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AI-informed Holistic Electric Vehicles Integration Approaches for Distribution Grids

D1.1

Usage and Charging Patterns Analysis

January 2025 (M8)

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EXECUTIVE SUMMARY

Deliverable D1.1 presents the outcomes of Task 1.1, titled “Current and future vehicles and vessels usage patterns and charging behaviours,” as part of Work Package 1 of the AHEAD project. The task was designed to: 1) assess current preferences for charging locations, 2) analyse the charging behaviour of electric vehicles (EVs), electric heavy-duty vehicles (HDVs), and electric vessels, and 3) evaluate the present status and provide projections for the EV fleet and its necessary charging infrastructure. Each objective is addressed in a dedicated chapter in this report.

We first examine the charging infrastructure and location preferences. To establish consistent terminology for this deliverable and the AHEAD project, we begin by distinguishing the vehicle types in focus, namely light- and heavy-duty vehicles, based on the European Union's definition. Understanding these categories is crucial when discussing the charging infrastructure for EVs, as each category has unique requirements and usage patterns. We discuss potential charging locations and their characteristics for light-duty electric vehicles (referred to as EVs in this document, for simplicity), followed by an analysis of infrastructure needs for HDVs, highlighting differences based on usage patterns (e.g., HDVs operating on recurrent routes versus long-distance commutes). Additionally, we examine the specific characteristics of charging infrastructure for vessels and review existing and planned electric and hybrid vessels in Europe. Finally, we review current charging location preferences based on previous reports and surveys, focusing on EVs, as HDV and vessel infrastructure remain in the early development stages. This review centres on the AHEAD project’s demonstration countries—Denmark, Italy, Portugal, and Slovenia—as well as Norway, given its advanced EV rollout. Home charging is generally preferred, with other types of infrastructure used only sporadically. However, findings suggest that the survey design may influence results and that the perceived importance of certain types of public infrastructure may differ from actual usage patterns.

Next, we analyse the charging behaviour of EVs, HDVs, and vessels using large, high-resolution datasets from various locations. For EVs, we examine home charging, charging at hospitals and universities, kerbside charging, charging at large parking facilities, and fast charging at petrol stations. The HDV analysis centres on depot charging for a large fleet of electric buses in Milan and garbage trucks in Denmark, while other HDVs are excluded due to limited data availability. For each location, key characteristics are outlined, including power profiles, plug-in and plug-out times, connection and charging durations, maximum power and energy demand per session, and daily and seasonal trends in energy demand. The

considered datasets show that smart charging is already utilised for home charging in Denmark, where users are consciously shifting demand to nighttime hours. Other locations with significant flexibility potential, such as workplaces or overnight parking at kerbside and parking facilities, are not yet leveraging it within the considered datasets. The analysis also indicates that several locations exhibit behaviours from different user groups, which is important to distinguish for future smart charging applications. Fast charging at petrol stations shows variable, unpredictable patterns, while HDVs, like electric buses and garbage trucks, exhibit distinct charging behaviours tied to their operational schedules.

Due to the early stages of electric vessel operation, no real charging data could be obtained to analyse the charging behaviour of electric vessels. Therefore, this deliverable presents synthesised charging behaviour based on the technical specifications and operational schedules of the world's first electric ferry, the MV Ampere, operating in Norway. Additionally, the potential electrification of the port of Madeira is assessed, estimating the onshore power supply needed to meet the power demand of docked vessels, such as cruise ships. Results highlight potential grid challenges, as demand could increase significantly with a shift to electric onshore power supply.

Finally, we provide an analysis of the current state of the EV fleet and charging infrastructure in the aforementioned demonstration countries, future projections of the EV fleet up until 2035, as well as recommendations on the publicly available charging infrastructure capacity over the years. Three different scenarios are developed that utilise: 1) inputs and projections from the project partners, 2) regression-based projections using EV market data from the European Alternative Fuels Observatory (EAFO), and 3) an additional cap on the maximum number of EVs to account for the maximum achievable EV fleet size under full electrification, also using data from the EAFO. The projections based on market data are constrained by the limited number of years available, which affects the robustness of the interpolation. Despite this, it is evident that the EV adoption rate varies significantly across the analysed countries, with some achieving an 8-10% EV share, while others are around 1%. Notably, the numbers provided by the different governments align with the EU's target of 100% EV adoption by 2050 but tend to overestimate the number of EVs compared to market data, except in Denmark. The current public charging infrastructure capacity meets the recommendations by ICCT but will need to be expanded to meet the 2035 requirements.

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1. INTRODUCTION

In this section, we outline the objectives, methodology, and structure of this deliverable.

1.1. Background and Objectives

The primary goal of WP1 is to establish a shared knowledge base for the AHEAD project by examining technological trends and defining scenarios for electric vehicle (EV), heavy-duty vehicle (HDV), and electric vessel charging. Key objectives of the work package include analysing recharging patterns, assessing technological and ICT infrastructure challenges, reviewing frameworks for flexibility services, and defining use cases and scenarios for the demonstrations.

As part of this effort, deliverable D1.1 documents the work completed in Task 1.1, titled "Current and future vehicles and vessels usage patterns and charging behaviours". The task aims to provide an analysis of the current and future usage patterns of EVs, HDVs, and vessels. Information collected in this task will serve as a basis for simulations and analyses in WP3 and WP4. The task description included the following two key elements:

1. "A comprehensive analysis of the current and future usage patterns of EVs, HDVs, and vessels based on various scenarios, including daily commuting, long-distance travel, and the specific operational requirements unique to vessels."
2. "A thorough investigation into the availability of charging infrastructure and preferences regarding charging locations, aiming to understand when and where vehicles and vessels are typically charged."

Based on this task description, three objectives were identified which are addressed in this deliverable:

1. A review of current charging location preferences of EV users.
2. An analysis of current charging behaviours of EVs, HDVs, and vessels.
3. An analysis of the current state and future projections for the EV fleet and required charging infrastructure.

1.2. Methodology and Structure

Deliverable D1.1 includes a combination of literature review, analysis and simulation of charging behaviour, and the development of projections. The report focuses on the demonstration countries of the AHEAD project, namely Denmark, Italy, Portugal, and Slovenia and also includes insights from Norway, one of the world's leading countries in transportation electrification.

Chapter 2 provides the foundation of this deliverable by clarifying terminology and reviewing charging infrastructure location and characteristics. Furthermore, it addresses the first objective of reviewing charging infrastructure preferences for EV users based on several reports and surveys.

Chapter 3 addresses the main objective of this deliverable by analysing the charging behaviour of EVs, HDVs, and vessels. The analysis is based on extensive datasets provided by the project partners Spirii and ATM, as well as simulations of vessel charging behaviour in Norway and the electrification of the port in Madeira. Due to the limited availability of HDVs and vessels in the market, the analysis is mainly focused on the charging behaviour of EVs at different locations.

Chapter 4 deals with the last objective of this deliverable by providing future projections of the EV fleet size in the different demonstration countries up until 2035, and recommendations on the publicly available charging infrastructure capacity over the years. These values shall serve as an input to WP4 for the power system impact analysis tool that needs to be included in the AI charging infrastructure planning tool.

2. CHARGING INFRASTRUCTURE

In this section, we discuss the charging infrastructure for EVs, HDVs, and vessels, and review charging location preferences for EVs to provide a foundation for analysing charging behaviour and future projections in the following chapters.

2.1. Types of Vehicles and Charging Infrastructure

In the European Union (EU), vehicles are classified into distinct categories based on their design and intended use, as outlined by regulations such as Regulation (EU) No 168/2013 and Directive 2007/46/EC12 [1], [2]. These categories include passenger vehicles (Category M), goods vehicles (Category N), two- and three-wheel vehicles and quadricycles (Category L), and agricultural and forestry tractors (Category T). Understanding these categories is crucial when discussing the charging infrastructure for EVs because each category has unique requirements and usage patterns. For instance, passenger cars (M1) and light commercial vehicles (N1) may require widespread, accessible charging stations, while HDVs (N2, N3) might need specialised, high-power charging solutions. By recognising these distinctions, policymakers and industry stakeholders can develop more effective and tailored charging infrastructure strategies that cater to the diverse needs of all vehicle types. Acknowledging this, in this report we group vehicle types into light-duty, heavy-duty and vessels, emphasising usage patterns and not vehicle dimensions and weight.

2.1.1. Light-Duty Electric Vehicles

Light-duty electric vehicles can encompass electric passenger cars, as well as electric light commercial vehicles like small vans and 2- or 3-wheeled vehicles. The majority of the current electric light-duty vehicle fleet consists of private passenger cars, commonly referred to as EVs. For the sake of simplicity in this report, we will refer to light-duty electric vehicles as EVs, if not mentioned explicitly otherwise.

Conductive charging infrastructure for EVs is diverse and can be classified in various ways. Table 1 provides an overview of a potential classification, based on Danish and Norwegian charging experiences, distinguishing charging locations as follows: single-family homes, multi-family homes, work or education facilities, errand and leisure locations, kerbside, parking facilities, and dedicated fast-charging stations/hubs.

Table 1 – Overview of different types of charging infrastructure for EVs, along with important characteristics such as access, land ownership, maximum power per outlet, and total site capacity (Modified table based on [3]).

	Single-family home	Multi-family home	Work / Education	Errand / Leisure	Curbside	Parking facility	Dedicated station/ hub
Access	Private		Private / Public	Public			
Land owner	Private individual	Private association	Private / Municipality		Municipality	Private / Municipality	
Power (kW)	11	22	22	22 / 400	22	22 / 350	400
Site capacity	Small	Small / Medium	Medium		Small	Medium / Large	Large

Home charging in single-family homes, detached houses, or villas typically includes fewer than three charging points, with an increasing number capable of smart charging. Without upgrading the grid connection, the maximum charging power is usually 11 kW. Besides charging with a dedicated charger, users also have the opportunity to charger their EV using a normal household socket, leading to significantly longer charging times. Multi-family homes, apartment buildings, condominiums, and housing associations can have more than three, and up to 1,500, charging points. Shared home charging often includes dynamic power management, but usually only limited smart charging capabilities. These systems are typically dimensioned for between 1.5 kW and 3 kW when all parking spots are charging simultaneously, while individual outlet power is up to 22 kW.

Workplace charging, or charging at educational institutions, involves many shared points with varied usage patterns, supporting both employees and visitors during the day and workplace fleets at night. The maximum charging power of a single outlet can typically reach up to 22 kW, but load sharing is often employed to minimise grid connection costs. Such infrastructure often supports charging powers above 3 kW when all chargers are active.

Charging infrastructure at errand or leisure locations can include both slow and fast charging options, depending on usage. Public kerbside charging generally includes 2 to 16 points per location, with individual power levels up to 22 kW, often limited by a smaller grid connection, which necessitates load sharing under high utilisation. Additionally, parking times are often restricted, for example, to three hours during the day.

Charging at large parking facilities, such as in shopping malls, features multiple charging points with typical maximum power levels of up to 22 kW, though fewer fast charging points may also be included. In Norway, these large charging clusters are often underutilised, prompting some malls to open these spots to non-EV cars.

Finally, dedicated fast-charging hubs within cities, along highways, and at petrol stations provide charging up to 400 kW, where the power capabilities of the vehicles themselves are currently the main limiting factor.

2.1.2. Heavy-Duty Electric Vehicles

The electrification of transportation is not confined to EVs. HDVs are also a large contributor to CO_2 emissions [4] and are therefore an important part of the electrification efforts in Europe [5] and worldwide [6]. Before jumping into discussing the various charging infrastructure locations, it is important to outline which vehicles are considered heavy-duty and what type of infrastructure they include.

In Europe, vehicles are categorised into different types to streamline regulations and standards. Type M vehicles are designed primarily for the carriage of passengers and include cars, buses, and coaches. These are further divided into subcategories: M1 for passenger cars with no more than eight seats in addition to the driver's seat, M2 for vehicles with more than eight seats and a maximum weight not exceeding 5 tonnes, and M3 for vehicles with more than eight seats and a weight exceeding 5 tonnes [2], [7]. On the other hand, Type N vehicles are intended for the carriage of goods. These include light commercial vehicles and heavy-duty trucks, classified as N1 for vehicles up to 3.5 tonnes, N2 for those between 3.5 and 12 tonnes, and N3 for vehicles over 12 tonnes [2], [7] . This classification system helps in setting appropriate regulatory standards for safety, emissions, and operational efficiency across the EU [2].

From the perspective of charging infrastructure, one important categorisation not included in the regulatory framework described previously is the type of duty a vehicle undertakes. Many type M (buses) and type N (trucks) vehicles are used in tasks with regular routes often within a certain radius from a base (e.g. public transportation or garbage trucks). Other, typically larger tractors with trailers, are employed for long-distance commercial transportation and logistics. Intuitively, one can easily surmise that the charging infrastructure serving the two types can be radically different. For regular routes, slow and fast charging at the base could be sufficient, especially if the daily travel distance is close to the vehicle's range. Short stops at opportunity chargers along the route or base charging during reloading can complement the daily energy needs. On the other hand, for long-distance transportation, when long distances have to be covered daily, the charging needs are for ultra-fast and megawatt charging on highways that can minimise charging time. In addition to the CCS charging standard, the Megawatt Charging System (MCS) is considered the future global standard for heavy commercial vehicle charging. Most truck manufacturers plan to introduce MCS-capable vehicles starting in 2024/2025. MCS allows for significantly higher charging capacities, making heavy commercial vehicles suitable for long-haul journeys [8].

2.1.3. Electric Vessels and Electrification of Ports

In the near future, fully electric vessels are expected to be limited to short-sea commercial vessels, ferries, and small passenger vessels. Additionally, hybrid vessels, such as plug-in hybrids and combined diesel-electric or gas-electric, are also anticipated. A literature review of examples of existing and planned electric and hybrid vessels across Europe is provided in Table 2, highlighting a variety of approaches, technologies, and efforts to electrify the abovementioned types of vessels.

Charging infrastructure for these vessels will be tailored to their specific purposes, including commercial ports for goods transportation, marinas for leisure and recreational activities, smaller industries like local fisheries, and ferry terminals. Electric vessel charging equipment has rapidly evolved to meet the growing demand for maritime electrification. Vessel charging solutions work very similarly to those for light- and heavy-duty vehicles. However, these systems are not yet standardised [9], [10].

Based on existing electric vessel charging capabilities and the latest charging technology, some standards already in use for EVs are also applied to vessels. The latest CCS2 standard is capable of delivering up to 500 kW of power and is becoming increasingly common for electric ferries, tugboats, and recreational vessels. Other connector types include CHAdeMO, which offers DC fast charging with outputs of up to 240 kW, and SAE J1772, used for slower AC charging, typically for overnight charging of smaller vessels [11].

Looking further, and similarly to HDV charger development, there is an effort to create a custom interface connector capable of transmitting power via MCS above 1 MW and up to 3 MW. The MCS system has great potential in shipping and is already in use, though it still has some limitations, such as cooling requirements and the lack of cables long enough for vessel applications [9].

In terms of automated charging, custom solutions like charging pantographs play a crucial role, particularly for vessels with frequent, short stops. These systems typically consist of a shore-based tower structure with an extendable arm and charging head, which connects to onboard receptacles on the vessel. Pantograph systems offer several advantages, including rapid connection and disconnection, compensation for tidal changes and vessel movement, and high power transfer capabilities. For example, some pantograph systems can deliver up to 4.5 MW of power, with voltage ranges of 400-1000V DC and current capacities of up to 3000 A. Innovative wireless charging solutions are also emerging for marine applications.

These systems typically consist of inductive charging plates mounted on vessel sides and shore-based sending coils on hydraulic arms. Wärtsilä has demonstrated wireless charging systems capable of transferring over 2 MW of power with a 400-500 mm gap between coils [9].

When grid capacity is insufficient to supply the necessary energy, battery storage systems are used to alleviate grid peak power demands, as seen in the Ampere ferry in Norway [12]. This approach is particularly effective when high charging power is required for fast connection times, typically under 10 minutes, enabling ferries to charge their batteries during short turnarounds [13].

Besides electric-powered vessels, other vessels such as cruise ships and container ships are increasing their load demand on ports in order to shut down diesel generators and use renewable shore power for charging. Large cruise vessels can reach peak power demands of 15-20 MW when heating or chillers are in operation. Current legislation requires that both types of vessels must use shore power in EU ports starting in 2030 [14].

Table 2 – Literature review on existing and planned electric and hybrid vessels across Europe. For each vessel, the table provides the country, vessel name, location, year of operation commencement, operator, and description. Additionally, the source is directly linked in the Reference column for ease of access.

Country	Name	Location	Year	Operator	Description	Ref.
Belgium	Op Stroom	Antwerp	2022	DAB Vloot	The ferry encompasses a capacity of transporting 150 passengers and 75 bicycles. It is equipped with a 396 kWh battery pack as well as solar panels for auxiliary power and recharges on-shore between trips.	[i]
Belgium	Ferry 19 Electric	Antwerp	2023	DAB Vloot	This vessel accommodates 50 passengers and 25 bicycles, operating primarily in fully electric mode with a Corvus Orca Energy battery pack and solar panels.	[ii]
Bulgaria	/	Silistra/ Calarasi	TBD	Silistra Municipality	One of Bulgaria's notable projects is the planned introduction of an electric catamaran ferry on the Danube River. The ferry will measure 12 m in length and 6 m in width, powered by two electric motors.	[iii], [iv]
Croatia	/	Split	TBD	Jadrolinija	Three vessels, each with a capacity for 389 passengers and 8 crew members, will replace the existing ageing ferries which are almost over 60 years old. The ships will primarily use electricity stored in batteries for propulsion, with solar panels on the sun deck providing additional power and diesel generators as a backup.	[v]
Croatia	/	Dalmatian Islands	2024	Jadroplov	Jadroplov, another major operator, is also developing a sizeable electric ferry to transport 1,000 passengers and 156 cars, with an estimated cost of 30 million euros.	[vi]
Cyprus	Evploia Aphrodite	Larnaca	2024	/	This fully electric, battery-powered vessel is the first zero-emissions and near-zero-noise vessel to operate along Cyprus' shores. Designed for short sea routes, Evploia Aphrodite combines environmentally friendly and innovative features while also serving as a research platform for the Cyprus Marine and Maritime Institute.	[vii]
Czech Republic	Bella Bohemia	Prague	2019	Prague Boats	Prague's first fully electric boat in its class is part of the 'Bohemia' series, which includes other modern ecological vessels like Marie d' Bohemia, Grand Bohemia, Bohemia, and Agnes de Bohemia. It has a maximum capacity of 250 passengers and is roughly 25 m long and 10 m wide.	[viii]
Denmark	Ellen	Fynshav/ Soby	2019	Aero Kommune	An all-electric ferry that began operations in August 2019. Ellen boasts an impressive energy efficiency of 85% and has the potential to cut CO_2 emissions by up to 2,250 tonnes annually.	[ix]
Denmark	Electric Harbour Bus	Copenhagen	2020	Movia	7 electric ferries, each with a capacity of up to 80 passengers, operate year-round between Sluseholmen and Orientkajen in Copenhagen. Running 17 hours daily, they complete each journey in one hour. Equipped with 183 kWh batteries, the ferries require 17 charging sessions per day, each lasting under 10 minutes, facilitated by a secure mooring system.	[x]
Estonia	/	Virtsu/ Kuivastu	TBD	Estonian State Fleet	The ferry will accommodate up to 500 passengers and approximately 130 vehicles, relying primarily on shore-charged green electricity stored in batteries for propulsion. It will also feature biodiesel-powered auxiliary generators to ensure reliability in extreme conditions.	[xi]

Finland	Elektra	Parainen/ Nauvo	2017	FinFerries	Finland's first hybrid-electric ferry operates on a 1.6 km route in the Turku Archipelago between Parainen and Nauvo. It has a capacity for 90 cars and 375 passengers. Powered primarily by battery packs charged directly from the grid, the ferry also includes backup diesel generators.	[xii]
Finland	Altera	Parainen/ Nauvo	2023	FinFerries	Measuring 104 m in length and 16.5 m in width, it accommodates 92 cars and 375 passengers. The ferry is equipped with a dual 0.6 MWh battery system charged from shore, enabling it to primarily operate on battery power. It also features two electrically driven SCHOTTEL EcoPellers (950 kW each).	[xiii]
France	/	Paris	2024	/	3D-printed, autonomous electric passenger ferry operating on the Seine River. Measuring 9 by 3.90 m, it is the largest 3D-printed autonomous ferry, featuring advanced autonomy systems, electric propulsion, and a hull constructed from recycled materials. The ferry is designed for automatic mooring and charging, ensuring seamless operation.	[xiv]
France	Saint-Malo	Saint-Malo/ Portsmouth	2025	Brittany Ferries	The company's first LNG-electric ferry, *Saint-Malo*, has recently undergone sea trials to test its advanced drivetrain, and two LNG-powered ships are already in operation. The fleet will expand further with two shore-power-ready LNG-electric hybrids by the end of 2025.	[xv]
France	AR VAG Tredan	Lorient/ Locmiquélic	2013	/	A fully electric ferry for passengers powered by 128 supercapacitors, which covers a 10-minute route and needs to recharge after every trip. It is 22 m long, and hosts a maximum of 113 people, with a cruise speed of 10 knots.	[xvi]
Germany	Candela P-12	Berlin	TBD	Funkhaus/ Reederei Riedel	Funkhaus/Reederei Riedel has purchased the Candela P-12, an electric hydrofoil ferry in Berlin. Dubbed the "flying" ferry, this innovative vessel will connect the East Side Gallery to the cultural hub Funkhaus, travelling 25 knots across the Spree River.	[xvii]
Germany	/	Gehlsdorf/ Rostock	TBD	Rostock Municipality	The city of Rostock is planning to introduce an electrically powered ferry featuring solar cells as an additional energy source.	[xviii]
Germany/ Denmark	/	Puttgarden–Rødby	2014	Scandlines	Already ten years ago, Scandlines converted its four passenger ferries on the 45-minute-long Puttgarden–Rødby route into plug-in ferries. These vessels replaced one of the five diesel engines with a 1.6 MWh battery and are capable of charging at both Puttgarden and Rødby terminals.	[xix]
Greece	/	Athens/ Aegina/ Agistri	2026	Saronic Ferries	Saronic Ferries has joined forces with C-Job Naval Architects to develop Greece's first fully electric ferry. This vessel will have the capacity to carry 800 passengers and approximately 85 cars or a combination of 6 trucks and 55 cars.	[xx]
Ireland	Artemis EF-24	Belfast/ Bangor	2025	Condor Ferries	Featuring advanced hydrofoil technology, this ferry has a capacity for 150 passengers and 18 bicycles, with a top speed of 38 knots and a range of 115 nautical miles at a cruising speed of 25 knots. The vessel offers 85% fuel cost savings compared to conventional diesel ferries.	[xxi]
Italy	Sale Marasino II/ Sarnico	Iseo Lake	2024	Iseo Transportation Authority	Built by German shipbuilders Ampereship and Ostseestaal, two 26-m-long and 6.60-m-wide ferries are powered by two 100 kW electric drives with a battery capacity of 750 kWh. The batteries are charged using a combination of on-shore power and solar panels. Each ferry can carry up to 140 passengers.	[xxii]

Italy	Vittorio Morace	Aeolian/ Egadi Islands	2024	Liberty Lines	This 39.5-m-long ferry can carry 251 passengers and achieve speeds over 30 knots. It features an MTU hybrid propulsion system, allowing it to operate on battery-electric power during harbour operations and as a booster during transit. This vessel is the first of nine ferries planned to serve routes between Sicily, the Aeolian and Egadi islands, and destinations in Croatia and Slovenia.	[xxiii]
Italy	Ferrovie dello Stato	Messina	2022	IGINIA	Italy's first dual-fuel electric ferry equipped with a photovoltaic system, with plans for future hybridisation.	[xxiv]
Latvia	BB Green	Riga	/	Green City Ferries	The world's first electric-propulsion air-supported vessel operates in Riga. With a 70-passenger capacity and a top speed of 30 knots, this ferry is powered by a 200 kWh lithium-titanate battery system, enabling high-speed operation for over 30 minutes across a 14-nautical-mile range. Its charging system allows the battery to recharge in 15-20 minutes.	[xxv]
Lithuania	/	Klaipeda	2025	Klaipeda State Seaport Authority	Lithuania's first hydrogen-electric powered ship is under construction at Western Baltija Shipbuilding. This 42-m-long, 10-m-wide vessel is designed for waste management and will be powered by two electric motors, a 2,000 kWh battery system, and a hydrogen fuel cell system.	[xxvi]
Malta	/	Malta/ Comino Island	TBD	Comino Ferries	Two hybrid vessels will replace ten conventional smaller ferries operating near Comino, Marfa, and Cirkewwa, ensuring zero emissions and reduced noise in sensitive bay areas. Plans are also in motion to upgrade the Gozo Channel ferries to electric-powered vessels.	[xxvii], [xxviii]
Nether-lands	/	Amsterdam	2024	GVB	In Amsterdam, GVB is replacing older diesel-powered ferries with all-electric vessels, and introducing four new electric ferries as part of a broader plan to expand its fleet to 15 vessels. The ferries will be equipped with a battery capacity of 680 kWh and charging is done at two jetties that are each with 1,600 kW shore power.	[xxix]
Nether-lands	Altena VI/ Gorinchem XII	Altena/ Gorinchem	2023	Riveer	Two electric vessels, measuring 35.3 m in length and 7.6 m in width, are capable of accommodating 100 passengers and 100 bicycles. Powered by EST-Floattech batteries connected to two 171 kW permanent magnet motors, they are designed to reduce CO_2 emissions by 1,000 to 1,600 tonnes.	[xxx]
Nether-lands	/	Amsterdam	2021	GVB	Two ferries in Amsterdam use electric propulsion supported by diesel-powered generators and lithium-ion batteries, incorporating peak shaving technology to minimize the motor size. With a 4-minute crossing time and 2-minute docking periods, these hybrid ferries ensure efficient service on the IJ river.	[xxxi]
Norway	MS Ampere	Lavik/ Oppedal	2015	Norled	The world's first all-electric ferry, operating on a 5.5 km route in Norway, is capable of hosting 120 cars (350 passengers). The ferry's battery capacity is 1,000 kWh. Charging is performed via a pantograph system at a rate of 1.2 MW.	[13], [15]
Norway	MS Medstraum	Stavanger/ Hommersåk	2022	Kolumbus	The world's first full-electric fast ferry, funded by the European TrAM project, had a capacity of 147 passengers, and 23 knots cruising speed.	[xxxii]

Norway	Bastø Electric	Moss/ Horten	2021	Bastø Fosen	The hybrid vessel is 139.2 m long, able to host 600 passengers and 200 cars, or 24 trucks. It is powered by a 4.3 MWh battery and utilises a 9 MW fast charging system on the dock.	[xxxiiii]
Norway	/	Svolvær/ Skrova	2027	Torghatten Nord	The all-electric ferry, measuring 73 m in length, will have a capacity for 50 vehicles and 199 passengers. Equipped with a 3,600 kWh battery system, it is designed for fully electric operation between Svolvær and Skrova.	[xxxiv]
Poland	/	Baltic Sea	2025-2027	Polskie Promy	The Remontowa Shiprepair Yard is constructing three 195-meter-long hybrid-electric ferries, each equipped with two 7.5 MW Azipod electric propulsion units, multi-fuel engines integrated with battery power, an advanced Power and Energy Management System, and shore connection capabilities.	[xxxv]
Portugal	/	Lisbon	2023	Transtejo	Lisbon is leading Portugal's shift to electric ferries with an order for ten all-electric vessels to serve the Tagus River. The first ferry was already delivered by Astilleros Gondán shipyard to Transtejo, the city's urban transport provider.	[xxxvi]
Slovenia	Zlatorog/ Triglavska Roža	Ribčev Laz/ Ukanc	2023	/	On Lake Bohinj, two electric boats operate between Ribčev Laz and Ukanc, providing panoramic rides and enhancing the scenic experience for visitors while promoting sustainable tourism in the region.	[xxxvii]
Slovenia	/	Ljubljana	2020	Ljubljanca	The Ljubljanica River features a fully electric wooden boat, offering a 50-minute guided tour through the capital city, combining eco-friendly transport with cultural exploration.	[xxxviii]
Slovenia	/	Bled Lake	2020	Pletna Bled	This wooden electric boat line operates on Lake Bled, which provides daily service between the pier below Café Park and Bled Island. This initiative supports eco-friendly transportation in one of Slovenia's most iconic tourist destinations.	[xxxix]
Spain	Cap de Barbaria	Ibiza/ Formentera	2023	Balearia	This electric ferry is designed to accommodate 390 passengers and 240 linear meters of cargo.	[xl]
Sweden	Candela P-12 "Nova"	Stockholm	2024	Storstockholms Lokaltrafik	This electric hydrofoil ferry line utilises hydrofoil wings, drastically reducing energy consumption by 80% compared to conventional vessels. With a cruising speed of 25 knots, it has become the fastest vessel in Stockholm's public transport fleet. Serving a 15 km route, the vessel cuts commuting times in half.	[xli]
Sweden	E/S Movitz	Stockholm	2019	Green City Ferries	This vessel runs on a 10 km route and accommodates up to 98 passengers. Its Lithium Titanium Oxide battery is able to be charged at 500 kW power, taking approximately 10 min to reach full charge.	[xlii]

2.2. EV Charging Location Preferences

As the electrification of HDVs and vessels is still in its early stages and charging will take place at strategic and designated locations (e.g., company premises, charging hubs along highways, transhipment points, or mobile charging solutions for HDVs), the following section only addresses charging location preferences for EVs. The analysis focuses on the countries where the demonstration activities will take place within the AHEAD project, namely Denmark, Italy, Slovenia, and Portugal. Additionally, insights from Norway, one of the leading countries in EV adoption, will be discussed. Identifying charging location preferences ideally requires large representative surveys, which is beyond the scope of this task. Instead, we utilise several existing surveys and reports from different countries to highlight similarities, differences, and challenges in assessing charging location preferences among a diverse range of users.

2.2.1. Consumer Monitor in Denmark, Italy and Slovenia

To begin with, we present findings from the European Alternative Fuels Observatory's *Consumer Monitor 2023* report [16], which evaluated the charging frequency of EV users in, among other countries, Denmark [17], Italy [18], and Slovenia [19]. The report provides insights into charging location preferences based on the availability of current charging infrastructure. The results, presented in Figure 1, are based on the responses of 133, 142, and 340 EV drivers in Denmark, Italy, and Slovenia, respectively. Charging locations are classified into several categories: home charging via household socket, home charging with a dedicated charger, workplace charging, semi-public charging, public slow charging (either on-street or at parking facilities), and public fast charging. The charging frequency is grouped into three categories: (almost) never, a few times a month (occasionally), and often (daily or multiple times per week).

In all three countries, the most prominent charging location is at home with a dedicated charger; however, there are notable differences in the frequency of use. While over 75% of respondents in Denmark report frequent use, this figure drops to 60% in Slovenia and 54% in Italy. A surprisingly large share of users continue to rely on standard household sockets to charge their EVs. In Denmark, some survey participants appear to use both household sockets and dedicated chargers regularly. Additionally, more than 25% of Danish users frequently utilise the remaining charging infrastructure, particularly public slow and fast charging stations. In contrast, the utilisation of workplace, semi-public, and public charging is significantly lower in Italy and Slovenia, with usage in Slovenia falling to 15% or less at these locations. Additional surveys for Denmark, Italy, Portugal, and Norway will be discussed in the following sections.

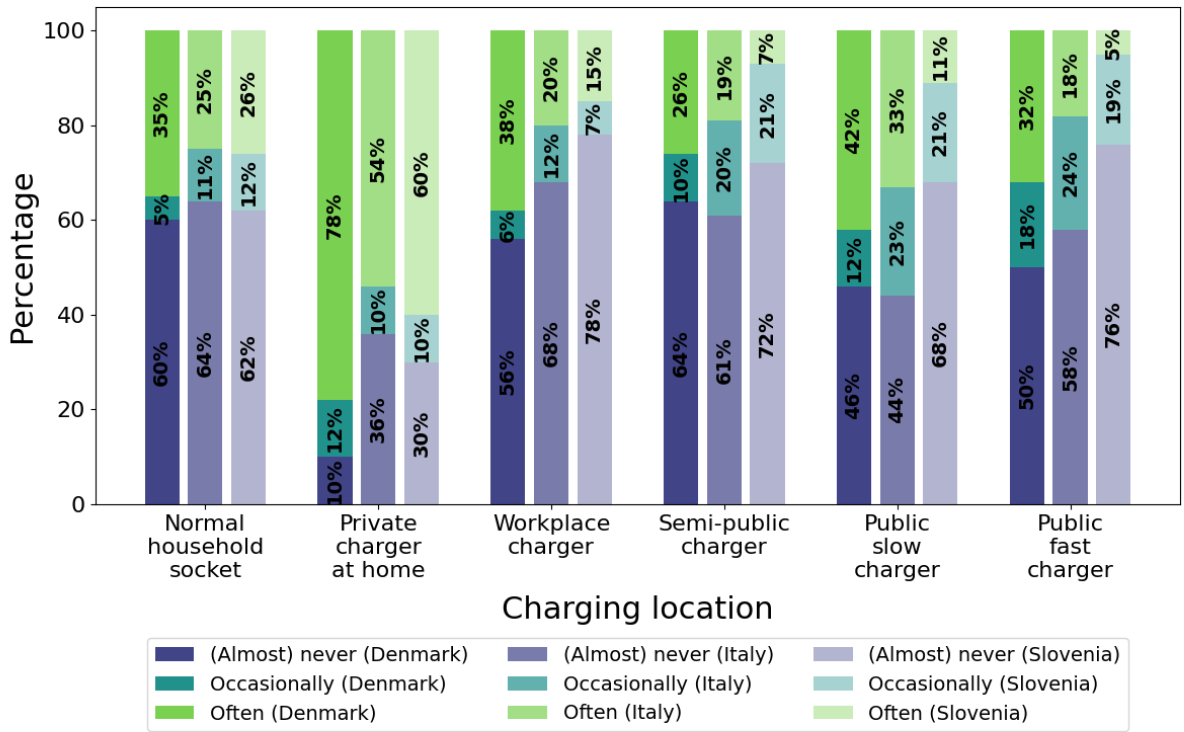

Figure 1 – Frequency of use of different types of charging infrastructure in Denmark, Italy, and Slovenia (Own illustration based on the European Alternative Fuels Observatory's *Consumer Monitor 2023* [17], [18], [19]).

2.2.2. Electric Vehicle and Charging Infrastructure Survey in Denmark

For Denmark, the *Elbiler og Ladeinfrastruktur 2022* report [20], a survey conducted by the Danish EV Drivers' Association (FDEL), the Federation of Danish Motorists (FDM), the Technical University of Denmark (DTU), and the Danish Society of Engineers (IDA), provides a more detailed view of Danish EV drivers' attitudes towards charging infrastructure, based on the responses of 1,792 car owners of which 516 are EV owners. Compared to the *Consumer Monitor 2023*, this report offers a more granular classification of charging locations, including home charging at a private car park, shared parking facility, or kerbside, as well as kerbside charging away from home, workplace charging, charging at large parking facilities, charging at errands/shopping facilities, and fast charging for either daily driving or long journeys. The frequency of use is also categorised in more detail: never, less than once a month, 1-3 times a month, 1-2 times a week, 3-4 times a week, and more than 5 times a week.

As shown in Figure 2, similar to the *Consumer Monitor 2023*, the majority of EV users charge their vehicles at home. Nearly 90% of home charging occurs regularly in private parking spaces while charging at shared parking facilities and kerbside locations is less common. This high prevalence of private home charging can be attributed to most EV users having access to private parking, with only 6% of respondents relying on kerbside parking. This highlights the significant influence of respondents' demographics on the survey results. Other charging locations are used sporadically, with under 10% of respondents charging weekly at these sites.

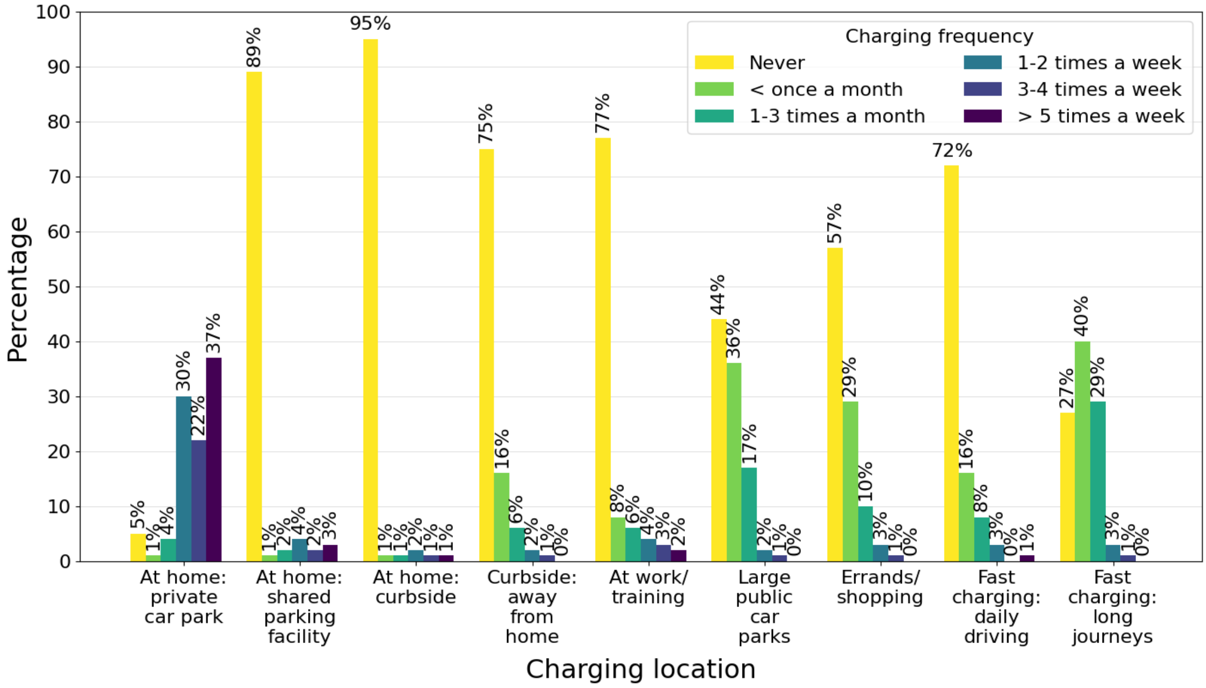

Figure 2 – Frequency of use of different types of charging infrastructure in Denmark (Own illustration based on the *Elbiler og ladeinfrastruktur 2022* Report [20]).

While Figure 2 examines the current charging behaviour, indicating charging location preferences that may be strongly influenced by the current availability of charging infrastructure, Figure 3 analyses the perceived importance of different types of charging infrastructure among survey respondents. Private home charging remains the most important, with over 80% of respondents rating it as very important. In contrast, home charging at shared parking facilities and kerbside locations is considered important/very important by less than 15%, likely due to approximately 80% of respondents having access to private parking. Although Figure 2 shows that fast charging infrastructure is used only sporadically by most EV users, Figure 3 highlights its perceived importance for long journeys, presenting a clear contrast in perception. Nearly half of the respondents emphasise the importance of charging at large public car parks, while around 20-30% also consider charging during errands/shopping and fast charging for daily driving as important. Overall, the perceived importance of away-from-home charging infrastructure does not currently align with its actual utilisation.

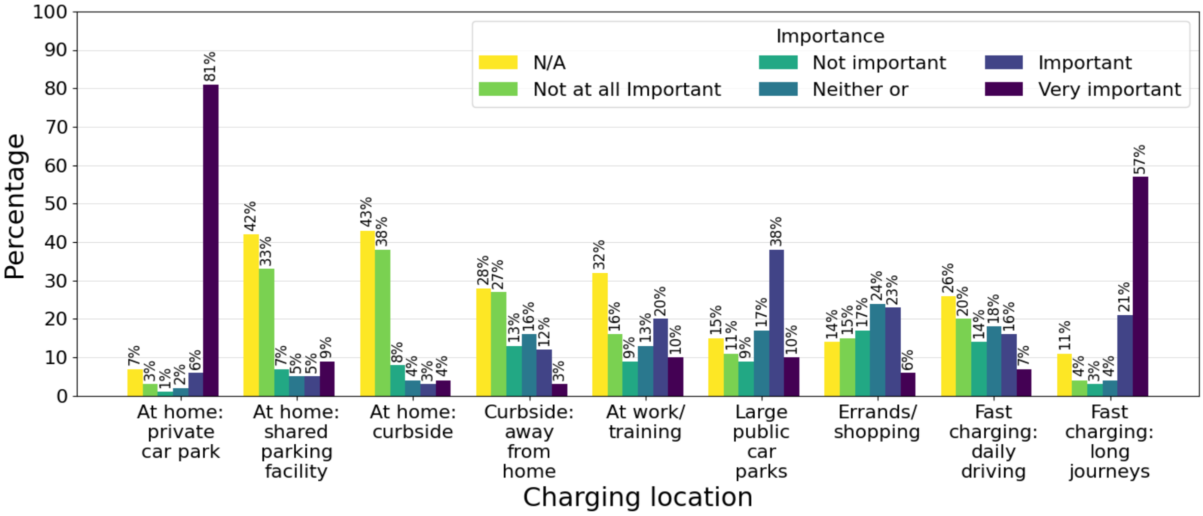

Figure 3 – Importance of different types of charging infrastructure in Denmark (Own illustration based on the *Elbiler og ladeinfrastruktur 2022* Report [20]).

2.2.3. Smart Mobility Study in Italy

For Italy, the *Smart Mobility Short Report 2023* report [21] provides another angle on the utilisation of current charging infrastructure, based on data from approximately 700 EV users. The report only distinguishes between home, work and public charging and assesses the frequency of use as a percentage of charging events, namely 0% (never), 1-25%, 25-50%, 50-75%, 75-99% and 100% (always) of charging events. As illustrated in Figure 4, and aligned with previous findings, the preferred charging location is at home, where 57%, 17%, and 15% of the respondents indicate that 50-75%, 75%-99%, and 100% of their charging events happen, respectively. Not shown in Figure 4, but contrary to Figure 1, the report also indicates that there is almost an equal split between people who charge at a dedicated charger at home and people using a regular household socket. Workplace and public charging only account for a small percentage of charging events. Only roughly 15% use those locations for more than half of their charging events.

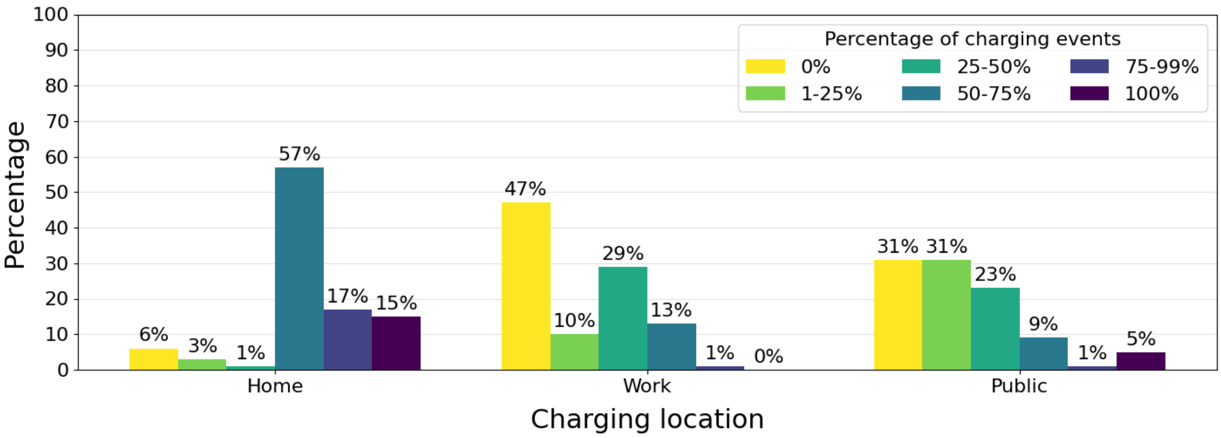

Figure 4 – Frequency of use of different types of charging infrastructure in Italy (Own illustration based on the *Smart mobility 2023* report [21]).

2.2.4. Study on Electric Mobility in Portugal

In Portugal, the “Estudio em mobilidade eléctrica em Portugal” [22] by the National Automobile Club examines the frequency of charging at different locations—namely home, work, and public—based on responses from 504 participants. Additionally, 208 respondents provided insights into their usage of various types of public charging infrastructure, including slow charging (≤ 22 kW), fast charging (22–50 kW), and ultra-fast charging (>50 kW). The former is shown on the left in Figure 5, while the latter is displayed on the right.

Home charging is the most popular option, with 18% charging daily at home and almost 80% charging at least once per week. In contrast, workplace and public charging are regularly used by only a small number of EV users; only up to 20% charge at these locations at least once a week. Regarding public charging, slow charging is the preferred method, followed by fast and ultra-fast charging, although the differences in charging frequency are minimal.

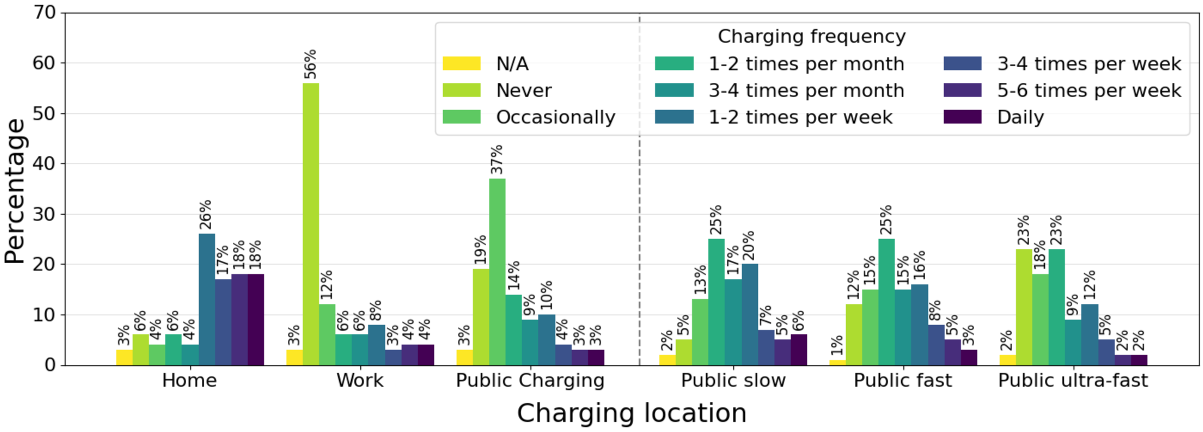

Figure 5 – Frequency of use of different types of charging infrastructure in Portugal (Own illustration based on the *Estudo Mobilidade Elétrica em Portugal* report [22]).

2.2.5. Norwegian EV Driver Survey

Finally, Figure 6 illustrates the charging frequency of EV users at home, work, public normal, and fast charging stations in Norway, based on the *Norwegian EV Driver Survey 2023* [23], which includes responses from over 16,900 participants. Consistent with previous findings, home charging remains the preferred option among EV users. The results show that only 20% charge at home daily, while 33% and 36% report that charging every 2–3 days or weekly is sufficient. These findings align with observations from other countries, such as Denmark and Portugal, where a certain share of users charge daily to meet daily energy needs but a significant portion charges only every few days, accumulating larger energy demands over time. This insight is crucial for assessing the impact of EV charging on the power distribution grid.

While not shown in the graph, the survey also indicates that roughly 90% of users charging at home use a dedicated charger, while only about 9% use a regular household socket. This is a significantly larger share of EV drivers using a dedicated home charger compared to the numbers presented for Denmark, Italy, and Slovenia in Figure 1. It also represents a significant increase from the 13% of users with private home charging boxes reported in the *Norwegian EV Driver Survey 2015*, indicating an expected rise in the use of dedicated home chargers as the EV market develops in other countries.

Charging infrastructure at work is used less frequently, with less than 15% of EV drivers charging once or multiple times per week, while more than 75% never use it. Public normal charging is also only used sporadically by most respondents, with half indicating that they use such infrastructure less than once a month. Public fast charging primarily supports occasional long-distance trips, with 29% and 55% of respondents indicating they use it once or less than once per month, respectively.

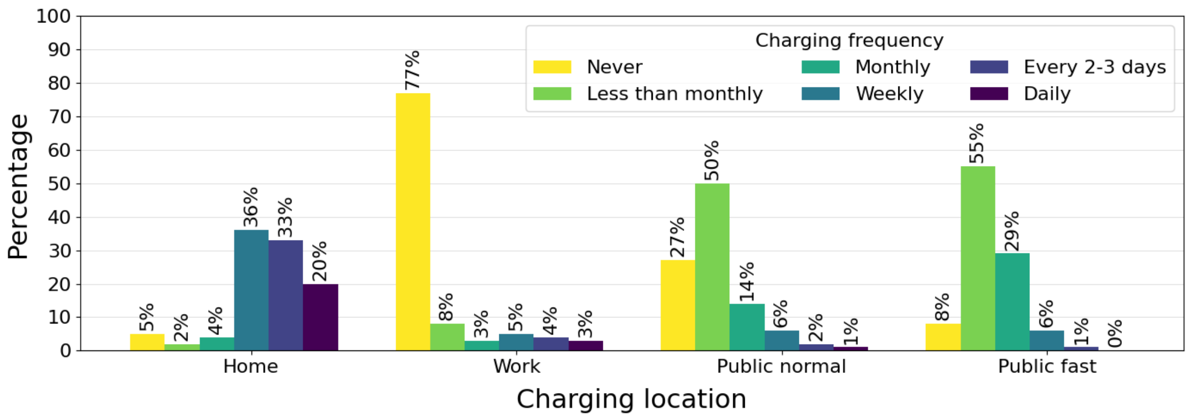

Figure 6 – Frequency of use of different types of charging infrastructure in Norway (Own illustration based on *The Norwegian EV driver survey 2023* [23]).

3. CHARGING BEHAVIOUR

In this section, we examine the charging behaviour of EVs, HDVs, and vessels. First, we describe the data used for the analysis, which includes EV charging at various locations, HDVs such as buses and trucks, and vessels. Next, we outline the methodology employed to analyse charging behaviour. Finally, we present the results for each type of charging.

3.1. Description of Data

To start with, we discuss the characteristics of the data used for each type of charging, differentiating between EVs, HDVs, and vessels. A summary of the characteristics of the data used in this work is presented in Table 3.

Table 3 – Summary of the data used to analyse the charging behaviour of EVs, HDVs, and vessels.

Location	Country	Description	Max. Outlet Power	Timeframe
Home	Denmark	Distributed across the country	11 kW	Jan 2023 – Dec 2023
University	Denmark	One site in an urban area	11 kW	Sep 2022 – Nov 2024
Hospital	Denmark	Three sites in an urban area	22 kW	Sep 2023 – Aug 2024
Kerbside	Denmark	Six sites in an urban area	22 kW	Aug 2022 – Aug 2023
Car parks	Denmark	Two sites in an urban area	22 kW	Jan 2023 – Dec 2023
Petrol station	Denmark	Four sites across the country	150 kW; 300 kW	Nov 2023 – Aug 2024
Bus depot	Italy	One site in an urban area	100 kW	Oct 2023 – Aug 2024
Garbage truck depot	Denmark	One site in an urban area	120 kW	Sep 2024 – Oct 2024
Ferry terminal	Norway	Oppdal/Lavik, rural area	1.2 MW	Simulated

3.1.1. Electric Vehicle Charging

The light-duty EV charging data originates from Denmark and was provided by the electro-mobility charging provider Spirii. Spirii's data comprises high-resolution records of charging sessions, with both power and energy measurements logged at approximately one-minute intervals. In the following sections, we describe the data characteristics and details for each charging location.

Home charging

The residential charging data is derived from approximately 4,000 individual wall boxes installed in households throughout Denmark. This dataset encompasses a one-year period from January 2023 to December 2023, with over 740,000 charging events. The majority of households in Denmark are equipped with 22 kW AC chargers. However, since most single-family houses in Denmark are typically limited to 25 A fuses, which do not support 22 kW without an upgrade to the grid connection, the actual charging power is often capped at 11 kW.

Charging at university

The university charging data was collected from a single charging cluster at DTU in Lyngby, spanning the period from September 2022 to February 2024. During this time, approximately 3,400 charging events were recorded. The charging cluster comprises six charging stations, each equipped with two outlets, allowing up to 12 EVs to charge simultaneously. Each charger has a maximum power output of 22 kW, with each outlet capable of delivering up to 11 kW.

Charging at hospitals

The hospital charging data originates from three different hospitals in Denmark, with data recorded for a one-year period from September 2023 to August 2024. In total, the three charging clusters consist of 46 individual charging outlets, each with a maximum power of 22 kW. Two charging clusters are publicly accessible, while one of the charging locations appears to be mostly used by hospital employees. In total, roughly 9,400 charging events were considered.

Kerbside charging

The public kerbside charging data was gathered from six residential kerbside charging locations with a total of 33 outlets, located in a densely populated urban area in Denmark. This data covers a one-year period from August 2022 to August 2023, during which we estimated a total of approximately 8,300 charging events took place. The charging clusters contain between four and six outlets each, with each outlet capable of providing a maximum power of 22 kW.

Public car park charging

The car park charging data originates from two large parking facilities located in two urban areas in Denmark, for a total of 46 outlets. Approximately 12,200 charging events were analysed for the one-year period between January 2023 and December 2023. Similar to the other charging sites, each individual charging outlet can deliver a maximum power of 22 kW. The charging sites cater to a diverse set of users. One parking facility is located near residential housing, offices, and leisure or errand-related activities such as a cinema, supermarkets, and restaurants; the other is situated close to residential housing, shopping malls, and event areas.

Fast charging at petrol stations

The fast charging data is sourced from four different fast charging stations located at petrol stations, each equipped with two outlets typically offering 300 kW per charger, split between the outlets. One charger, however, only offers 150 kW in total. Two of the charging locations are situated near a highway, while the other two are in more rural areas in Denmark. We examined a total of approximately 4,400 charging events between November 2023 and August 2024.

3.1.2. Heavy-Duty Electric Vehicle Charging

The heavy-duty charging data includes electric buses and garbage trucks. Other forms of electric heavy-duty transport could not be analysed due to limited data availability, as these technologies are only beginning to enter the market. The bus data originates from Italy, while the garbage truck data is from Denmark, as discussed in more detail below.

Buses

Data for the charging of electric buses was provided by the local public transport operator Azienda Trasporti Milanesi (ATM) of the Milan metropolitan area, which aims to achieve a 100% electric bus fleet by 2030. Currently, the e-bus fleet comprises 244 units, with plans to increase to 280 by the end of 2024, and to 490 by the end of 2025, ultimately reaching a target of 1,200 units.

So far, three depots (SAN DONATO, SARCA, GIAMBELLINO) host the electric fleet, maintaining a one-to-one ratio between chargers and vehicles. Generally, the chargers supply the e-buses with 100 kW DC power. Additionally, e-buses can be charged outside the depots using “opportunity chargers”. Currently, 14 charging points are distributed across three locations in Milan (4 in Piazza IV Novembre, 4 in Piazza Bottini/Via Viotti, and 6 in Viale Zara), with a maximum DC power of 200 kW, higher than in the depots due to the need to perform the charging operations of the buses in a shorter amount of time. To accommodate the growing e-bus fleet, ATM plans to complete the electrification of the existing depots and construct three new depots (PALMANOVA, TOSCANA, and TRIBONIANO) dedicated entirely to e-buses.

The data shared by ATM for this report comes from the charging operations at the GIAMBELLINO depot, encompassing 75 charging outlets. Data from the SAN DONATO depot and the opportunity chargers were excluded due to insufficient quality, and the SARCA depot was not considered due to the significant influence of an Energy Management System on operations. The dataset covers an 11-month period from October 1, 2023, to August 31, 2024, encompassing a total of 29,900 charging events. The time resolution is 10 seconds, and the following variables are provided for each charger: the State of Charge (SoC), the Vehicle ID, and the charging power in kW (allowing identification of the start and end times of each charging session).

Garbage trucks

The garbage truck charging data, provided by Spirii, originates from Denmark and spans approximately six weeks between September and October 2024. The dataset encompasses five chargers with two outlets each, maximum power per charger of 120 kW, 60 kW per outlet if two outlets are used simultaneously. Approximately 270 charging sessions were analysed, although the exact size of the vehicle fleet using the chargers is unknown.

3.1.3. Charging of Vessels and Electrification of Ports

Similar to HDV charging data, datasets on vessel charging are scarce and often subject to confidentiality restrictions. As a result, a common strategy is to synthesise data based on the available information. Due to this lack of data, in this deliverable, we synthesised two scenarios: the operation of a fully electric ferry in Norway, and the onshore power supply for vessels at Funchal Port on Madeira Island, Portugal.

Scenario 1: Fully Electric Ferry in Norway

The first scenario involves the Ampere ferry, the world's first fully electric ferry, launched in 2015 and operated by Norled. The ferry operates on the Sognefjorden between Lavik and Oppedal, a 6 km route with a 20-minute crossing time and a 10-minute turnaround at each port. Each crossing consumes approximately 150 kWh of energy (based on a 450 kW motor running for 20 minutes). The ferry's battery capacity is 1000 kWh. Although three ferries serve this route, only one is fully electric. Charging is performed via a pantograph system at a rate of 1.2 MW, with power supplied by onshore batteries, due to the local grid's limited capacity. On both sides of the fjord, there are two independent battery rooms, each equipped with 260 kWh batteries [13], [15].

For data synthesis, a 450 kW grid connection was assumed, based on subsequent analysis, which showed this to be the minimum power required to support the operation of three electric ferries with the current infrastructure. Using the ferry schedule, it was possible to simulate the operation of all three ferries as fully electric. The methodology for simulating ferry operations is straightforward. The first trip is assigned to the first ferry, which continues to operate until it reaches either the battery depletion point or encounters a scheduling conflict. At that point, the second ferry takes over and operates under the same conditions, and so forth. Several assumptions were made for this emulation, including:

- No energy losses during charging;
- Each ferry operated between 10% and 90% SoC levels;
- Constant energy consumption throughout the year and across different times of day;
- The operation is not impacted by weather conditions;

- Battery efficiency remains constant over time;
- The onshore battery system remains operational without downtime for maintenance.

It is important to mention that, shortly before the hand-in of the deliverable, it was announced that Ampere and the other ferries will be replaced by new electric ferries that are expected to operate autonomously by the years 2027/2028 [24].

Scenario 2: On-Shore Power Supply at Funchal Port

The second synthesised dataset concerns the on-shore power demand at Funchal Port, a frequent stopover for transatlantic vessels, particularly cruise ships. The synthesis methodology followed the approach in [25] and involved gathering data on scheduled shipping traffic for 2024 according to the port authority of Funchal, calculating the average power demand for each vessel based on its gross tonnage (GT) and schedule, and generating a forecasted load diagram for the port's on-shore power supply. A linear regression model, using data from Table 4, was applied to estimate each ship's on-shore power consumption based on its GT. The methodology considers power requirements in 15-minute periods.

Table 4 – Estimated power requirement per moored vessel in kW (Modified table based on [26]).

Ship Category	<= 999 GT	1k – 4.9k GT	5k – 9.9k GT	10k – 24.9k GT	25k – 49.9k GT	50k – 99k GT	>=100k GT
Cruise	20	119	272	570	1194	2100	2912

The following assumptions were made in this scenario:

- Power consumption was assumed to be constant during the vessel's mooring period, regardless of fluctuations in power demand (e.g., due to heating or air conditioning requirements).
- The regression model assumes a linear relationship between GT and power demand, which might not account for outliers or non-linear consumption patterns for specific ship types.
- The dataset does not account for ship auxiliary systems that may remain powered by onboard generators rather than shore power.

3.2. Charging Behaviour Analysis Results

In the following, we highlight the results for each category presented in Table 3, starting with EVs, followed by HDVs, and concluding with vessels.

3.2.1. Presentation of Results

To enable a better comparison of the different charging sites, to the best of our possibilities, we aimed to present the results of the charging behaviour analysis in the same format. As a result, the analysis of the charging behaviour for EVs and HDVs follows the same structure. For vessels, we had to take a different approach due to the lack of real charging data, as highlighted in Section 3.1.3.

The analysis of EV and HDV charging is presented through eight subplots. The first subplot illustrates the weekly statistical distribution of the aggregated power demand with a 15-minute resolution. In other words, each boxplot displays the statistical distribution of power measurements taken every 15 minutes, grouped by the hour of the day. This power profile serves as a critical indicator of potential impacts on the power distribution grid and the required grid connection capacity. Understanding power demand patterns is essential for grid operators to ensure stability and prevent overload, while also guiding the design of infrastructure to meet future charging needs. Note that all the time values are in local time, i.e. Central European Time (CET) in winter (UTC+1) and Central European Summer Time (CEST) in summer (UTC+2).

The second and third subplots highlight several key characteristics of charging events, including the time of plug-in (which often, but not necessarily, corresponds to the time of arrival), start of charging time, stop of charging time, and time of plug-out (which usually, but not necessarily, corresponds to the time of departure). The y-axes of the histograms represent the percentage of charging events binned by the values on the x-axis at a 15-minute resolution throughout the day. Subplot 2 shows the plug-in and start of charging times, while Subplot 3 examines the end of charging and plug-out times. It is noteworthy that the start of charging only diverges from the plug-in time when active management of the charging session is employed. Consequently, only the home charging data distinguished between the plug-in and start of charging time as many users delay the start of charging, while the other locations treat plug-in and start of charging times as equivalent. Hence, for the sake of simplicity, only the plug-in times are indicated. Significant differences between the stop of charging and plug-out time indicate a high flexibility potential of a charging site to postpone or modulate charging. Analysing these temporal characteristics is crucial for understanding user behaviour and optimising charging strategies that can alleviate peak demand and enhance grid efficiency. Subplot 4 further explores this flexibility by illustrating the resulting connection and charging duration, expressed as percentages of events in 15-minute intervals. Significant differences in connection and charging durations suggest a high flexibility potential for the analysed charging location.

The fifth subplot examines the maximum charging power during each session, presented as the share of maximum power values falling into the bins on the x-axis, providing insights into the types of EVs that primarily use the charging location. In the absence of a management system, maximum charging power is influenced by the power capabilities of the EVs, the charging infrastructure, the SoC of the EV, as well as the battery management system. When maximum charging power diverges from the capabilities of the respective outlets (detailed in Table 3) it indicates that the bottleneck lies in the power capabilities of the EVs themselves. Analysing maximum charging power is essential for identifying infrastructure upgrades needed to accommodate evolving EV technology and increasing charging demands. The sixth subplot analyses the energy demand of charging events, presented as percentages and categorised into 5 kWh intervals.

Finally, Subplots 7 and 8 display the total daily charged energy for the respective location, based on different days of the week (Subplot 7) or months of the year (Subplot 8). Each boxplot represents the statistical distribution of total daily energy consumed at the location, binned by days of the week or months. This approach allows for an analysis of daily differences based on the day of the week and seasonal changes. Focusing on total daily charged energy is crucial, as several datasets span over a year, making it impractical to examine accumulated energy demand on a monthly basis alone. It is also important to note that seasonal differences may arise from variations in EV energy consumption, as well as factors such as holidays and an increasing number of vehicles—though the latter is unlikely to significantly impact the results in the short term. Subplot 7 further includes an analysis of the number of charging sessions per outlet per day, illustrating the median along with the upper and lower bounds, providing a comprehensive perspective on the utilisation of the charging infrastructure. This analysis is essential for understanding how effectively the charging resources are used, guiding future investments in charging infrastructure, and improving overall network efficiency.

3.2.2. Electric Vehicle Charging Behaviour

In this section, we highlight the EV charging behaviour at the six previously described EV charging locations: charging at home, charging at university and hospital premises, kerbside charging, charging at large public car parks, and fast charging at petrol stations.

Home Charging

Figure 7 illustrates the charging behaviour analysis results for home charging in Denmark. Figure 7.1 suggests that contrary to the initial stages of market ramp-up when users were charging upon arrival in the evening, a significant proportion of EV owners now delay charging until nighttime when electricity costs are lower, as indicated by the load peak between 00:00 and 03:00, previously highlighted in [27]. It is further evident that weekdays and weekends exhibit different characteristics. On weekdays, peak consumption occurs during nighttime hours, while weekends show an additional notable peak around noon, suggesting that people also charge their EVs after running errands in the morning.

Figure 7.2 highlights the smart charging behaviour [28] by illustrating the differences between plug-in times and the start of the charging process. The majority of vehicles connect to the charger between 15:00 and 23:00; however, the plug-in time and the start time are often unequal, as users frequently delay the charging process. Consequently, strong peaks in charging starts are observed during the late evening and at the beginning of each hour, particularly at 00:00 and 01:00. This is made possible either through the Spirii application or the EV user interface, which allows users to schedule the charging windows. Figure 7.3 illustrates the differences between the completion time of the charging process and the plug-out time. The highest frequency of plug-out times occurs in the morning hours. After this peak, there is a plateau in plug-out probability throughout the day. However, most charging processes are completed before this time, as shown by the histogram representing the end of charging time. This plot also shows two peaks for the completion time of charging: one at night, likely due to smart charging, and another in the evening, likely corresponding to charging processes that end shortly after the vehicle is plugged in.

Figure 7.4 highlights significant flexibility potential, as most vehicles are connected longer than the actual charging duration (the peaks in the two histograms are displaced by approx. 7 hours). Some of this flexibility is already utilised by EV users who postpone charging, as shown in Figure 7.3, thereby increasing idling time before charging, and reducing idle time after charging is completed. Most charging processes last between one to four hours, with only a few exceeding eight hours. In terms of connection duration, short durations are most common. After one hour, the frequency decreases, but a plateau forms between eight and sixteen hours due to many vehicles having long connection durations. After sixteen hours, the probability decreases steadily, with a slight peak at 24 hours.

Figure 7.5 shows that the most common charging powers are 3.7 kW, 7.4 kW, and 11 kW, corresponding to the capacity limits of the vehicles' onboard chargers and/or the chargers themselves. In the analysed dataset, there are no sessions with charging power higher than 11 kW, despite the installed capacity of the EVSEs being 22 kW. The discrepancy arises from the standard household fuse limits in Denmark, which cap the capacity at 25 A per phase, equivalent to 17.2 kW. As highlighted in Figure 7.6, the most common amount of energy charged per session is up to 15 kWh, corresponding to approximately 75 km of range on a standard passenger car [29], after which the probability decreases continuously.

Figure 7.7 illustrates the total daily charged energy and sessions per day per outlet. Energy consumption is lower on Mondays and Tuesdays and slightly higher on Saturdays and Sundays, suggesting that more energy is charged over the weekend, reducing the need for charging at the start of the week. A similar pattern is observed for sessions per day per outlet, with the highest median of approximately 0.5 sessions per outlet (1 session every 2 days) occurring on weekends and the lowest, around 0.4 (1 session every 2.5 days), on Mondays. It must be noted that the session is considered to start on a Monday if the plug-in time is before midnight on Tuesday, so the charging start delay from Figure 7.2 doesn’t influence Figure 7.7. Finally, Figure 7.8 highlights the seasonality of daily charged energy, peaking in the winter months and reaching its minimum in July. This trend can be attributed to increased energy demand in winter and the main holiday season in Denmark, which typically falls in July.

Although the dataset considered does not cover all residential customers nationwide, the general behaviour aligns with the findings in [30] for another Danish CPO, the values reported in [31], and the *Norwegian EV Driver Survey 2023* [23]. According to the survey, about 30% of the more than 16,900 respondents control their charging via the car or car app, 23% use the home charger, roughly 10% rely on an operator, and approximately 23% manage it manually by plugging the EV in and out. Only about 12% do not control their EV charging. Additionally, 70% of respondents charge their EVs between midnight and 07:00, around 37% charge between 20:00 and midnight, and less than 20% charge during peak grid hours between 16:00 and 20:00. The significant interest in smart charging in Norway can likely be attributed to the country's advanced state of EV adoption. This trend may be less pronounced in markets where EV adoption is still in its early stages.

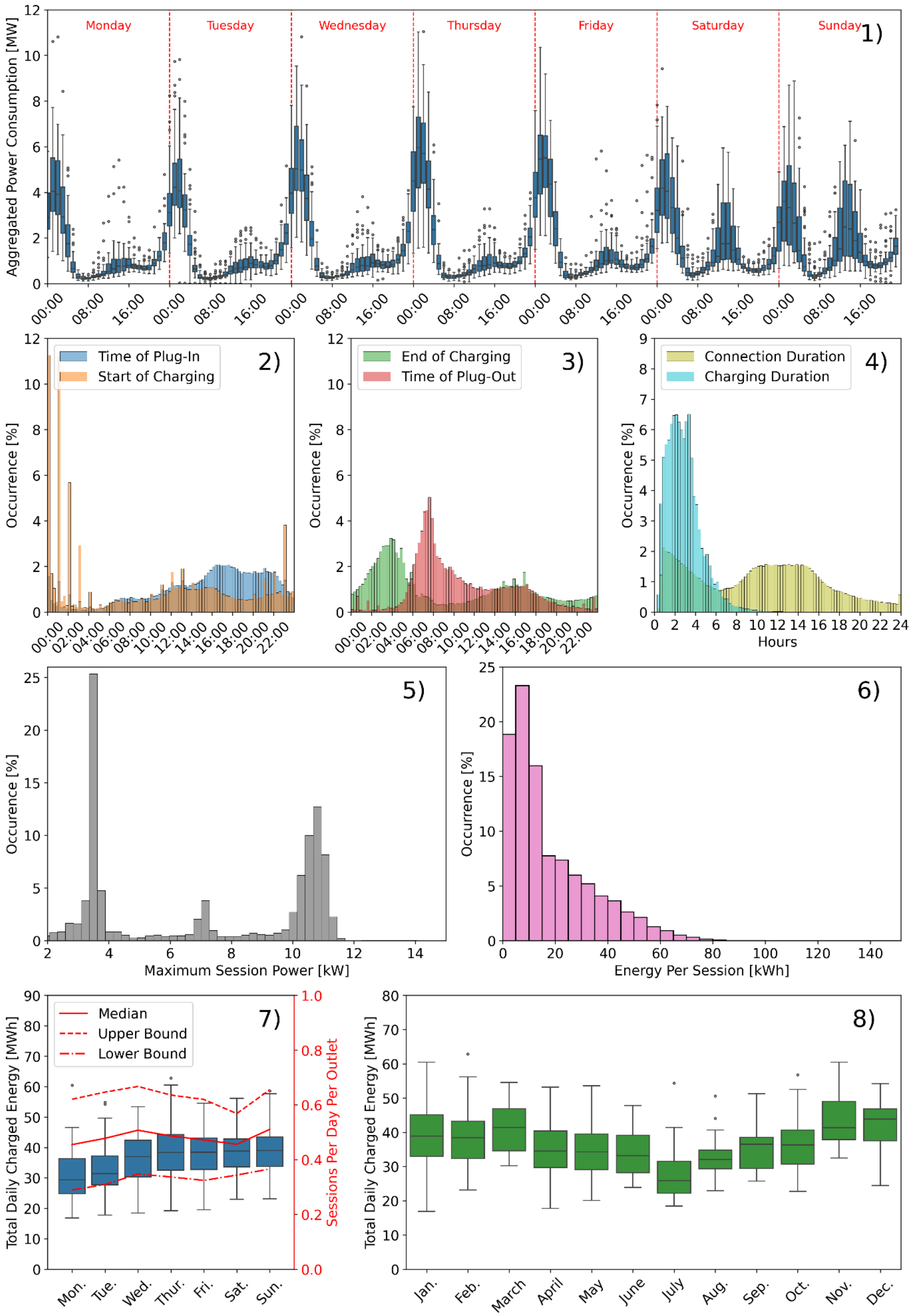

Figure 7 – Home charging behaviour in Denmark.

Charging at University

Charging behaviour at the analysed university parking lot, consisting of twelve 11 kW outlets, exhibits typical workspace charging patterns, as illustrated in Figure 8. On weekdays, there is a distinct morning peak as users arrive for work or study, while the load is significantly lower on weekends. The peak power for the charging cluster is around 09:00 on working days, whereas on weekends, it occurs around noon and is less pronounced. Figure 8.1 shows that the aggregated cluster rarely exceeds a power of 70 kW, while the maximum recorded power is 80 kW, which can be assumed as the size of the parking lot electric fuse.

Figure 8.2 shows that most people plug in their EVs between 07:00 and 09:00 in the morning. Since the charging cluster does not use smart charging (i.e. postponing or scheduling), charging sessions begin upon plug-in. Hence, only the plug-in pattern is shown. Figure 8.3 indicates that most vehicles complete their charging by noon. However, the majority of EVs remain connected and only depart from the charging cluster in the afternoon, highlighting a large flexibility potential for smart charging. This finding is confirmed by Figure 8.4, which shows that only a few charging sessions exceed six hours, with most lasting one to four hours. In contrast, the most common connection duration is around eight hours, yet there is a notable number of shorter charging sessions, peaking at two to four hours.

As depicted in Figure 8.5, the most common charging powers are 11 kW and 3.7 kW. The 11 kW limit corresponds to the maximum power per outlet, while the 3.7 kW is used by vehicles unable to charge at higher rates. Figure 8.6 shows that the most frequent energy consumption per session is between 5 and 10 kWh (25-50 km range), although over 40% of sessions consume more than 20 kWh (80 km range).

The stark contrast between weekdays and weekends is further emphasised in Figure 8.7, where the total daily energy charged is significantly lower on weekends. Additionally, the charging cluster sees higher usage at the start of the working week, with a slight decline in sessions per outlet per day over the week. This could be due to more people working from home later in the week. Figure 8.8 illustrates the seasonality of daily charged energy, showing generally higher usage during winter and lower usage in summer, particularly in July when holidays happen in Denmark. December is an exception, as many users do not charge their EVs at the workspace due to holidays.

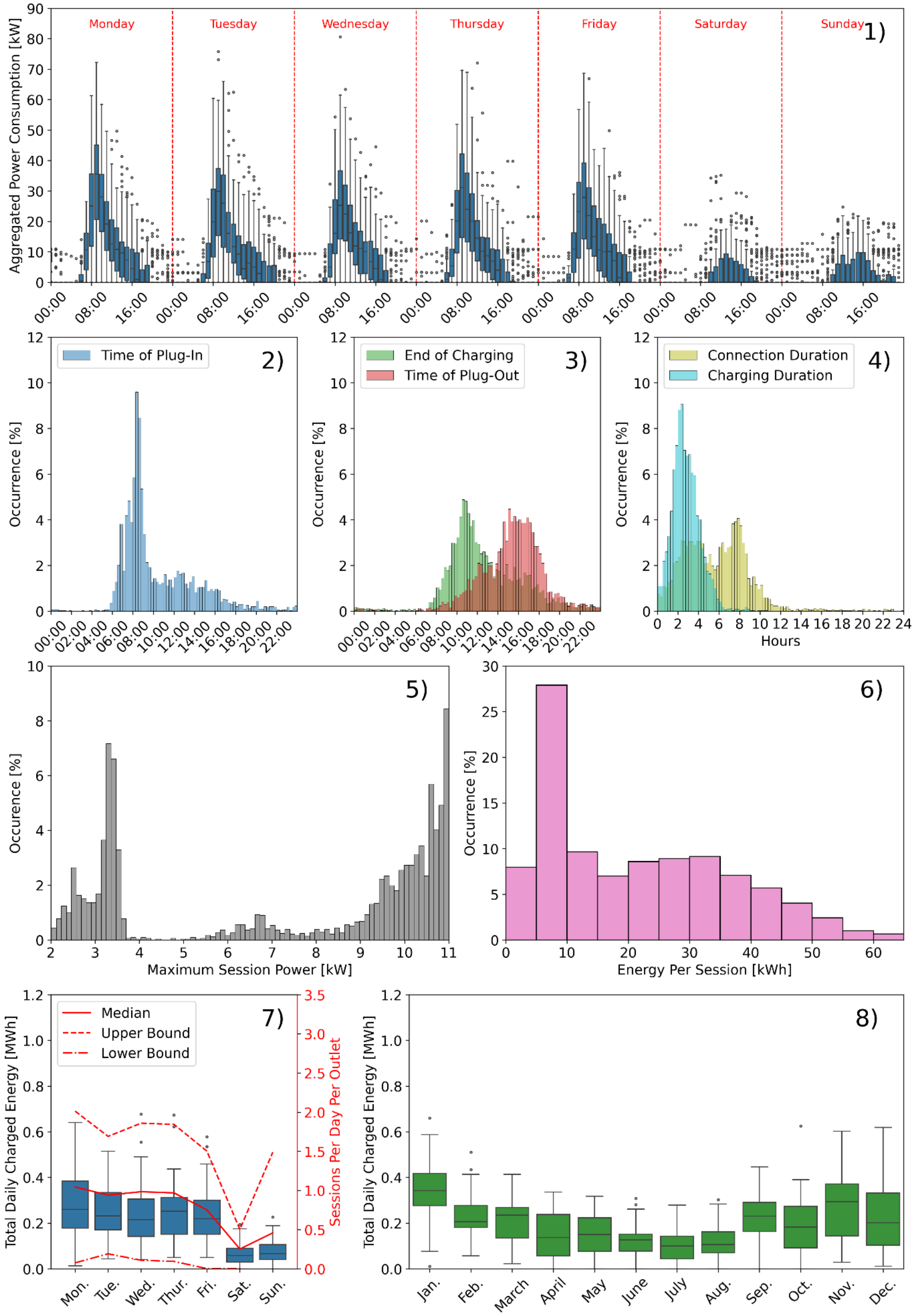

Figure 8 – Charging behaviour at a Danish university parking lot.

Charging at Hospitals

Charging at urban hospital locations exhibits a distinct behaviour between weekdays and weekends, reflecting characteristics typical of workplace charging clusters. The analysed dataset includes 46 charging outlets from three hospitals in Denmark. The load boxplot in Figure 9.1 shows a double-peak pattern on weekdays, one in the morning (120 kW) and another in the afternoon (140 kW), while charging activity is minimal during the night. On weekends, the load is generally considerably lower compared to weekdays and does not exhibit significant peaks. This could be due to the reduced number of routine medical examinations performed at the hospitals during the weekends.

The charging process begins immediately upon plug-in, without delay. Hence, only the plug-in pattern is indicated in Figure 9.2. Vehicle plug-in times exhibit three notable peaks: the largest in the morning around 07:00, another around 16:00 in the afternoon, and the smallest around 22:00 in the evening. While charging is semi-public (accessible by both employees and visitors), this behaviour may be primarily explained by hospital employees charging during specific hours following their work shifts. Figure 9.3 highlights that the most common plug-out time is around 16:00, coinciding with the end of the morning shift. The majority of charging sessions are completed during the day, with relatively few sessions extending into the night. Figure 9.4 shows that vehicles are typically connected to the EVSE for longer than the actual charging duration, suggesting significant flexibility potential. Additionally, a peak in connection times at about two hours is visible, likely attributable to visitors. Still, compared to the other peaks, it is not as pronounced, underscoring the influence of work shifts on EV charging. Most charging sessions conclude within six hours, with the most common duration being between two and four hours. In contrast, connection times frequently span either eight to nine or sixteen to eighteen hours.

The most frequent charging powers are 3.7 kW and 11 kW, while 7.4 kW and 22 kW are less common, as shown in Figure 9.5. Figure 9.6 presents the distribution of total energy charged per session, with the most common range being 5–15 kWh (25-75 km range). The likelihood of larger energy amounts decreases steadily. The differences between weekdays and weekends are further emphasised in Figure 9.7, where the energy charged and the number of sessions per day are similar on weekdays but drop significantly on weekends. Finally, Figure 9.8 highlights no significant seasonality, except for a notable increase in January.

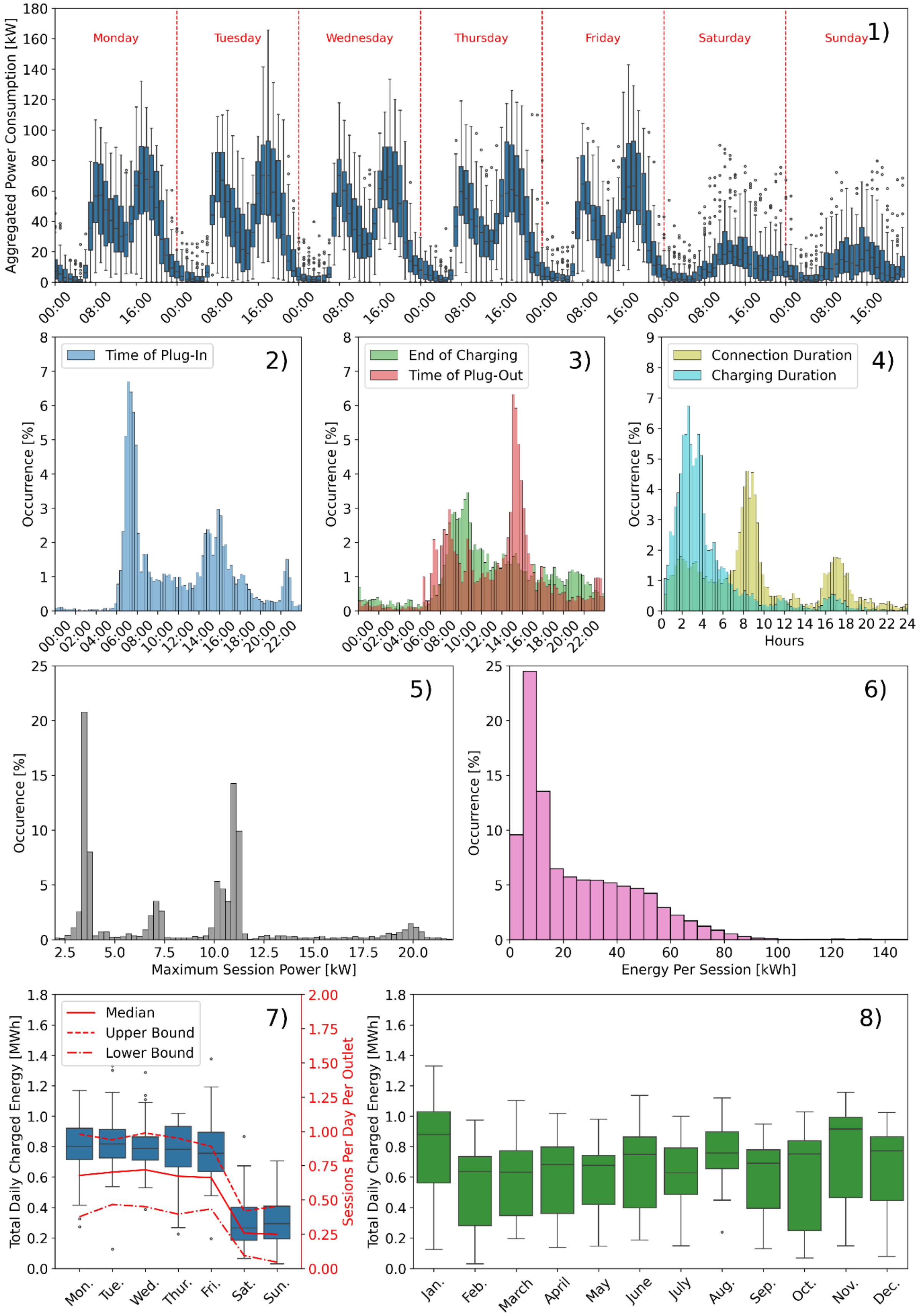

Figure 9 – Charging behaviour at three Danish hospital parking lots.

Kerbside Charging

The urban kerbside charging results reveal a combination of overnight charging and short-term usage throughout the day. A significant number of users utilise the charging clusters as a substitute for home charging, primarily due to their location in areas dominated by apartment buildings. In contrast to the private home charging behaviour results illustrated in Figure 7, delaying charging processes in time is not employed. Peak power demands coincide with grid peak loading around 18:00 when people return home and plug in the EV, as illustrated in Figures 10.1 and 10.2.

While charging activity during the day is limited, there is minimal charging overnight. Most charging sessions conclude in the evening or early nighttime hours, despite a significant number of users leaving the charging sites in the morning, as indicated in Figure 10.3. Two user groups are identified by the connection duration histogram in Figure 10.4: one that connects for only a few hours (e.g., during the day when parking restrictions limit the duration to a maximum of three hours) and another that remains connected for over eight hours overnight. The majority of charging durations range from one to three hours. Consequently, for users connected for extended periods (e.g., overnight users), there is substantial flexibility potential to shift charging demand from peak periods to nighttime hours.

Figure 10.5 highlights that approximately one-quarter of users charge single-phase at around 16 A (3.7 kW), while the second-largest group utilises three-phase charging at approximately 11 kW. Charging at 32 A is less common, with even fewer users charging at the nominal power of 22 kW. Figure 10.6 demonstrates that a majority of users charge only a small amount of energy per session, with over half charging less than 20 kWh (100 km range), most frequently between 5 and 10 kWh (25-50 km range).

Figure 10.7 exemplifies the utilisation of the charging site, with a median of 0.4 charging sessions per day per outlet and a peak of 0.8 sessions on Mondays. Figure 10.7 further illustrates that the median of the total daily energy demand is approximately 500 kWh/day, with a rather stable daily energy consumption throughout the week. Monthly data presented in Figure 10.8 reveals seasonal trends, with values between 400 and 700 kWh/day when looking into the summer and winter months respectively.

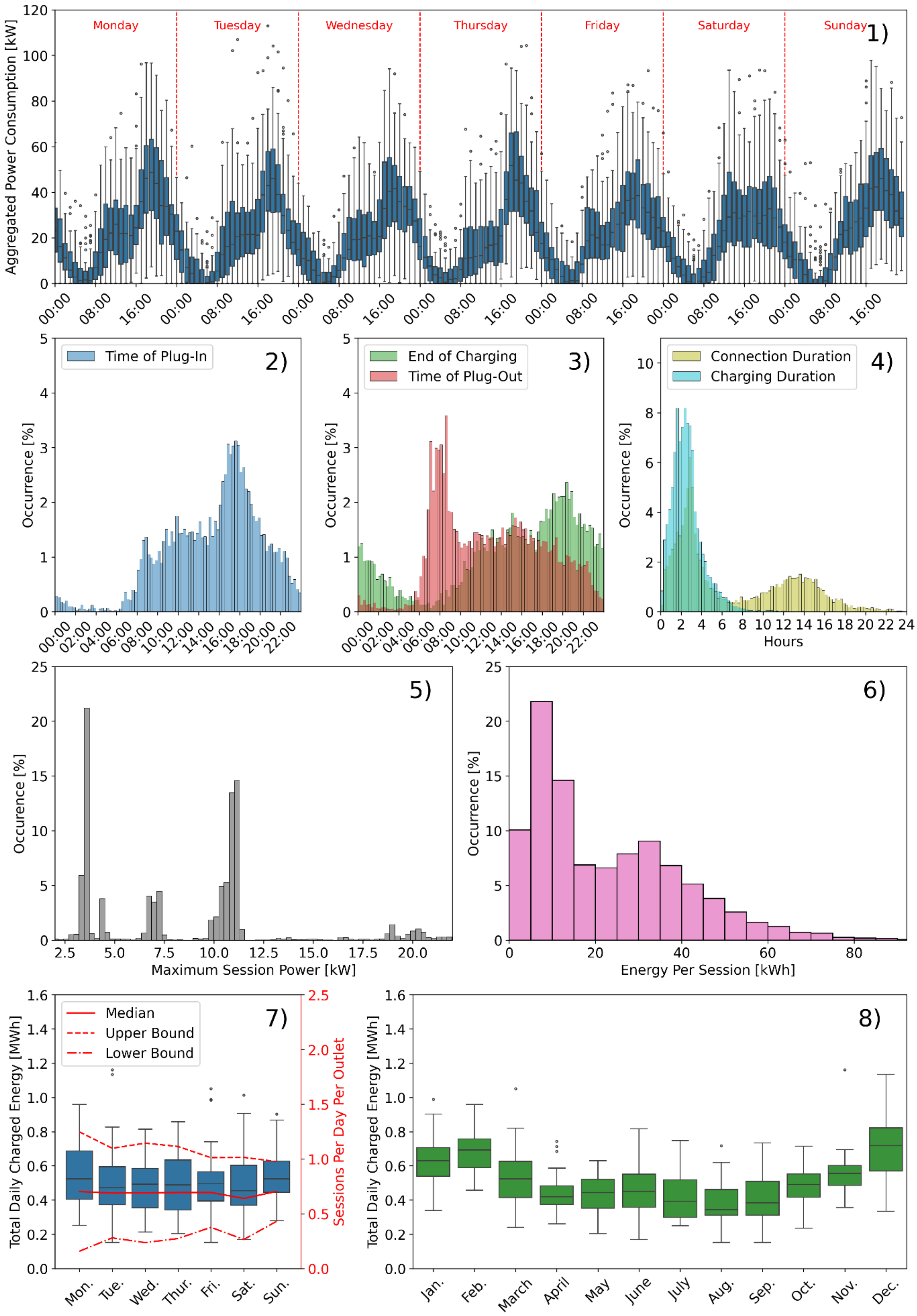

Figure 10 – Charging behaviour at Danish residential kerbside charging clusters.

Charging at Public Car Parks

Charging at urban public parking facilities exhibits three distinct patterns: residential overnight charging, workplace charging, and short charging sessions for leisure activities or errands. These patterns arise because the car parks serve both as public charging stations and rental garages available for longer-term use ("subscription" mode). As shown in Figure 11.1, two load peaks can be observed during the week: one in the morning around 09:00–11:00 when people arrive at work, and one in the evening around 17:00 as people return home or park their EVs for after-work leisure activities. On Monday, the morning and afternoon peaks are similar in magnitude, whereas the morning peak from Tuesday to Friday is less pronounced. On the weekend, the morning peak is absent, reflecting reduced work-related activity.

The pattern observed in the load profile is further supported by Figures 11.2, 11.3, and 11.4. The plug-in pattern in Figure 11.2 shows the aforementioned morning and evening peaks. EVs are plugged in and charged upon arrival, thus only the plug-in times are shown. Figure 11.3 displays the corresponding plug-out pattern, with EVs connected for overnight charging departing in the morning and those connected during work hours departing in the afternoon, producing two distinct peaks. Charge completion times peak around noon and late evening. Figure 11.4 reveals that charging durations predominantly fall between one and four hours. In contrast, connection durations vary more widely, with three different peaks aligned with the previously described main user groups. The peaks around eight and fifteen hours correspond to workday and overnight charging, respectively, while a notable peak of shorter connections is visible as well, likely due to errands or leisure activities. Smart charging has potential in this charging location, thanks to the amount of hours that EVs are parked for work and overnight. However, the potential of smart charging is phased by the chargers' nature of being public and thus very dependent on user behaviour, which is more difficult to predict.

The most common charging powers are 3.7 kW and 11 kW, with fewer users charging at 7.4 kW, as highlighted in Figure 11.5. The maximum outlet capability of 22 kW is seldom utilised. Figure 11.6 demonstrates that most users charge only small amounts of energy per session, with more than 60% of events involving less than 20 kWh (100 km range), most frequently between 5 and 15 kWh (25-75 km range). Figure 11.7 shows a small but consistent decrease in total daily energy charged over weekends, especially on Saturdays, which is also reflected in the number of charging sessions per day and per outlet. Mondays exhibit the highest median total daily demand, while Fridays show the largest spread. Finally, Figure 11.8 highlights no significant seasonality, with random monthly fluctuations throughout the year, including elevated demand in June and at year-end. For some days in September there are a few cases with zero daily consumption values, probably due to the parking lots being closed.

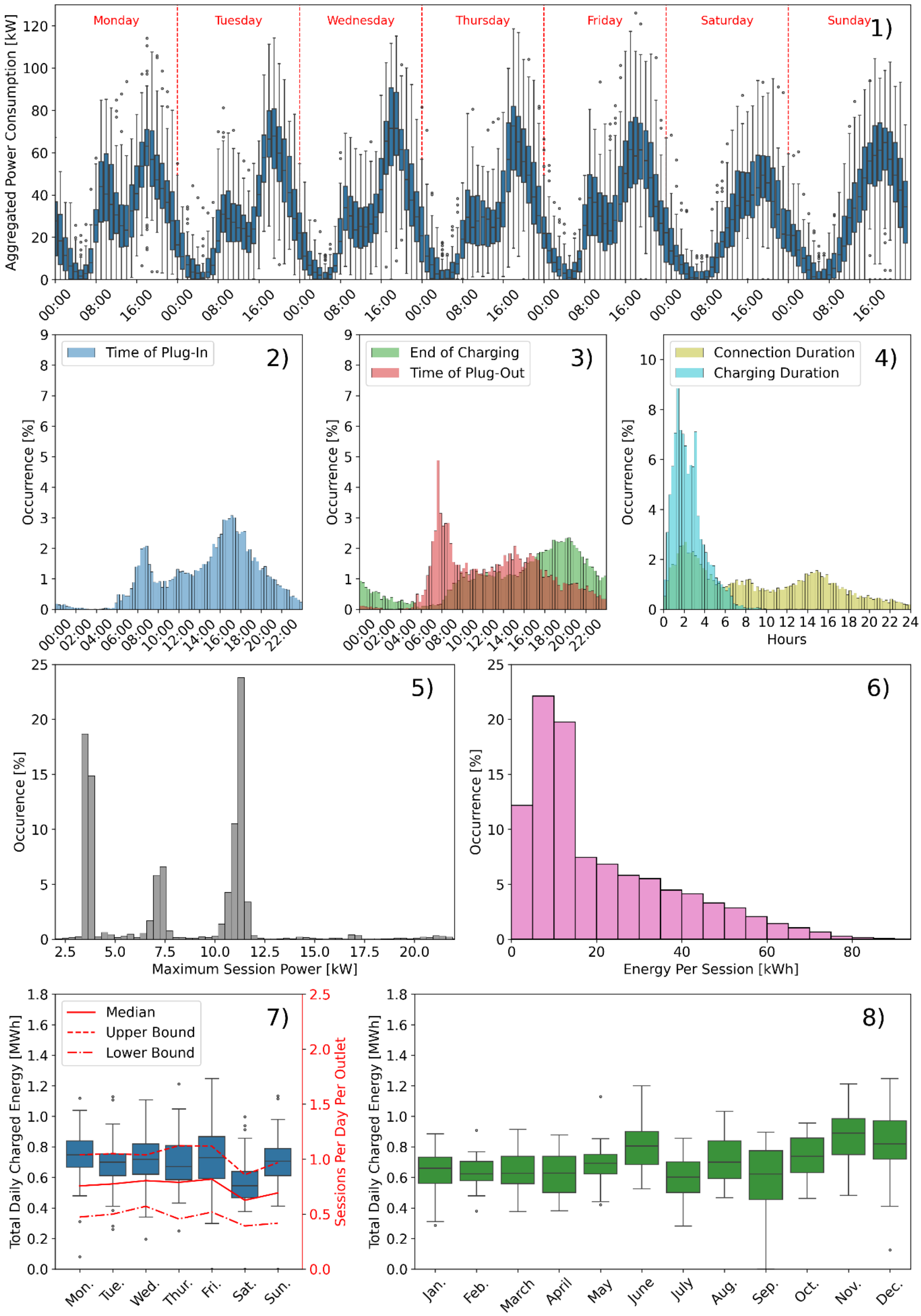

Figure 11 – Charging behaviour at urban Danish public parking facilities.

Fast Charging at Petrol Stations

Figure 12 illustrates the charging behaviour at four charging clusters located at petrol stations, equipped with a total of eight charging outlets. These charging clusters, being publicly accessible, can accommodate both light and heavy-duty EVs, particularly given the limited availability of dedicated HDV charging infrastructure.

The load pattern depicted in Figure 12.1 exhibits a consistent trend throughout the week, with charging predominantly occurring between 10:00 and 17:00 on both weekdays and weekends, aligning with peak transportation periods. Generally, the aggregated load remains low, with loads exceeding 200 kW considered outliers. On weekends, the aggregated load tends to be slightly higher than on weekdays. This is further illustrated in Figure 12.7, which shows that Sunday experiences the highest total daily energy demand and sessions per outlet.

As shown in Figure 12.4, over 90% of the recorded charging sessions have a connection duration of less than one hour. Due to the nature of these chargers, EVs are plugged in and start charging immediately, while also not staying plugged in without charging, as evidenced by the uniformity of the plug-in and plug-out graphs in Figures 12.2 and 12.3. The maximum session power, illustrated in Figure 12.5, reflects the diversity of EV types. Peaks are observed around 22, 75, 130, and 150 kW, but outside of those values, the distribution is quite uniform. It is noteworthy, however, that some sessions are capped at 22 kW, indicating that certain EV owners with EVs not supporting high-power charging still choose this site even if they don’t utilise the full charging capacity.

Seasonal variations in total daily energy demand, depicted in Figure 12.8, appear to be influenced by holidays, with higher values observed in July and December, coinciding with summer holidays and Christmas travel. This suggests that fast chargers are less affected by the increased winter charging demand compared to other charging locations, although the underlying reasons for this remain unclear. Finally, it is important to note that the boxplots for September and October are absent due to a lack of data for those months.

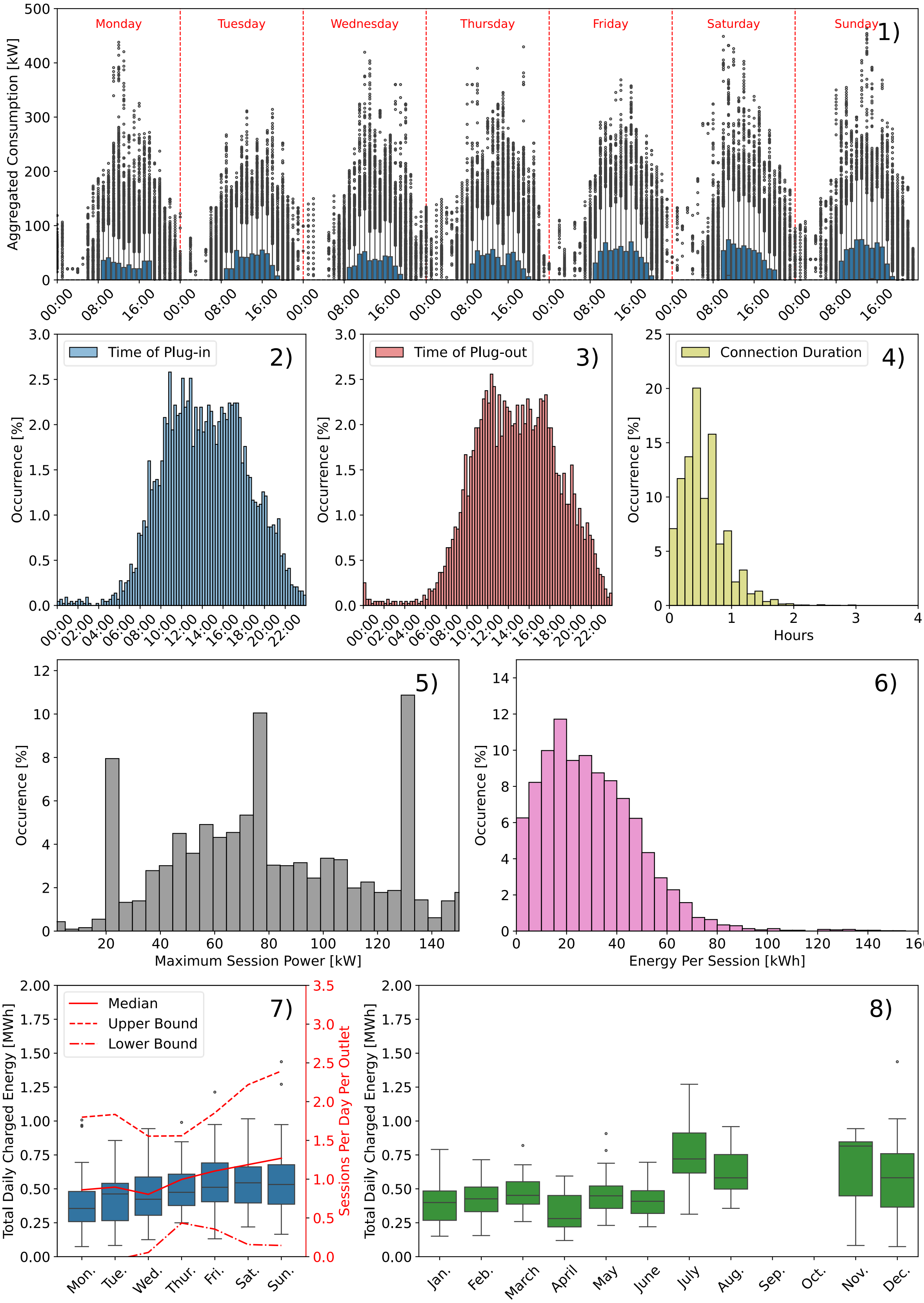

Figure 12 – Charging behaviour at Danish fast charging clusters located at petrol stations.

3.2.3. Heavy-Duty Electric Vehicle Charging Behaviour

In this section, we describe the HDV charging behaviour, i.e. that of electric buses and garbage trucks.

Depot Charging of Electric Buses

The charging behaviour observed at the bus depot reflects patterns commonly seen in fleet operations, where buses return to recharge at specific intervals.

As illustrated Figure 13.1, weekdays exhibit distinct charging peaks during the night, late morning, and late afternoon. These peaks align with buses returning to the depot after completing high-demand routes during peak commuting hours. This pattern suggests a high dependency on recharging after each operational cycle, likely to ensure buses are fully charged and ready for the next high-demand period. The nighttime peak, in particular, indicates a coincidence of charging activity, likely preparing buses for the intensive morning routes when public transportation demand is at its highest. Moreover, charging demand is significantly lower on weekends, as public transportation demand decreases and fewer buses are in operation. This is especially noticeable on Sundays when charging between 08:00 and 16:00 is considered an outlier event.

As previously mentioned, the data collected only encompasses the start and end times of charging events, alongside the associated power consumption. Consequently, it lacks direct insights into the actual plug-in and plug-out times of the buses at the depot, limiting analysis to charging patterns alone. The charging behaviour observed at the depot demonstrates distinct patterns aligned with typical bus route schedules, as shown in Figure 13.2. Peak start times of charging occur around 03:00–04:00, 11:00–12:00, and 21:00–23:00, with the highest frequency observed between 21:00 and 23:00. These time windows coincide with breaks in operational schedules when buses return after completing high-frequency routes that cater to peak public transit demand. The start of charging activity between 10:00 and 18:00 suggests that buses may be completing shorter mid-day routes or returning for intermittent charging in preparation for higher demand later in the day. Notably, a peak in charging activity occurs around 22:00 when most buses have finished their daily operation and return to the depot. Overall, the depot demonstrates consistent utilisation throughout the day to accommodate the diverse operational needs of the fleet. By strategically timing charging during these intervals, the depot can maintain operational readiness without overloading the charging infrastructure.

Figures 13.3 and 13.4, which are closely related to Figure 13.2, show that most bus charging sessions are completed within approximately one to two hours (corresponding to 100-200 kWh at 100 kW, which is close to the battery size of the buses). This results in a charging stop pattern similar to the start times, albeit shifted by the duration of the charging sessions. Further data on precise arrival and departure times are crucial for accurately assessing depot occupancy and identifying opportunities for smart charging strategies to optimize load management. This is particularly important as buses may complete charging but remain stationed at the depot until their next scheduled route. Implementing smart charging strategies, such as scheduling or deferring charging sessions, can improve depot efficiency, reduce peak load demands, and support grid stability.

Figure 13.5 shows that the predominant charging rate at the depot is 100 kW, corresponding to the maximum output capacity of each charger. As indicated in Figure 13.6, the most common energy consumption per session ranges between 50 and 180 kWh. However, more than 10% of sessions exceed 180 kWh, while roughly 17% fall below 50 kWh. The higher consumption sessions (exceeding 180 kWh) may correspond to buses that operate on longer routes, serve high-demand areas, or require extended operational time during peak periods, necessitating a larger energy intake per session. On the other hand, sessions consuming less than 50 kWh likely represent short routes or midday top-up charges for buses that have returned to the depot between peak hours.

Figure 13.7 highlights the contrast between weekday and weekend charging patterns, showing significantly lower total daily energy demand on weekends compared to the consistent usage observed throughout the working week. This difference may reflect reduced bus schedules and lower ridership demand during weekends compared to weekdays in Milan, where public transportation usage is generally higher due to commuter needs. Fig 13.8 provides insight into the seasonality of daily energy demand, showing increased usage during winter and decreased usage over summer months. This pattern likely reflects several contextual factors specific to Milan, where the winter season sees a higher demand for public transportation services. Milan, as a densely populated urban center, experiences high public transit use in winter, partly due to greater commuter traffic, and less reliance on individual vehicles during colder months. In contrast, summer months, particularly during the holiday period, see reduced ridership as residents and commuters often take extended leave, and some bus services may reduce their frequency accordingly. The month of September was not available in the provided dataset, hence the missing demand.

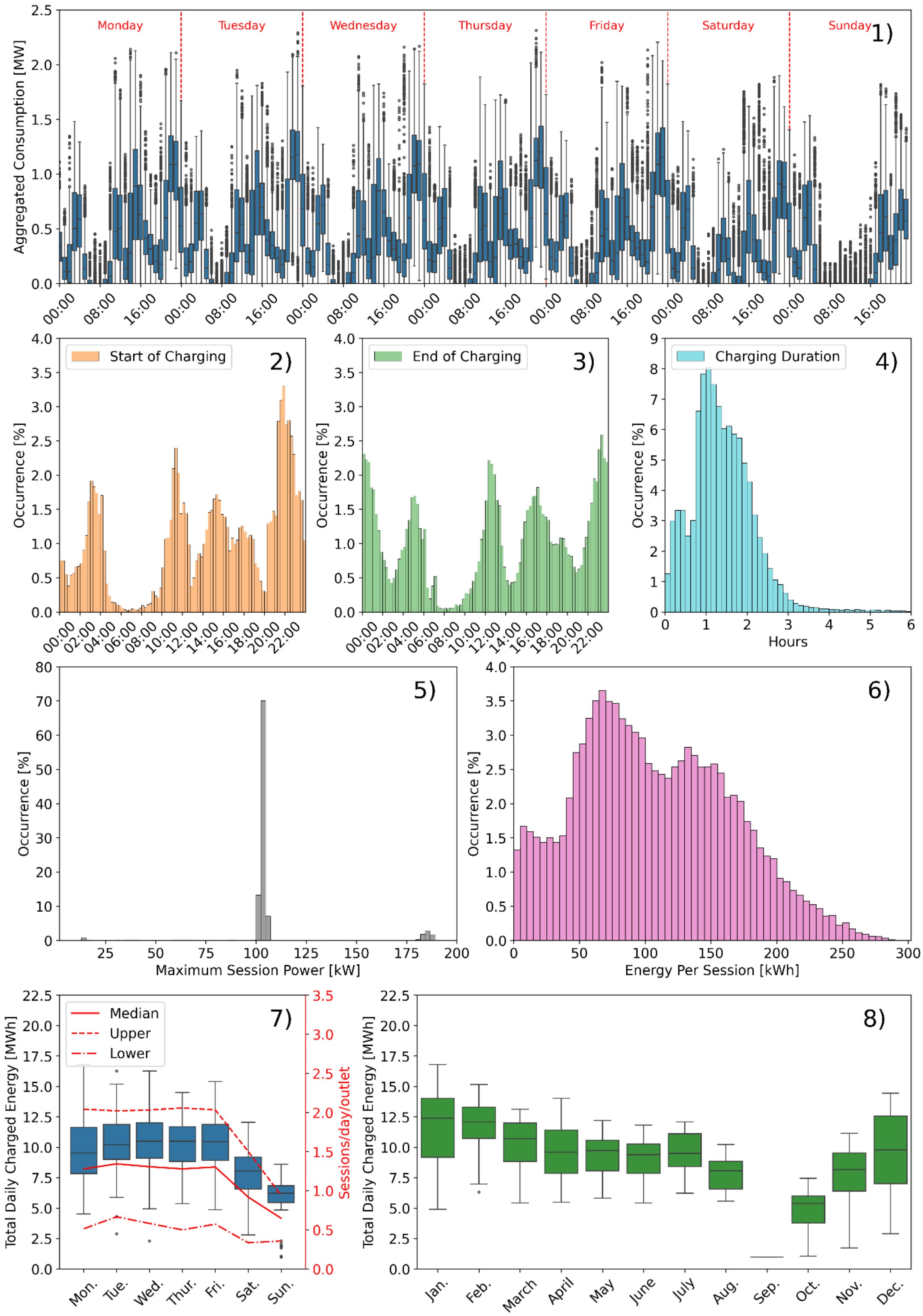

Figure 13 – Charging behaviour of electric buses at a depot in Milan, Italy.

Depot Charging of Garbage Trucks

The analysis of the charging behaviour of garbage trucks is based on six weeks of operation, with only the start and end of charging time being available for analysis. Therefore, it is important to mention that the presented results should be considered with caution as charging data over a longer period needs to be collected to provide a coherent picture of the charging behaviour. Nevertheless, several insights can be drawn from the limited amount of data.

To begin with, the load profile depicted in Figure 14.1, indicates a typical profile for commercial fleets that are operational during the week while not being used on weekends. Charging only occurs during weekdays, with charging demand centred during working hours, except for a few exceptions. The boxplots exhibit a large spread due to the limited amount of data. Peaks typically occur between noon and the afternoon when garbage collection is finalised and trucks return to the depot to charge, as confirmed by Figure 14.2. The trucks start charging immediately when plugged in, so the plug-in time coincides with the start of charging. Figure 14.3 illustrates that the majority of charging is finalised in the late afternoon.

Figure 14.5 shows a large variance in the maximum power per session. While more than 25% of sessions utilise the maximum power of 120 kW, the remaining sessions fall below this value, with notable peaks in frequency around 60, 70, 80, and 90 kW. On one hand, this could be due to charging at different SoCs, as the maximum charging power is likely only attainable when the state of charge is initially low. On the other hand, the charging power is influenced by the load management system, which ensures that the total grid connection capacity and maximum power per charging station are not exceeded. Figure 14.6 shows that the energy demand per event appears to follow a normal distribution centred around 150 kWh (the typical size of a garbage truck battery is in the 280-375 kWh range [32]). Notably, there is also a peak at lower energy values, probably due to trucks running shorter distances, and coming back to charge immediately after.

Figure 14.7 illustrates a relatively steady total energy demand and number of charging sessions on weekdays. From a forecasting perspective, this suggests that the expected power for the following day can be predicted with low uncertainty, enabling the potential flexibility of the garbage trucks to be utilised to a high degree.

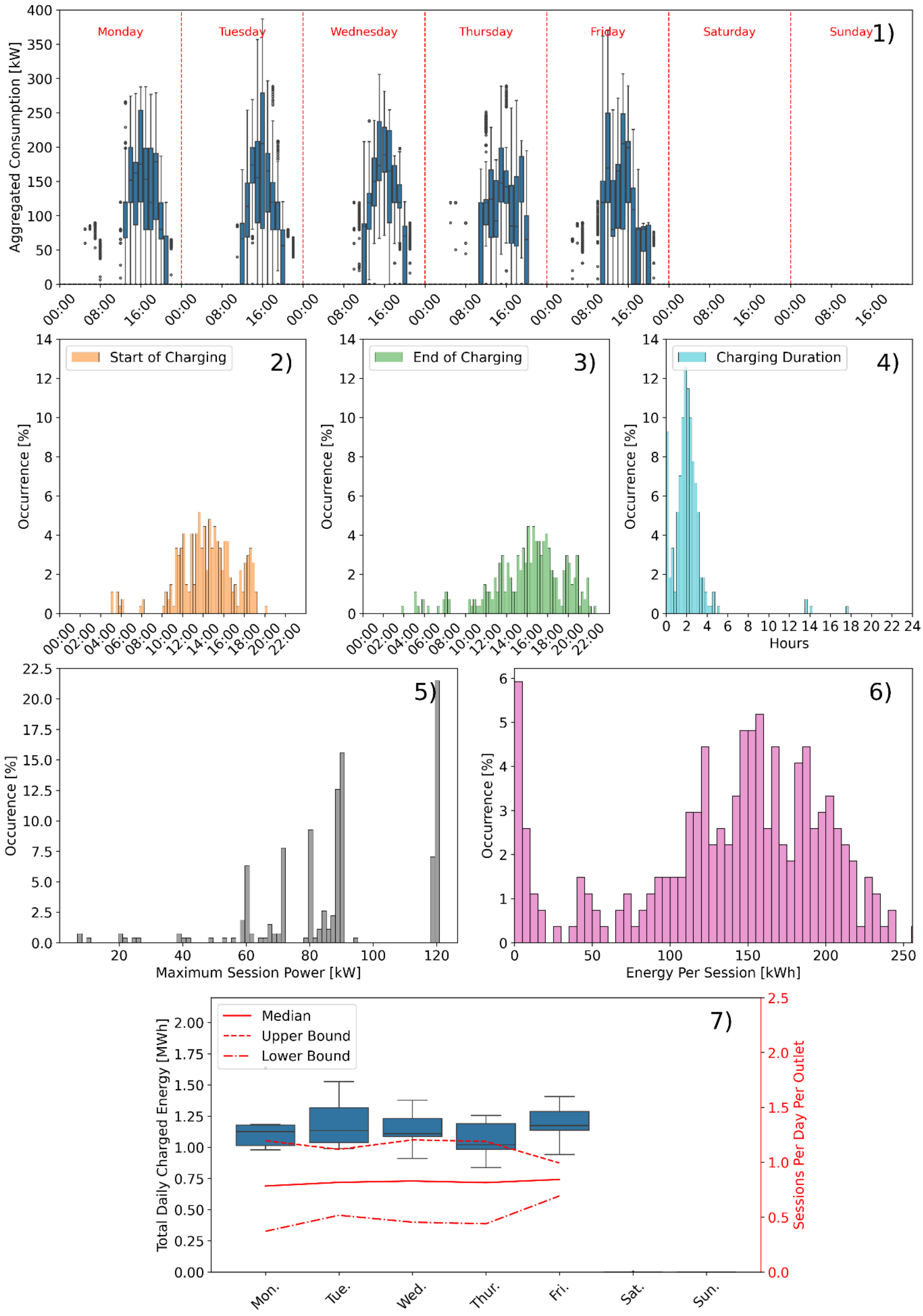

Figure 14 – Charging behaviour of garbage trucks in Denmark.

3.2.4. Charging of Ferries and Electrification of Ports

Charging profiles for vessels differ from those of EVs and HDVs mainly due to the higher predictability of load demand. Mooring periods are scheduled down to the minute, allowing power demand to follow a predictable load curve.

In Scenario 1, the operation of three electric ferries, similar to the Ampere, is simulated. In reality, only one ferry is electric, but it is not possible to determine which specific services it operates.

Figure 15 shows the simulated SoC of each vessel under different schedules. It is observed that each ferry enters operation according to peak periods throughout the day, based on the schedule. For instance, from Monday to Friday, Vessel 1 handles almost all services throughout the day, Vessel 2 operates from mid-morning until midnight, and Vessel 3 covers peak hours from early to late afternoon.

It is also noticeable that the ferries do not utilise their full battery capacity. This is primarily because the current configuration of the only electric ferry on the route requires it to perform more than one service without charging, due to the limited grid capacity or the potential unavailability of the battery buffer at each shore. Since this simulation involves three electric ferries, the primary bottleneck shifts to the battery buffer and grid capacity.

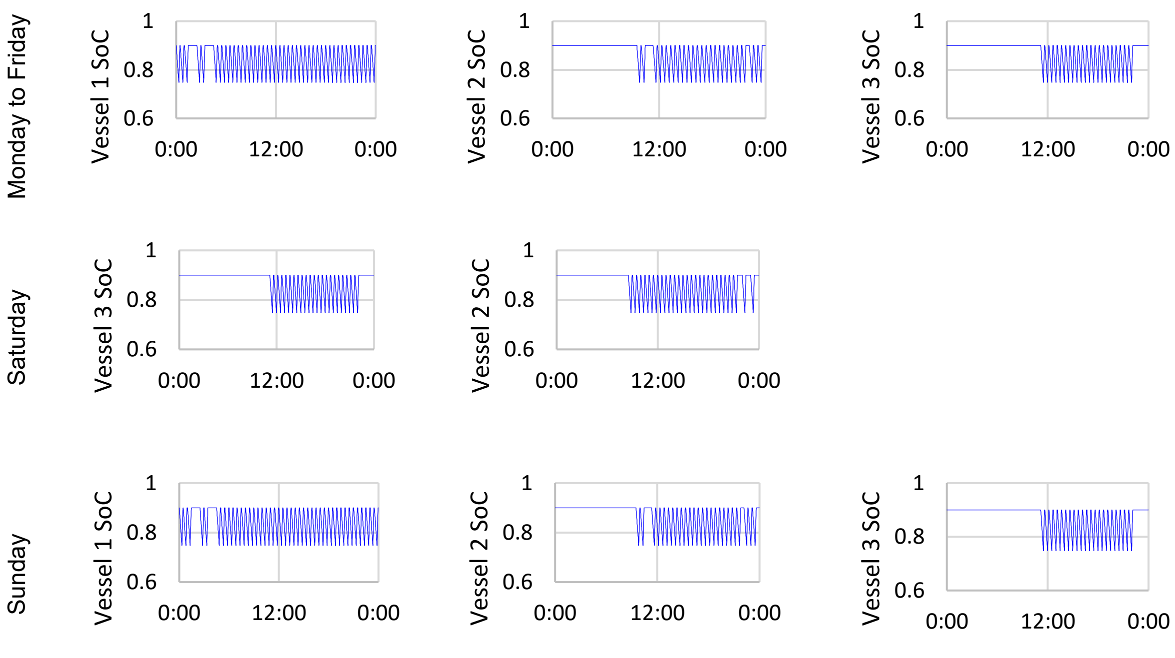

Figure 15 – SoC for the full electric operation scenario on the Lavik–Oppedal ferry service.

From Figure 16 it can be noticed that with a 260 kWh battery buffer capacity on each side, the operation requires a 450 kW grid connection at each port. By the end of peak hours, both shore-based battery buffers are close to 10% SoC from Monday to Friday, and from mid-morning to late afternoon, the power demand reaches grid capacity. This suggests that the current grid capacity is likely lower than in this scenario, given that only one electric ferry is currently in operation.

For this simulation, the daily energy consumption is 15.3 MWh on weekdays (Monday to Friday), 8.4 MWh on Saturdays, and 13.6 MWh on Sundays.

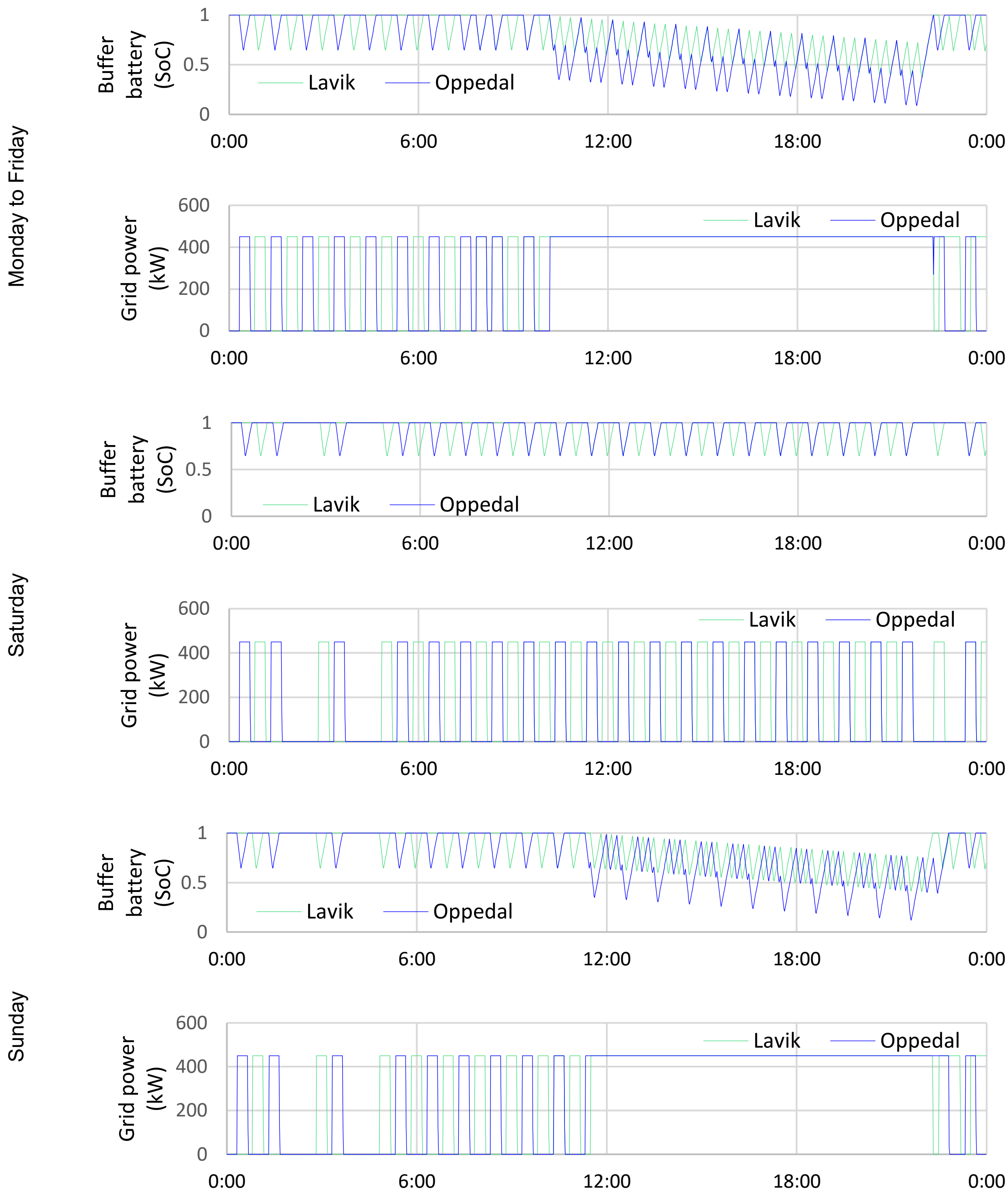

Figure 16 – Battery buffer SoC and grid power output for each shore on the Lavik–Oppedal ferry service.

In Scenario 2, Figure 17 shows the average power demand for a full electrification scenario at the Port of Funchal. The average peak power ranges between 15 to 20 MW, though this does not account for load variability during each ship's stay.

The seasonal variance in power demand is largely influenced by the geographical location of Madeira Island and the primary use of the port for cruise ships. During the summer months, many cruise ships are operating in the Mediterranean and Caribbean regions, leading to lower demand at the port.

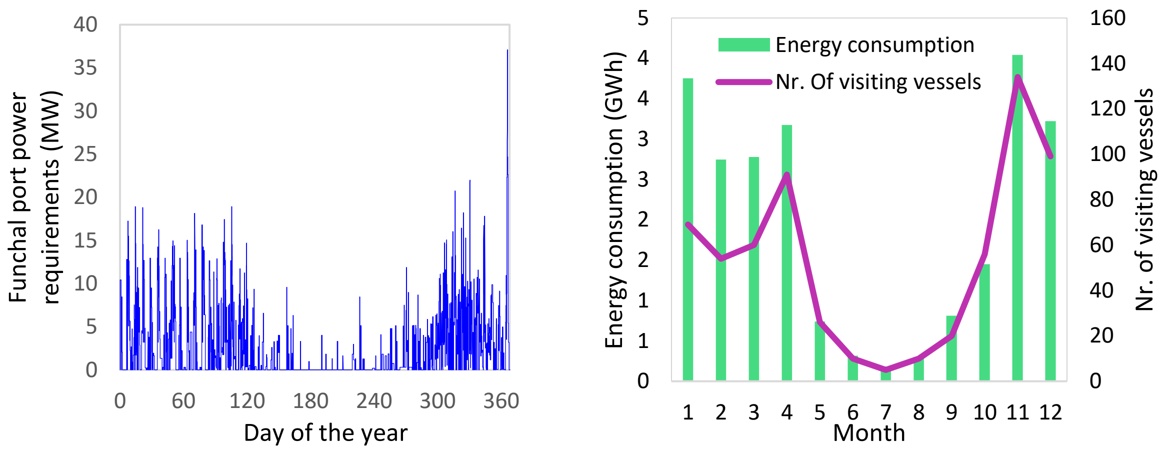

Figure 17 – Funchal power requirements (left) and the total monthly energy consumption (right) for the full electrification of the Funchal port scenario.

Another observation is that if all moored vessels were to use on-shore power, the power demand during peak events, such as New Year's Eve, could exceed 35 MW. This would account for more than 20% of Madeira Island's total peak load, which is projected to be around 150 MW in 2024. It's important to note that not all ships would be docked during this period. However, this scenario suggests that, in the near future, some vessels may need to partially rely on onboard power generation during such high-demand periods in similar ports.

In terms of energy consumption, full electrification of the port would require over 23 GWh of electricity per year, which is more than 2% of the island's current total energy consumption [33].

4. FUTURE SCENARIOS

The future charging behaviour of EV users is highly uncertain, as it will be shaped by a range of factors, including the availability of charging infrastructure, EV adoption rates, advancements in charging and EV technology, socio-demographic trends, market influences such as electricity prices and tariffs, the availability of related products and services, and regulatory frameworks [34], [3], [35]. Given the unpredictability of many of these factors, this report focuses on future scenarios related to charging infrastructure availability and EV adoption rates. These, in conjunction with current charging patterns outlined in this report, provide a basis for estimating future charging demand as the necessary input for the other WPs on flexibility services (WP3) and power grid simulation (WP4).

This chapter examines the status and future outlook of e-mobility in the four demonstration countries within the AHEAD project. We focus on estimating: i) the number of EVs, i.e. passenger cars and small vans, and ii) the recommended publicly installed charging capacity in Italy, Slovenia, Denmark, and Portugal. As mentioned before, these countries have been selected as the demonstration sites for the AHEAD project.

4.1. Scenarios and Assumptions

We present three different scenarios based on various assumptions and data sources:

- **The *EAFO* Scenario**: Using EV market data from the European Alternative Fuels Observatory (EAFO) [36], future EV fleet projections for each country are derived by extrapolating a trend through linear regression from 2016 to 2023 (the latest available data) and extending it to 2035. In this projection, there is no cap on the total number of EVs, so countries with rapid EV adoption between 2016 and 2023 could theoretically exceed 100% of EV share by 2050. This scenario illustrates the outcome if the EV sales trend from the past eight years were to continue uninterrupted and without major shifts. However, such projections can overestimate EV shares in the long term, as they don't account for potential market saturation or slowing growth.

- **The *Sources* Scenario**: Current conditions and projections are based on data from project partners within each country or from direct contacts of the partners in their respective countries. Government policy and action plan predictions are also included. This scenario reflects the expectations of lawmakers and/or companies for developments in the e-mobility sector from now until 2035.

- **The *EAFO 2050* Scenario:** To address the limitations of the original *EAFO* scenario, the *EAFO 2050* scenario sets a cap, ensuring that by 2050, the entire vehicle fleet in each country is electrified, aligning with the EU Commission's *Fit-for-55* plan established in 2021 [37]. This scenario assumes i) that the total fleet size remains constant over the years, and ii) that the number of EVs cannot exceed the total current number of vehicles on the road. This scenario thus represents the pathway needed to meet transportation decarbonisation targets by 2050.

For the *Sources* scenario, we obtained projections for the number of EVs and the publicly available EV charging capacity from the project partners. For the *EAFO*-based scenarios, we derived the recommended publicly available charging capacity as suggested by the International Council for Clean Transportation (ICCT) in [38], following the methodology applied in [37].

We chose to present installed capacity rather than the number of outlets, as this more accurately reflects the target for charging infrastructure, given the challenge of establishing a single charging power level for all outlets. This approach is especially relevant in light of the increasing adoption of high-power charging in urban areas.

Finally, we did not distinguish between battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs), as obtaining an accurate model to predict their numbers separately proved challenging. Their numbers are interdependent; for instance, a higher BEV count implies a lower PHEV count if the total fleet size remains constant.

The following two sections present the methodology used for estimating the EV fleet numbers and the recommended public charging capacity.

4.2. EV Fleet Size Projection Methodology

The number of EVs circulating in the different countries by 2030 and 2035 was estimated as the dependent variable of a polynomial regression based on data from 2016 to 2023. Figure 18 illustrates an example of the estimate for Italy in the *EAFO* and *EAFO 2050* scenarios.

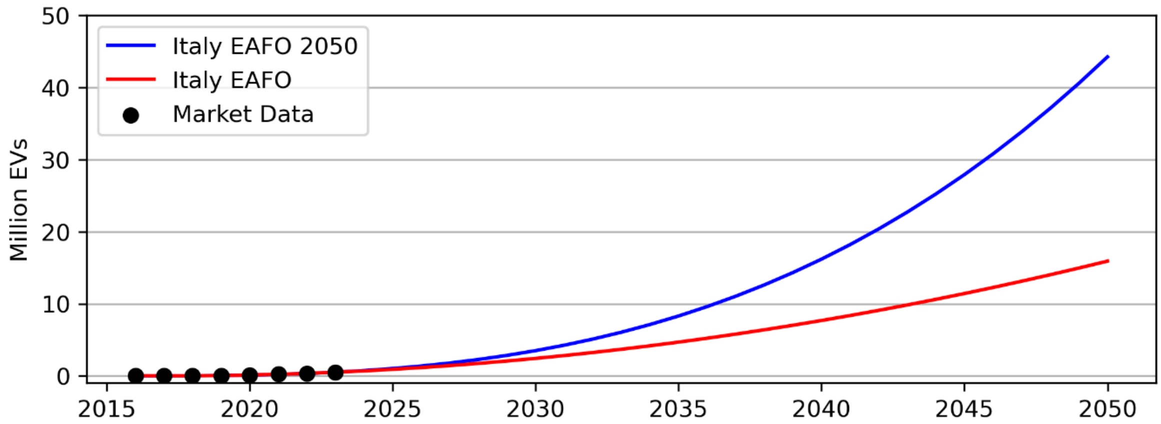

Figure 18 – Example of the methodology applied to Italy's EV fleet size prediction.

The *EAFO 2050* scenario outlines the number of EVs required in the country to achieve the 100% decarbonisation target of the *Fit-for-55* plan. In contrast, the *EAFO* scenario projects what would happen if the trend from the last eight years (2016-2023) would continue.

The projection was validated by estimating its accuracy in predicting the values from 2016 to 2023. Results show that, although the R-squared values are quite high (around 0.98-0.99 for all countries), the residual standard error in estimating the number of EVs can range between 3.4-8.4%. This indicates that the share of the variance explained by the model is quite high, but the spread of the residuals is higher. This is likely due to external factors affecting market data, such as price increases or incentives, which the model cannot predict given its simplicity.

If we consider the third-degree polynomial shown above as a good estimate for the analysed countries, it is possible to model the EV fleet size $N_{EV}(y)$ in year y as:

$$N_{EV}(y) = a \cdot y^3 + b \cdot y^2 + c \cdot y + d + \varepsilon,$$

which represents a third-degree polynomial model with constant coefficients a, b, c, d over the years y from 2016 to 2023. These coefficients can be estimated by minimising the errors using a least squares regression, which in this report was performed using the LINEST function in Excel.

4.3. Recommended Public Charging Capacity Methodology

To estimate the recommended public charging capacity, we followed the methodology presented in the ICCT report on e-mobility infrastructure [38], which has already been applied in [39] and [37]. The ICCT report proposes to use a “recommended ratio of installed capacity to number of BEVs and PHEVs” to derive the recommended charging infrastructure capacity. The values utilised are contingent upon the prevailing share of EVs within the country, as detailed in Table 5.

Table 5 – ICCT’s recommended ratios of publicly installed EV charging capacity and numbers of EVs.

EV_{share} [%]	R_{BEV} [kW/unit]	R_{PHEV} [kW/unit]	R [kW/unit]
2	2.10	0.95	1.87
5	1.64	0.76	1.46
10	1.26	0.64	1.14
15	1.13	0.61	1.03
20	1.00	0.55	0.91

It should be noted that, since we do not distinguish between PHEVs and BEVs, we assumed the ratio R to be the average of the ratios for PHEVs and BEVs, weighted on the predicted split between BEVs and PHEVs in the EU by 2035, which is 80% and 20% [37].

This ratio is a function of EV_{share}, i.e. as the number of EVs increases, the recommended installed capacity for public charging becomes more lenient due to more efficient utilisation of public charging and the broader availability of domestic chargers. By 2035, the considered values align with the recommendations of the European Alternative Fuels Infrastructure Regulation (AFIR).

Using the projections obtained with the methodology from Section 4.2, we determined the recommended capacity C_{rec} as a function of the $R(EV_{share})$ ratio between the number of EVs $N_{EV}(y)$ at year y and the total EV fleet size $N_{EV,TOT}$:

$$C_{rec} = N_{EV}(y) \cdot R(EV_{share}),$$

where:

$$EV_{share} = \frac{N_{EV}}{N_{EV,TOT}}.$$

4.4. Results for Italy

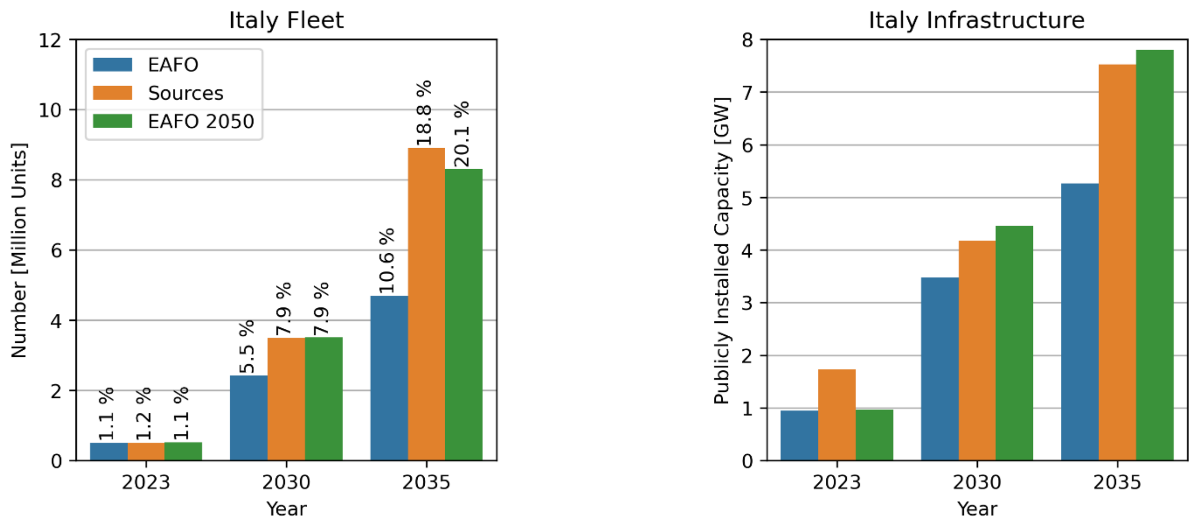

Figure 19 – Current and projected status of the EV fleet and public charging infrastructure in Italy. Percentage numbers in the left plot represent the share of EVs in the total fleet of vehicles.

The data for the *Sources* scenario was obtained from the "conservative" scenario presented in the Motus-E Charging Infrastructure report [40] (October 2024). According to this report, the current EV fleet in Italy is around 500k units, while in 2030 it will reach at least 3.5M. This value is in line with the number of EVs required to reach a 100% EV share in 2050 (*EAFO 2050* scenario), assuming the total number of cars will not change (around 44M at present [36]). However, the market data (*EAFO* scenario) indicates that by 2030, Italy will have only 2.43M EVs, approximately 69% of the aforementioned 3.5M. By 2035, the Motus-E report forecasts 8.9M EVs (a 20% share of the total fleet), which is 590k units more than the target for carbon neutrality in 2050. Conversely, the *EAFO* scenario shows that the market needs to accelerate to meet these targets, as only 4.69M EVs are projected for 2035, representing a share of approximately 10.6%.

Concerning charging infrastructure capacity, the Motus-E report indicates that, at present, 1.73 GW of publicly available charging power is installed in Italy. By 2030, this is projected to increase to 4.18 GW, slightly below the 5.6 GW anticipated in the “slow” EV adoption scenario outlined by the Italian government in the 2019 plan for mobility transition [37]. The 4.18 GW are in line with the recommended values for both the *EAFO* scenario (3.48 GW), and the *EAFO 2050* scenario (4.46 GW). By 2035, the capacity projected by the Motus-E report is in line with the climate targets at around 7.8 GW (*EAFO 2050*).

However, since the EAFO scenario predicts a lower number of EVs due to the market lagging behind climate target-driven values, the recommended public charging capacity will also be higher. In other words, if EV sales continue at the pace of the last seven years, there will not be a need for the high public charging power recommended by the EAFO 2050 scenario. It should be noted that these numbers also depend on the evolution of installed domestic charging power, which is difficult to predict and thus outside the scope of this study.

One final note regarding the Motus-E study is that the “accelerated” EV adoption scenarios appear overly optimistic given the current EV sales in the country and will not be reported.

In summary, both in terms of EV adoption and public charging infrastructure availability, the numbers foreseen by the Motus-E report are on track with the *Fit-for-55* targets. However, if the market and adoption rate remain the same as in recent years, the country will not meet the numbers expected by 2035.

4.5. Results for Slovenia

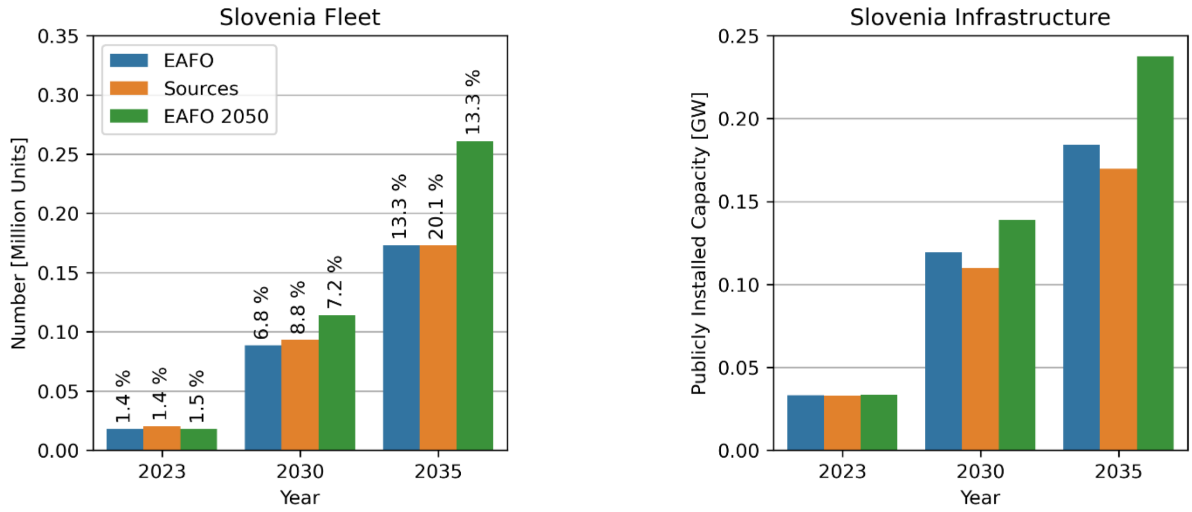

Figure 20 – Current and future status of the EV fleet and public charging infrastructure in Slovenia. Percentage numbers on the left plot represent the share of EVs in the total fleet of vehicles.

The data for the *Sources* scenario was obtained from one of Slovenia's DSOs, Elektro Gorenska, which is part of AHEAD's project, and it aligns well with the market projections from the *EAFO* scenario. Currently, there are 17-20k EVs in the country, according to all the analysed scenarios, with 89-93k (6.8-7.2 % of the total fleet) projected for 2030. In 2030, the target number of EVs to reach a 100% EV penetration by 2050 is approximately 114k EVs, representing 8.8% of the total car fleet. If the current trends continue, by 2035, both the *Sources* and *EAFO* scenarios will lag behind the *EAFO 2050* scenario by around 90k EVs (173k vs. 261k EVs).

The situation for public charging infrastructure is similar. Currently, 33 MW are installed in the country, with projections increasing to 110-139 MW by 2030. Both the *EAFO* and *EAFO 2050* scenarios recommend slightly higher capacity than the *Sources* scenario. If the *Sources* scenario prediction is confirmed, by 2035, this difference will increase, with a foreseen value of 170 MW, while the recommended values are between 184 and 238 MW. These numbers, however, greatly depend on the growth and availability of domestic charging infrastructure, which is difficult to estimate and thus falls outside the scope of this report.

In summary, while the DSO forecasts are coherent with the current market data, Slovenia needs to increase its adoption rate to meet the 2050 decarbonisation targets set by the EU Commission. This also holds true for the public charging infrastructure capacity, where both the DSO forecasts and the market-based projections are slightly lower than the recommended values for the full decarbonisation scenario (*EAFO 2050*).

4.6. Results for Denmark

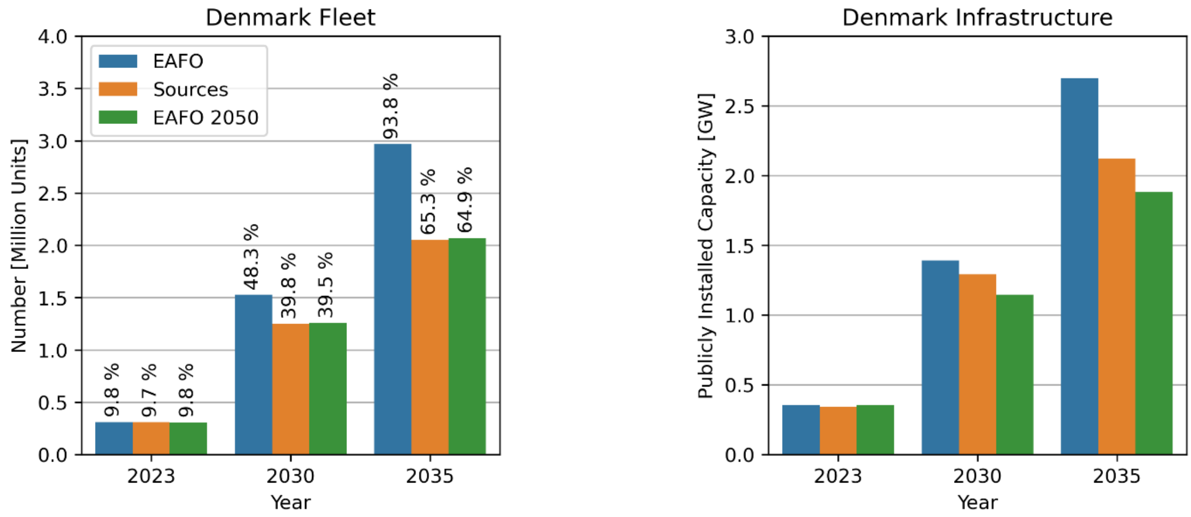

Figure 21 – Current and future status of the EV fleet and public charging infrastructure in Denmark. Percentage numbers on the left plot represent the share of EVs in the total fleet of vehicles.

For Denmark, no fleet size or charging infrastructure capacity predictions were found for 2035. Hence, those values were obtained by assuming the ratio between the *Sources* and *EAFO 2050* numbers will remain constant and will therefore not be discussed further.

The EV fleet size data for the *Sources* scenario was obtained from FLOW's project Deliverable 1.2 [39] and comes from the Danish car importers association, Elbiler, and the Federation of Danish Motorists, FDM. The charging infrastructure development data was retrieved from EV4EU's deliverable 1.2 [41]. The EV fleet size in the country recently surpassed 300k units, and around 1.25M BEVs are foreseen for 2030, in line with the *EAFO 2050* scenario, which assumes the country will convert its entire car fleet to EVs by 2050. Interestingly, the EAFO scenario shows that if the EV market trend from the last seven years continues, Denmark will have around 1.5M EVs by 2030, aligning with the "accelerated" EV adoption scenario created by the Danish government [39].

It should be noted that if the EAFO scenario is not constrained by the current total number of cars in Denmark (2.8-3M), it predicts almost 3M EVs by 2035 (93.8% EV share). Assuming the total number of cars remains constant over the years (or even decreases due to higher public transportation use), a 93.8% EV share in 2035 could be unrealistic. This high prediction is influenced by the rapid EV adoption in the last seven years. Therefore, it is more realistic to expect the adoption rate to slow down or even saturate by 2035, as described by the "Sources" scenario, which is slightly lower than the "EAFO 2050" scenario for both 2030 and 2035, with an EV share of around 65%.

The situation for the installed public charging infrastructure is fairly similar to the number of EVs for both the *EAFO* and *EAFO 2050* scenarios, as they are based on that number. Currently, 340-350 MW are installed, but this capacity needs to increase to 1.15-1.39 GW by 2030. Excluding the EAFO scenario for the aforementioned reasons, the recommended capacity will be around 1.88 GW. Currently, most EV charging in the country occurs at residential charging infrastructure, as shown in Section 2.2.2. Therefore, the capacity values presented in this section will highly depend on the development of home charging infrastructure, which is outside the scope of this report.

In summary, since Denmark already has high levels of EV adoption, market-based projections should not be considered accurate unless constrained by the maximum number of EVs attainable in the country. To achieve the recommended publicly available charging capacity, Denmark needs to slightly increase the number of publicly installed EV chargers per year. The EV adoption rate, however, is adequate.

4.7. Results for Portugal

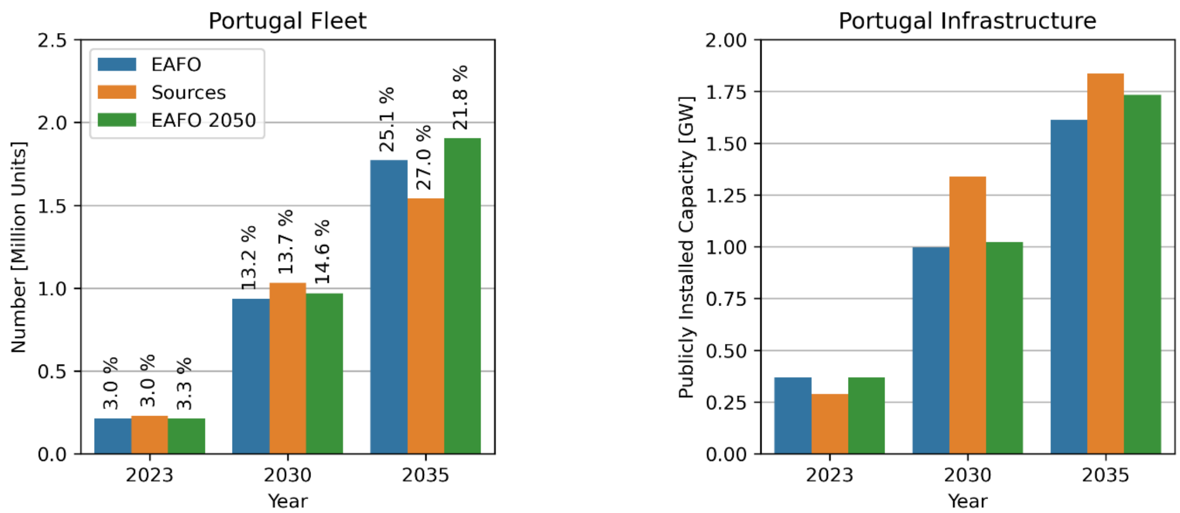

Figure 22 – Current and future status of the EV fleet and public charging infrastructure in Portugal. Percentage numbers on the left plot represent the share of EVs in the total fleet of vehicles.

The data for the *Sources* scenario was obtained from one of Portugal's utility companies, EDP, using their "Intermediate" development scenarios. These values for the EV fleet closely align with the projections of the *EAFO* and *EAFO 2050* scenarios up to 2030. Currently, there are 213-230k EVs in Portugal, and their number is projected to increase to between 930k and 1M by 2030, representing 13-14% of the total car fleet across all analysed scenarios. However, by 2035, the *Sources* scenario projects around 1.54M EVs, whereas both the market-based projection (*EAFO*) and the 100% conversion scenario (*EAFO 2050*) predict higher figures, ranging from 1.77M to 1.9M EVs, or 25-27% of the total car fleet. This discrepancy is attributed to the Portuguese government's expectations of a reduced motorisation rate and an overall population decline by 2035.

Regarding public charging infrastructure, the *Sources* scenario anticipates an increase from 168 MW in 2023 to 1.72 GW by 2035. In comparison, the *EAFO*-based scenarios recommend capacities in the range of 1.61 to 1.73 GW for 2035. This suggests that while Portugal needs to enhance its installed capacity to meet the 2050 decarbonisation targets, it remains generally aligned with the recommended capacities up to 2030.

In summary, if current market trends persist, Portugal is on track with the EV adoption rate until 2023. However, a slight increase is necessary between 2030 and 2035 to achieve the 100% transition to e-mobility targets. In terms of publicly available EV charging capacity, the projected values exceed the minimum required levels.

5. CONCLUSION

This section concludes the report by summarising the main findings of this deliverable, providing insights into the charging infrastructure needs and behaviours of EVs, HDVs, and vessels across multiple countries, and providing recommendations for different stakeholders.

5.1. Summary

The report begins by emphasising the importance of distinguishing between vehicle categories—such as light- and heavy-duty vehicles—and their use cases, as these factors significantly influence charging infrastructure requirements. Drawing on previous reports and surveys about charging infrastructure usage, the charging location preferences for EV users are highlighted. The findings reveal that most EV users still primarily rely on residential home charging. However, there are notable differences between the countries considered, including Denmark, Portugal, Italy, Slovenia, and Norway. For instance, Norway and Denmark, with higher EV adoption rates, have seen more advanced deployment of dedicated home EV chargers. Interestingly, user perceptions of the importance of charging infrastructure often differ from actual usage patterns. For example, a majority of EV users in Denmark consider away-from-home charging to be more important than its current utilisation suggests. This discrepancy is particularly evident with fast-charging infrastructure, which is perceived as highly important, but seems, at present, to be significantly less utilised than home charging infrastructure.

The main body of this report investigates the current charging behaviour of EVs, HDVs, and vessels using a novel high-resolution dataset. For EVs, six distinct and representative charging locations are analysed: home, workplace such as universities and hospitals, kerbside, petrol stations and dedicated parking facilities. Concerning home charging, it is worth highlighting that many EV users are already actively employing smart charging in the form of delaying the start of charging. For instance, in Denmark, users shift their charging to nighttime hours to take advantage of time-of-use grid tariffs and dynamic pricing, which are also integrated into some EV user interface apps (e.g., Spirii Go app). However, this behaviour may vary depending on the country and charging point operator/service provider.

In contrast, for users without access to home charging—such as those charging at kerbside or parking facilities upon arriving home—delayed charging is not practical and thus it is more difficult to benefit from cheaper nighttime rates. These locations then contribute to the evening peak demand, despite demonstrating significant flexibility potential. Additionally, these locations also exhibit charging behaviour associated with work or leisure activities, underscoring the importance of distinguishing between different user groups for potential future smart charging applications. Charging at universities and hospitals, on the contrary, primarily reflects workplace charging behaviour that aligns with the respective work schedules. Conversely, fast charging at petrol stations, as expected, exhibits more random charging patterns. However, this behaviour remains uncertain due to limited data availability and the possibility of increased charger utilisation over time as their locations become more familiar to EV owners and as HDV usage patterns evolve.

For HDVs, such as electric buses and garbage trucks, unique usage patterns are observed based on their specific use cases and operational schedules, which should be further investigated in the future when more data is available. The report also examines an electric ferry in Norway, supported by a simulation developed to project the vessel's state of charge (SoC), energy demand, and grid connection requirements. Additionally, based on the estimated power demand of vessels docked at the port of Madeira, the report highlights potential challenges for the power distribution network if the electricity demand of vessels docked in port is to be fully supplied by on-shore power.

Finally, this report provides future projections for EV fleet growth and recommended charging infrastructure capacities across the demonstration countries. These projections include three scenarios based on different data sources and hypotheses. In Italy, both the EV adoption rate and charging infrastructure installations, as projected by the Motus-E organisation, align with 2050 targets. However, the adoption rate needs to increase to remain in line with the recommended values. For Slovenia, both the adoption rate of vehicles and installations of charging infrastructure must increase to meet the carbon neutrality targets set by the EU, although the forecasts provided by the project partners are in line with EU requirements. Depending on the scenario, it is found that Denmark needs to increase public charging infrastructure installation rates to meet EU goals, although the EV adoption rate is more than adequate. In Portugal, the EV adoption rate aligns with EU targets, while projections from the project partner slightly underestimate it, likely due to a predicted decrease in the total circulating car fleet. Regarding installed charging capacity, the values foreseen by the project partners and presented above, exceed the EU requirements.

5.2. Stakeholder Recommendations

In the following, we provide recommendations for different stakeholders based on the findings of this report.

5.2.1. Charge Point Operators

By investing in smart charging-capable hardware and adopting smart energy management strategies, charging point operators can unlock additional revenue streams through flexibility services. This approach not only helps reduce charging costs and CO_2 emissions but also attracts more customers, positioning CPOs as leaders in sustainable and efficient charging solutions.

5.2.2. Electric Mobility Service Providers

Electric Mobility Service Providers play a key role in enabling charge point operators by offering a wide range of smart charging services, helping them optimise their operations and unlock new revenue streams. For example, by providing transparent electricity cost forecasts, including multi-day projections, EMSPs can empower EV owners to make informed charging decisions, further enhancing customer satisfaction and driving the growth of sustainable mobility solutions.

5.2.3. Aggregators

Based on the analysis in Chapter 3, aggregators can tailor energy consumption forecasts to individual charging sites to optimise the control of EV charging for flexibility services. This is because it was observed that charging behaviour varies significantly due to site-specific factors, including usage type (e.g., public, workplace, kerbside), geographic location, parking restrictions, and contracted grid capacity.

5.2.4. Distribution System Operators

The charging behaviour analysis in Chapter 3 revealed a significant shift towards residential night-time charging in Denmark, driven by lower grid tariffs and electricity spot prices and improved smart charging capabilities. This underscores the need for distribution system operators to carefully design network tariffs, as they influence EV charging patterns and grid loading. While lower night-time tariffs effectively shift peak consumption at low EV penetration levels without introducing secondary peaks, increasing EV adoption will amplify charging synchronisation effects, posing risks for bottlenecks. To mitigate these challenges, distribution system operators need to consider a variety of alternative solutions such as localised tariffs, conditional connection agreements, and local flexibility markets to reduce reliance on costly grid reinforcements. Additionally, close collaboration with EV aggregators and transmission system operators will be essential to prevent unnecessary congestion in low- and medium-voltage networks.

5.2.5. Transmission system operators

Transmission system operators can both benefit from and face challenges with large-scale EV adoption. While EVs are already contributing to ancillary services in some countries, such as Denmark, the synchronisation of charging processes can lead to steep power ramping, which must be accounted for in system balancing. Successful large-scale EV integration requires close coordination with distribution system operators and aggregators, as well as the establishment of appropriate market frameworks, such as prequalification requirements for ancillary service provision.

5.2.6. EV Users

EV users can benefit from understanding the general charging behaviour of other users in their area. By charging during off-peak hours, as informed by EMSPs, they can avoid congestion at charging sites and reduce transportation costs by taking advantage of lower electricity prices and network tariffs. However, without allowing aggregators to manage their charging, individual EV owners limit the potential for utilising the flexibility services that EV fleets can offer.

5.2.7. Electricity Providers

Electricity providers should account for dynamic EV charging patterns to optimise electricity procurement for each hourly market slot, ensuring accurate pricing for EV users while minimising financial risks. Furthermore, trading in the intraday or other near real-time markets should be encouraged to limit grid disturbances.

5.2.8. Policy Makers

Municipalities and governmental entities should take into account the dynamic charging behaviour highlighted in this report. For instance, when implementing parking time restrictions at EV charging locations, it is essential to consider the potential reduction in smart charging capacity and its associated positive and negative impacts on the broader energy system.

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