-05	$\%^{SOH}/h$	Base calendar capacity loss per hour at 10°C
$\delta^{cal}_{ad,w}$	3.26E-05	$\%^{SOH}/h$	Additional calendar capacity loss per hour for high SOC at 10°C
α^{cal}	354	$€/\%^{SOH}$	Battery degradation cost per percent of SOH
α^{cyc}	1.062	€/cycle	Battery degradation cost per cycle
τ^{TSO}	0.0616	€ cents (ct.)/kWh	Feed-in and balance tariffs imposed on producing electricity, set by TSO Energinet
τ^{DSO}	0.0751	€ct./kWh	Feed-in tariff imposed on producing electricity category C/A-low, set by DSO Cerius
τ^{PES}	0.536	€ct./kWh	Tariff imposed on handling electricity feed-in by PES Nettøpower
χ	5	%	Maximum market share EV fleet is allowed to cover