Project deliverable D5.1

Best Practice of MCS Hub Designs - Initial Version

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Editor/Lead author	Odbratt, Johanna (Lindholmen Science Park)				
Co-authors	Danebergs, Janis (Lindholmen Science Park), Gosavi, Sneha (Lindholmen Science Park) Herrmann, Florian (Lindholmen Science Park), Kruse, Ted (Lindholmen Science Park), Ohlin, Gunnar (Lindholmen Science Park)				
Peer reviewers	Safdarian, Amir (Kempower) Sandin, Carl-Oscar (Plugit)				
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Legal Disclaimer

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EXECUTIVE SUMMARY

Deliverable 5.1: Best practice of MCS hub designs - initial version is a deliverable produced within Work Package 5 of the MACBETH project. Its primary objective is to establish a consolidated framework of design concepts and best practices for Megawatt Charging System (MCS) hubs. These guidelines are intended to support the design of the project's pilot demonstrations and serve as a reference for the future mass deployment of light and heavy-duty vehicle (LDV and HDV) charging infrastructure.

There are practically no MCS hubs yet in commercial operation, as the technology and standards are currently in the final stages of development. Consequently, the best practices outlined in this document are derived from an analysis of existing Combined Charging System (CCS) hubs and truck stops. By evaluating state-of-the-art facilities, the task 5.1 has discussed key learnings and suggestions regarding user needs, spatial layout, and service provision to apply them to the forthcoming MCS context.

The report identifies and analyses four critical design subsystems, each playing an important role in forming a successful hub. The vehicle related subsystem focuses on the physical interaction between the vehicle and the hub. Key aspects include site layout, parking, and local roads. The human related subsystem centres on the user experience, primarily the driver. This system includes amenities, restaurants, and recreation areas for the drivers to use during the break. The supporting information subsystem represents the digital layer of the hub. It manages the signage, road markings, and surveillance. The energy supply subsystem is the backend infrastructure ensuring the power availability. It comprises of chargers, electrical architecture, and energy storage.

The design concepts established here provide the technical and operational recommendations for the MACBETH pilot sites in Sweden (Plugit) and Belgium (Milence). The initial analysis concludes that as MCS technology matures from early adoption to mass deployment, best practices must evolve from a focus on interoperability to a future defined by operational management and digital transparency. Success hinges on synchronising the physical 'forward-flow' of vehicles with the 'time-flow' of drivers, while mitigating grid connection delays and costs through energy storage and shared microgrids. Ultimately, these guidelines transform the charging hub from a simple utility into a strategic, resilient node within global supply chain, prepared for future advancements in high-power charging and automation. Data from the pilot projects will be used to update this deliverable in two future iterations, managing the alignment with the industry and technological progress.

LIST OF ABBREVIATIONS AND ACRONYMS

Acronym	Meaning
AFIR	Alternative Fuels Infrastructure Regulation
ANPR	Automatic Number Plate Recognition
API	Application Programming Interface
BESS	Battery Energy Storage System
BET	Battery Electric Truck
BEV	Battery Electric Vehicle
CCS	Combined Charging System
CMS	Charge Management System
CPO	Charge Point Operator
DSO	Distribution System Operator
EMS	Energy Management System
eMSP	e-Mobility Service Provider
EV	Electric Vehicle
FMS	Fleet Management System
HCT	High-Capacity Transport
HDV	Heavy Duty Vehicle
LDV	Light Duty Vehicle
MCS	Megawatt Charging System
NAP	National Access Point
OCPI	Open Charge Point Interface
PSR	Parking Security Requirements
PV	Photovoltaics
SoC	State of Charge
SSTPA	Safe and Secure Parking Areas
UC	Use case
WP	Work Package

1 PURPOSE OF THE DELIVERABLE

1.1 Attainment of the objectives and explanation of deviations

Task 5.1 addresses the aspect of achieving improved designs of future integrated multipoint megawatt charging system (IM-MCS) hubs, in support of future battery electric trucks (BETs) mass deployment, by consolidating best practices in hub design concepts for various use cases. The purpose of this initial version of the deliverable is to provide guidance to WP6 by outlining suitable design concepts for the pilot demonstrations (MS3), based on preliminary user needs and use cases identified in WP2 tasks T2.1-2 and experiences from the participating industrial partners (Plugit, Milence, Kempower, Power Electronics and Rocsys). A second version of the deliverable, to be used as input to (WP7), is scheduled for M30. A final version will be delivered by the end of the project (M48), consolidating best practice for future IM-MCS hubs.

A hub design concept is a system-level design representation containing vehicle related sub-systems (e.g. locations for charging, parking, local roads), human related sub-systems (e.g. amenities, restaurants, recreation areas), supporting information sub-systems (e.g. signage, road markings, surveillance) and energy supply sub-systems (e.g. chargers, electrical architecture, energy storage). The possible design concepts will be evaluated through examining several factors, such as site conditions, user requirements, functional needs, regulations and environmental considerations.

1.2 Intended audience

This deliverable is intended for a broad and diverse audience, reflecting the collaborative nature of the transition toward high-power EV charging. It is open to all who are interested in understanding and shaping the future of mass deployment of interoperable MCS charging.

Key stakeholders include professionals from the truck and vehicle industry, who are directly impacted by the development of charging infrastructure and standards. It also addresses the needs of those working in the charging technology sector like CPOs but also includes developers and suppliers of charging solutions, who require a clear understanding of future requirements for interoperability, functionality, and scalability. The energy industry plays a critical role in enabling this transition, and this document provides valuable insights for them to align their infrastructure and services with the demands of high-power EV charging. Academic institutions and research organisations will find relevant information to support studies in electrification, energy systems, and sustainable mobility. Finally, regulatory bodies and policy agencies are also a key audience, as they are responsible for creating frameworks and standards that will guide the deployment of charging technologies.

1.2 Structure of the deliverable and links with other work packages/deliverables

Chapter 2 in this deliverable explains the adopted methodology. Chapter 3 mentions the hub design concepts and best practice along with the subsystem definitions. Chapter 4 lists the best practices in the ten use cases with respect to T2.2. Chapter 5 mentions a detailed discussion and conclusion of Task 5.1. This task is connected to all other WPs, as it will gather information on best practice for MCS hub design throughout the project, which can be information acquired from the WPs. However, the work carried out in WP5 will play an important role in providing input to WP7 and WP8.

2 METHODOLOGY

To achieve the objective of T5.1 described above, different methodological elements were combined. In addition, information from T2.2 (*D2.2 System-level requirements for the pilot sites*) regarding the selected use cases as well as input from the stakeholder interviews conducted within T2.1 (*D2.1 Stakeholder needs on the exploitation of MCS*) was incorporated.

In the first step, various subsystems that a hub design concept combines were identified. This task was developed from a systems perspective, with the overarching goal of enabling a comprehensive analysis of current and future hub design concepts. As a result, the four subsystems “Vehicle related”, “Human related”, “Supporting information” and “Energy supply” were defined. The description of each subsystem contains information about its main elements as well as interlinks to other subsystems. In addition, a visualisation was created that highlights the central elements of a subsystem with their spatial positioning.

Building upon this, a comprehensive analysis of existing sites and supplementary literature related to the subsystems was conducted to gain the best possible insight into existing concepts. With respect to the vehicle related subsystem three different archetypes of charging hubs with respect to the location, physical shape of the land and main users were investigated. The analysis of the human related subsystem on the other hand studied aspects like core regulatory needs, safety and security of the physical environment as well as charging ergonomics and accessibility, digital interaction, and information. The analysis of the supporting information subsystem focussed on aspects like signage, road markings, surveillance support information or digital interfaces. The investigation of the energy supply subsystem in turn, looked deeper into aspects of physical backbone, physical features, digital features, and business models.

Subsequently, the selected use cases from T2.2 were used to conduct an analysis regarding the existing best practices. These practices were identified through a mapping and data collection of existing sites (e.g., charging stations, truck stops, and gas stations) as well as through literature research. Moreover, the interviews made in T2.1 and the internal expertise within the project group served as input.

In a concluding discussion, key points and interdependencies regarding future developments were highlighted.

3 HUB DESIGN CONCEPTS & BEST PRACTICES

A hub design concept can be seen as a system-level design representation containing different subsystems. Within this chapter, subsystems with a high relevance for this task are defined and described. Secondly, an analysis of existing hub design and best practice is conducted in relation to these subsystems.

3.1 Definition and description of hub design subsystems

In the course of the work, a total of four subsystems were identified as relevant for the analysis and design of current and future hub design concepts.

- Vehicle related sub-system (e.g., locations for charging, parking, local roads)
- Human related sub-systems (e.g., amenities, restaurants, recreation areas)
- Supporting information sub-systems (e.g., signage, road markings, surveillance) and
- Energy supply sub-systems (e.g., chargers, electrical architecture, energy storage).

All these subsystems play a crucial role for the design and operation of a charging hub and there are also interlinks between them. In this deliverable, the focus is on public charging stations. Figure 1 illustrates a schematic hub design including elements from all of the four subsystems.

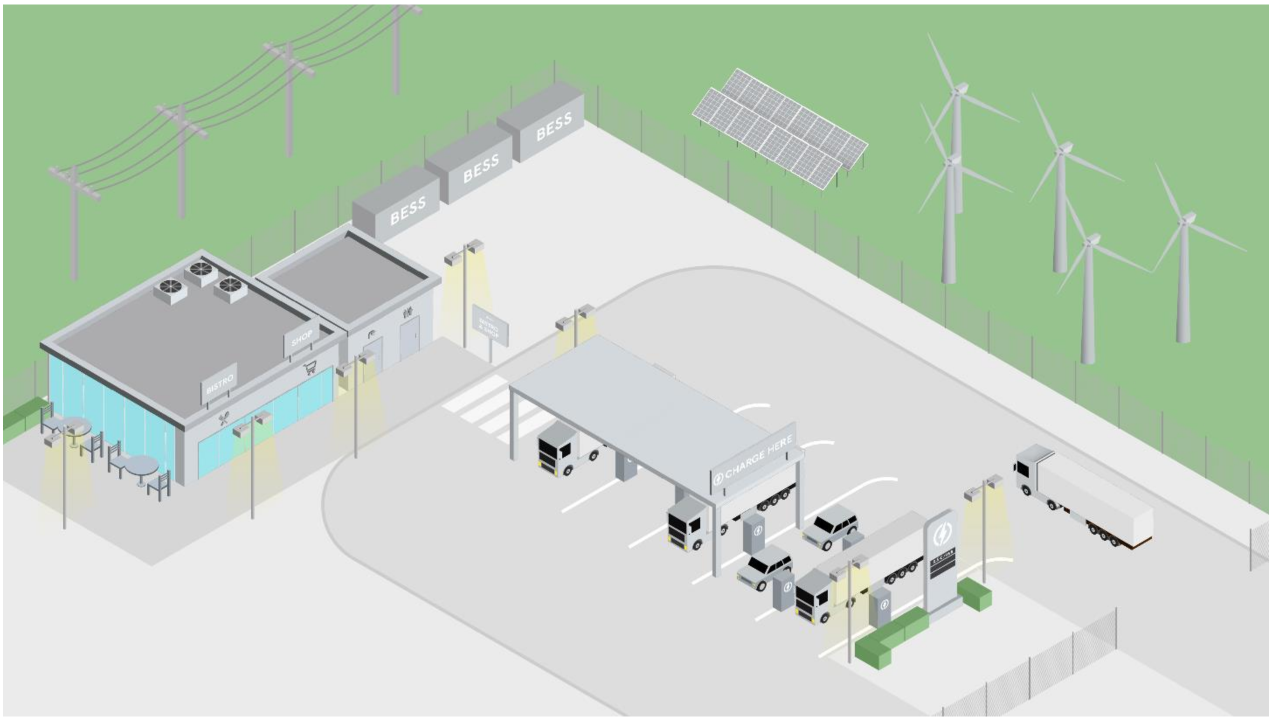

Figure 1 A schematic hub design including elements from the four different subsystems: Vehicle related, Human related, supporting information and Energy supply which are highlighted in the following figures.

3.1.1 Vehicle related subsystem (physical)

Objectives and scope

This subsystem focuses on how the vehicle physically interacts with the charging hub which is directly connected to the design and layout of the hub itself. Key aspects include the placement of chargers, parking, and accessibility for different vehicle types. Figure 2 highlights the vehicle related subsystem in orange.

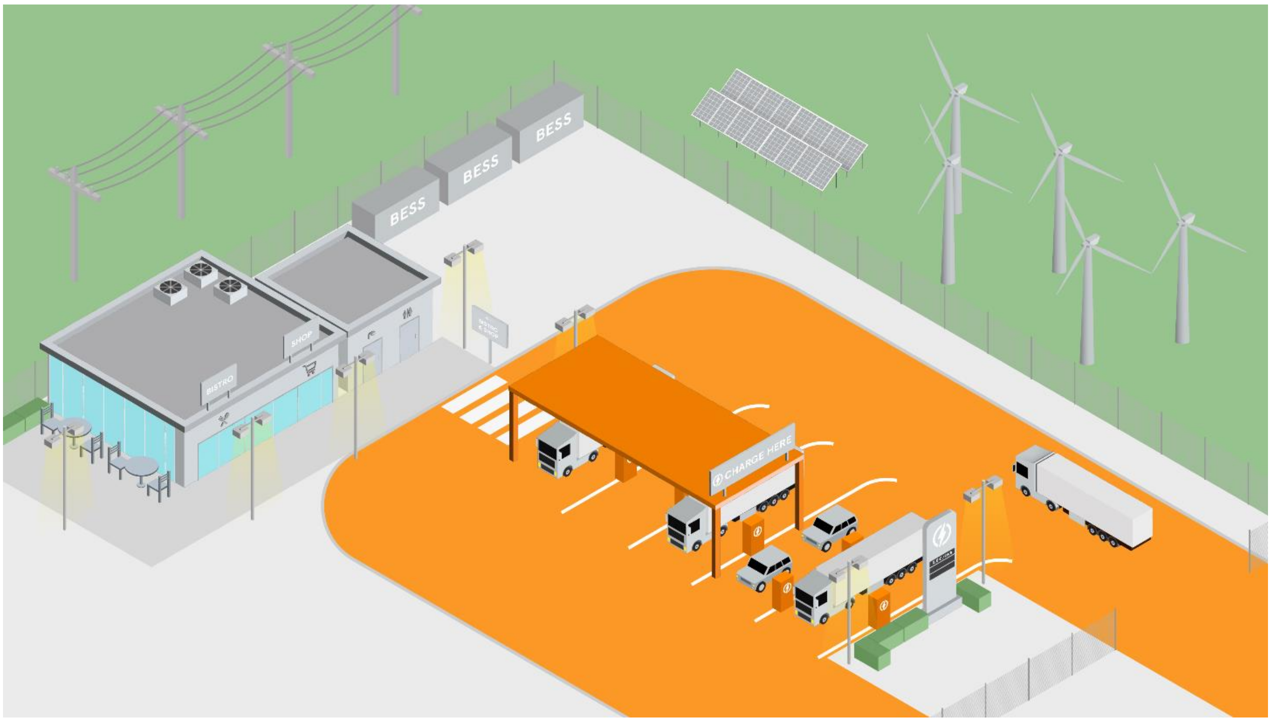

Figure 2 Illustration of a typical hub design with the vehicle related subsystem highlighted in orange.

Main elements

The main elements in the vehicle related subsystem are:

- Roads
- Entrance and exit from connecting roads
- Parking bays
- Charging bays
- Location of chargers
- Roof

Further, there are two important aspects that impact the vehicle related subsystem:

The physical shape and location of the land where the site is located constrain the physical design of the charging station. These constraints, along with the characteristics of the ground and surrounding terrain, affect the construction possibilities from both a technical and regulatory perspective, which can vary by country. Geographic location also dictates weather-related design; for instance, hubs in snow-prone regions must incorporate specific infrastructure for snow removal. The location of the hub itself may also determine its role in providing charging services and the required power levels. For instance, a hub located directly along a major motorway or close to high traffic areas will likely need to support higher power levels in total compared to one in a low-traffic area.

The associated vehicle also plays an important role for the design parameters. Which type of vehicle is the station designed for? HDV, LDV (light-duty vehicle), commercial vehicles, personal cars or even MC? Even within a category, such as trucks, there can be significant differences in length, weight, and cargo type, ranging from hazardous materials to high-value goods. When designing the hub, this is usually something that must be considered. For example, many do traffic flow simulations, which require vehicle dimensions. Additionally, the vehicle affects various aspects such as the size of parking spaces, cable length, and the need for secure parking. Trucks also often prefer drive through charging to minimise reversing and risk of collision, compared to charging solutions for cars which do not need the same space, also due to that trucks often are on more time dependent journeys and need to leave without delay. The vehicle also plays a role in how it interacts with the different parts of the hub, for instance communication with the chargers, numberplate reading for access, power need, connector type, etc. This part is closely associated with the supporting information related subsystem.

Interlinks with other subsystems

It is closely connected to the other subsystems: Human related, Supporting Information, and Energy Supply, as many of their features have physical requirements that must be considered in the design. For example, user behaviour and accessibility needs (human related), the location of screens or indicators (supporting information), and the positioning of energy infrastructure (energy supply) which all place specific requirements on the physical layout.

3.1.2 Human related subsystem

Objective and Scope

The human related subsystem focuses on the experience and needs of users - HDV drivers, but also car passengers given the frequent co-location of LDV and HDV charging. The approach is the optimisation of ‘waiting time’. However, this time is perceived and utilised differently depending on the vehicle category. For HDV drivers, charging is coordinated with the mandatory rest periods by European road safety regulations. Waiting is not merely a delay but a strictly timed window for recovery, hygiene and nutrition. Efficiency here is measured by the proximity of amenities and the reliability of the MCS connection, ensuring the vehicle is ready to depart the moment the legal break ends. For LDV passengers, while traditionally seen as a disruption, waiting time is increasingly viewed as a necessary and well-needed rest for food, coffee, or hygiene, especially given the range of modern EVs. The focus remains on convenience and the quality of short-term amenities.

The provision of these facilities is not merely a service but a core component of the hub’s business case. High-quality amenities act as a key differentiator for CPOs in a competitive market. For HDVs, premium services (secure parking, high-end hygiene) help secure long-term contracts with logistics fleets. For LDVs, co-located services like cafes and shops represent significant secondary revenue streams that can offset the high capital expenditure of megawatt-scale infrastructure.

The objective of this subsystem is to enhance driver experience, support long-haul logistics, and increase hub attractiveness and usage rates by integrating amenities and services that promote comfort, safety, and accessibility. The scope of this subsystem begins once the driver enters the charging hub and continues until they leave the hub premises. This includes all interactions with the physical and digital infrastructure (including the surrounding environment, designed to support human needs).

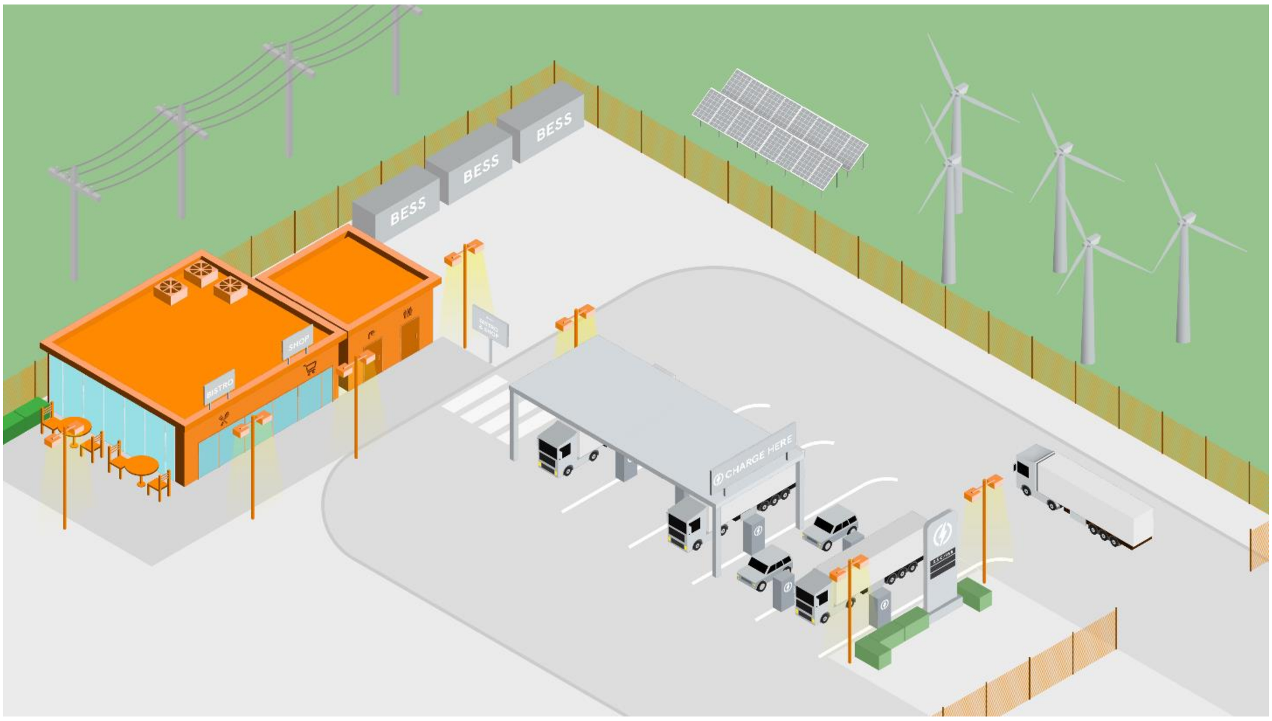

Figure 3 Illustration of a schematic hub design with the human related subsystem highlighted in orange.

Figure 3 highlights the most important human subsystem related components. Key components for hubs with both LDVs and HDVs:

- **Hygiene and Nutrition:** Provide clean, 24/7 accessible washrooms and showers. While HDVs prioritise showers, LDVs prioritise family-friendly restrooms and baby-changing facilities. Food options for HDVs should include substantial meals for long-haul driver and quick grab-and-go snacks for LDV drivers/short-stop travellers.
- **Rest and Recover:** Facilities should feature ergonomic seating and sleeping pods or quiet zones for HDV drivers. For LDV drivers, provide indoor and outdoor seating.
- **Recreational and Family Spaces**: Walking paths, fitness corners and green zones for all to promote well-being. Safe outdoor/indoor play areas for children are essential to manage waiting time for children.
- **Connectivity and Entertainment:** Ensure access to free Wi-Fi, charging points for personal electronic devices. TV lounges are an option but are often a good source of entertainment for the drivers.
- **Lightning and Shelter:** Implement comfortable, high visibility and ergonomic lighting throughout the site. Comprehensive weather protection such as large roofing structures over the charging stations and walkways, ensure a comfortable experience regardless of the climate.
- **Safety Features:** Safety requirements vary by stay duration. For "Top-up" charging (45 min), the focus is on "perceived safety" through high-intensity lighting and visibility. For Overnight or High-Value charging (+8 hours), secured fencing parking with monitored access is required to protect the cargo and the resting driver. Well-lit pedestrian paths must not cross heavy truck traffic lanes.

While integrated hubs serve both HDVs and LDVs, the human related requirements differ significantly due to the nature of their journeys, economic constraints, and the value of the assets involved. The primary difference is the risk profile. An HDV often carries high value cargo. This necessitates security features like TAPA PSR Level 2 certification which includes robust fencing and monitored access. In contrast, an LDVs ‘cargo’ is typically a personal luggage; therefore, the LDV drivers prioritise ease of access and perceived safety (lighting and visibility) over hard physical barriers/ secured fencing. Truck drivers and fleet operators are significantly more cost-sensitive than private car-owners. For a CPO, the investment in high-end amenities for HDVs (showers, washing machines and gyms) is often seen as a strategy to secure long-term fleet contracts and ensure high utilisation. For LDVs, amenities like cafes and shops are primary source of revenue.

Human Interaction with Charging Infrastructure

- Authorisation and Access: User-friendly interfaces for identification (e.g., license plate recognition, RFID).
- Payment Systems: Multiple and transparent payment options including card, apps, cash and fleet accounts.
- Error Handling and Support: Clear fault reporting mechanisms and on-site or remote assistance.

Interlinks with other Systems

The human-related subsystem is deeply interlinked with the other subsystems: vehicle subsystem, the layout of amenities must accommodate vehicle flow, parking dimensions, and driver movement. For instance, rest areas should be easily accessible from parking zones without a need of long (defined as distances exceeding 200–300 meters) walks or unsafe crossings. For the energy subsystems, the safety and usability of chargers are critical. Charger must consider human ergonomics, weather protection, and visibility. The design should also support intuitive interaction with energy systems (e.g., status indicators, cable management). For the information subsystems, the digital signage, wayfinding, and real-time updates (e.g., charging status, queue times) enhance user experience. In addition, multilingual interfaces and accessibility features ensure inclusivity.

3.1.3 Supporting information related subsystem

Objectives and scope

This subsystem focuses on the information support connected to the planning, execution and follow-up of the charging activity. Information support is both digital and analogue. The objective is to secure a predictable, efficient, safe and secure overall charging experience, i.e.:

- ensure users can easily find, book and access charging stations
- clear guidance to charging station location and charging outlet
- real time monitoring of charging performance
- immediate assistance in case of any malfunctions
- site surveillance
- all support information should have multilingual support and/or graphical signs, road markings etc.

The subsystem is highlighted in orange in Figure 4 below, however, a lot of the functions related to this subsystem are digital and not visualised in the image.

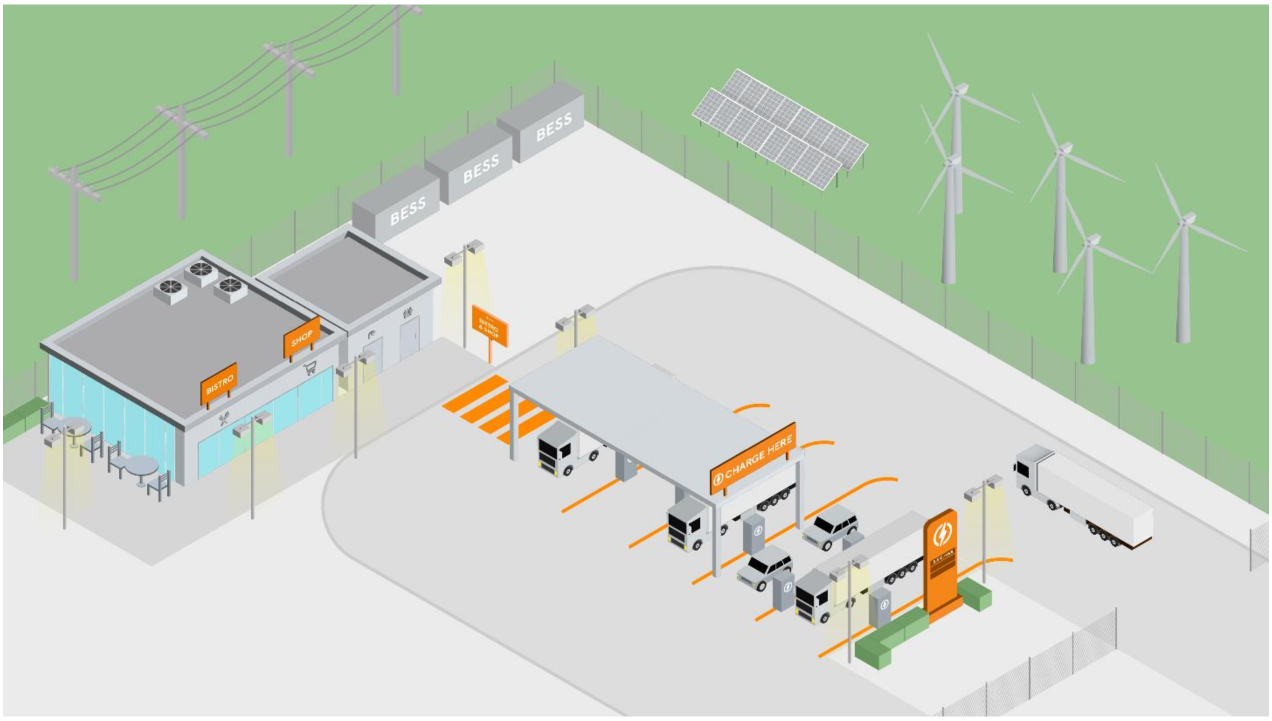

Figure 4 Illustration of a schematic hub design with the supporting information related subsystem highlighted in orange.

Main Elements

The main supporting information elements are:

- Static charge station information (MCS/CCS, parking, services, booking possibilities, physical limitations, amenities, etc.).
- Dynamic charge station information (available charging slots, available power, available parking lots, etc.).
- Navigation, access and guidance services information (how to get there, how to get access, how to find available/booked charger, how to pay, etc.).
- Physical and digital signage for access, parking/charging time limits and reserved (booked) charging bay.
- Information about the available digital interfaces to book, pay, follow-up (e.g. mobile apps, websites, connection to charger).
- Information to enable consistent operation and monitoring of chargers.
- Information about how to get customer support (24/7 helpline).

Interlinks with other subsystems

The supporting information subsystem is closely connected to all the other three subsystems, since the information shared and needed in the various phases of the charging experience are based on the setup or attributes of the other three. The static charge station information has e.g. a strong connection to the vehicle related subsystem, but also to the human related subsystem. The dynamic charge station information is strongly connected to the energy supply subsystem.

3.1.4 Energy supply related subsystem

Objectives and scope

The main objective of the energy supply related subsystem is to provide the required amount of energy and power for the defined scope and set-up for the site regarding the charging function. The main physical element of the subsystem is grid connection, local grid, chargers, and they are often complemented with local stationary battery and local renewable energy production from sun and wind. The physical main elements of the subsystem are highlighted in orange in Figure 5.

Figure 5 Illustration of a schematic hub design with the energy supply subsystem highlighted in orange.

Main Elements

The energy supply subsystem consists of several elements. The **physical backbone** contains the grid connection to the public distribution grid including transformers and switchgears, the local electrical grid and the chargers. When it comes to charging technologies, the energy supply system should provide both CCS and MCS.

Several **physical features** build upon this backbone. This includes various energy elements supporting the energy supply, e.g. an energy storage system for peak shaving, buffering or ancillary services, photovoltaics (PV) or wind turbines to produce green energy on site. All those elements are connected to the physical backbone and orchestrated through the charging station’s energy management system (EMS). For future use cases, the vehicle-to-grid connection allows the vehicles to feed in electric energy back to the grid.

The current state of the art local grid is based on alternating current (AC) just as the vast majority of local grids worldwide. However, core hardware in chargers, batteries and PVs operates with direct current (DC), which gives potential efficiency increases when using DC based local grids (Fraunhofer IISB, 2026).

In addition, **digital features** enrich the functionality of the energy supply system. In the core of this stands the EMS to monitor, control and optimise the performance of the system. To optimise the interface between the fleet operator and the CPO, a digital booking system brings major benefits to the EMS functionality. From this perspective, the use of modern software and the utilisation of data (such as the vehicles' required energy need, forecasted vehicle maximum charging speed, schedule charging/break time etc) enables more efficient load management and a more seamless experience for the drivers and fleet managers.

Innovative **business models** can be seen as a fourth main element of the energy supply subsystem. Through the utilisation and linking of individual aspects of the previously presented elements, new services and added value can be created for various stakeholder groups. This might include the utilisation and monetisation of renewable power, provide grid services or create value through upcoming vehicle-to-grid functionality.

Interlinks with other subsystems

There are many interdependencies with the other subsystems where the following have high relevance for the design of the energy sub-system. The installation of the local grid, power electronics and chargers can be configured in multiple ways. The design of the system is strongly influenced by the available space and planned vehicle flow through the station. It creates strong interlinks with the vehicle and human-related subsystems. Such an interlink handles both space restrictions as well as the different charging needs for the different vehicle types. Regarding the supporting information subsystem, there is a clear link, especially to the digital features EMS and digital booking system. Safety and user friendliness should be considered when designing a charger and how it is installed at the charging station to ensure a pleasant and accident-free stay at the site. Hence it is an important interlink with the human-related subsystems.

3.2 Analysis of existing sites and literature related to subsystems

This chapter covers the best practice for charging hubs made through an analysis of existing sites and literature. The analysis is divided into the four subsystems. A list of the sites that have been analysed for each subsystem is attached as Appendix 1.1-1.4.

3.2.1 Vehicle related subsystems (physical) analysis

As mentioned earlier, the vehicle related subsystem refers to how the vehicle physically interacts with the charging hub. How the vehicle can move within the hub is defined by the design and layout of the hub itself, including roads/driveways, charging bays and areas for parking. The design and layout of existing hubs and rest areas have developed over time and with increasing traffic and transport volumes. There is a great need for truck rest areas all over Europe and as a result new truck stops or secure parking areas are established. These new truck stops are naturally located close to where the trucks operate and ideally in direct contact with or close to the motorway. Figure 6 displays examples of newly deployed and extended sites; notably, the new constructed areas constitute a major addition to the sites.

Figure 6 Example of expanding rest area a) Lichtendorf Süd, in Nord Rhein Westfahlen, Germany b) Rastplatz Heuchelheim, Germany. *Images from Google Maps*.

There are general aspects of hub design that may be considered best practice independent of where the hub is located. However, in order to define best practice for the vehicle related subsystems, the location of the hub needs to be taken into consideration as it will place limitations on the physical design of the charging station. The focus in this section has been on two important deployment scenarios where the second one has been divided into two and their different layouts:

A: **Locations along the motorway, where the entrance and exit are in the same direction**

B: **Locations not in direct contact with the motorway:**

B1: **Locations not in direct contact with the motorway which allows for LDV/HDV**

B2: **Locations not in direct contact with the motorway which allows for only HDV**

The following sections provide an analysis of these groups with a general best practice in the end.

A: Locations along the motorway, where the entrance and exit are in the same direction

Truck stops and rest areas along the motorway, especially along the TEN-T network, are often strategically placed in relation to the traffic and therefore also highly utilised. Since the number of rest areas for trucks along the motorway is limited and the cost of establishing completely new sites is high due to road infrastructure investments, existing sites will play an important role in making the electrification of long-haul trucks a reality. However, the space for truck parking is currently very limited along motorways. Hence it is crucial to minimise any reduction in truck parking capacity when installing or expanding necessary charging infrastructure (Plötz, P *et al*, 2024). A few examples of rest areas and truck stops have been analysed below, see Figure 7 for a typical layout of an A site.

Figure 7 Rest area Neckarburg, Germany with a typical design for a rest area along high-traffic motorways in the TEN-T network. The purple rectangles highlight parking spaces which allow for extra-long vehicles or other non-typical vehicles to park. *Image from Google Maps*.

When analysing truck stops and rest areas which are in direct contact with the motorway and are limited in space, the following patterns were observed:

- Angled fishbone is a common design and best practice for the parking spots to maximise capacity. The angle makes it easier to enter and exit.
- The LDV and HDV parking spots are usually separated (shorter and longer bays), however, it is common that the entrance and exit are the same.
- In some cases, it could be seen that LDVs and especially LDVs with caravans used the longer “truck parking bays” especially at smaller locations. This is illustrated in Figure 8 Rasteplads Hylkedal, Denmark.
- Parking spots for buses are clearly marked (usually road markings with text). In some cases, they have used boom barriers to prevent other vehicles from parking at these locations. The parking spots for buses are almost always co-located with the LDVs and not with the trucks when the parking bays are separated. See Figure 9b for an example.
- The truck parking bays are often drive-through, however not always.
- There often exists one long stretch where trucks can park where parking bays are not drawn up, see purple rectangle in Figure 7. This configuration also offers the added benefit of accommodating various truck combinations and vehicle lengths.
- A notable trend is that many trucks tend to park at the edges, particularly adjacent to wooded areas. These locations likely offer the benefits of natural shade and a calmer environment compared to the central charging zones.
- It is common to have rest stop on each side, many of the modern built ones look identical on both sides. See example in Figure 9a.
- LDVs are commonly placed closer to the amenities, or that the amenities are located between the LDV and HDV parking/charging areas. However, it differs whether it is the LDVs or the HDVs that are placed closest to the motorway.

A general observation from all analysed hubs and rest areas is that the parking bays are as narrow as possible to accommodate as many trucks as possible. Converting these parking bays to charging bays without reducing the parking capacity is challenging since the charging equipment requires additional space between the trucks. See more about this in Chapter 4.4.

Figure 8 Rest area Hylkedal, Denmark along the E45 where it can be observed that there are both short charging bays for LDVs and longer for HDVs. However, LDVs also park in the longer charging bays, where multiple LDVs can fit in one long bay. *Image from Google Maps.*

The above examples in Figures 7 and 8 can both be considered fairly small and have limited extension perpendicular to the motorway. If these sites would be equipped with chargers for HDVs some of these chargers will definitely be out of order from time to time. In case a truck driver needs to find another charger there is no possibility to turn the vehicle and go back, i.e. without reversing. This is actually the case also in Oberlausitz in Figure 9 below although this rest area is a much larger site and probably built and designed at a later stage. LDVs can drive in circles while trucks lack this possibility. In general, larger rest areas provides greater freedom in design and can offer the opportunity to have these lanes where it is possible to drive back to the entrance again.

Figure 9 Example of a recently expanded rest area in Oberlausitz, Germany. (Left) Notice the layout which is more or less identical on both sides of the motorway. (Right) A zoomed in image where the separation between vehicles is clearly dedicated to buses, LDVs and HDVs from up to down in the image. Observe that the buses are located on the LDV side and not by the trucks. *Images from Google Maps.*

The examples in Figure 10 illustrates how rest areas can be expanded along the motorway or perpendicular to the motorway. In both of these cases, the HDV parking is further away from the motorway than the LDV parking, probably due to that LDVs stay for a shorter time period and that LDVs with passengers represent a larger potential income for the owner of the amenities. In the left example though, Lüneburger Heide, there are specific amenities close to the HDV parking area.

Figure 10 Examples of larger rest areas in direct contact with the motorway. Raststätte Lüneburger Heide, Germany (Left) and Autogrill Villoresi Est, Italy (Right). *Images from Google Maps,*

B: Locations not in direct contact with the motorway

Although the most attractive locations for rest areas are in direct contact with the motorways, new charging stations are often established adjacent but not in direct contact with the motorway. The reason for this is availability and cost of land. These stations can be divided in two groups: Stations built for both LDVs and HDVs (B1) and stations built for HDVs (B2). Long-haul operators are seen as willing to detour slightly if charging is cheaper and more reliable. It is also in this type of location that many of the existing charging hubs exist.

B1: Locations not in direct contact with the motorway which allows for LDV/HDV

In Figure 11, two typical designed rest areas in a B1 location are displayed.

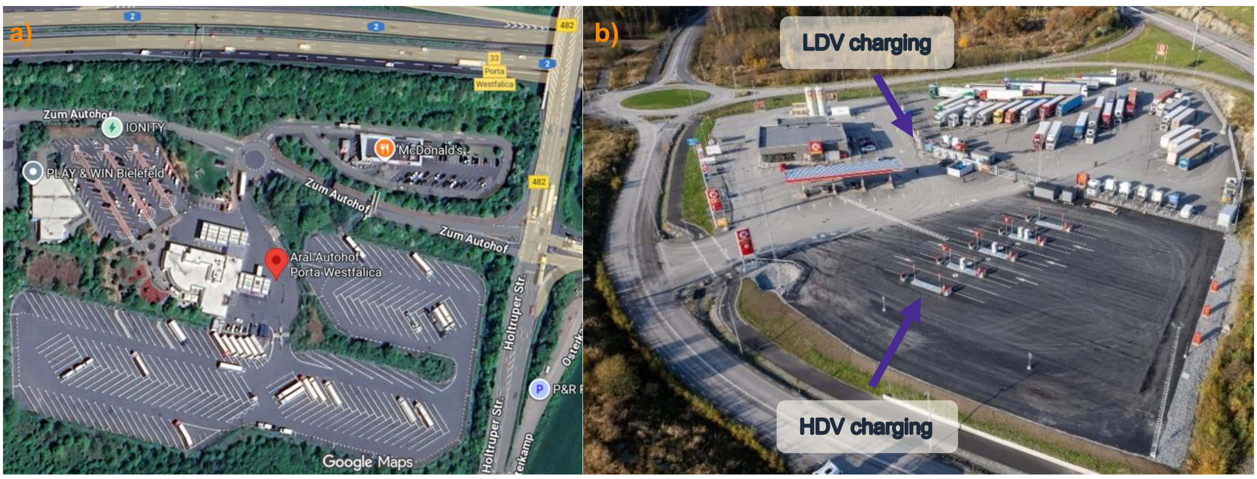

Figure 11 A typical layout for a B1 rest area a) Aral Autohof Porta Westfalica, Germany, with many parking spots for trucks. Image from Google maps. b) Circle K Vädermotet, Sweden, with charging for both LDVs and HDVs which are separated. *Image from Circle K.*

The following observations have been made:

- Some of the charging bays are built and adapted for HDVs but allow LDVs to charge *
- Some of the charging bays are built and adapted for both HDVs and LDVs*. An example of this is DC Handal Mall of Medini EV charging hub, shown in Figure 12.
- Many rest areas and charging hubs allow for both HDVs and LDVs but separate them from each other, as illustrated in Figure 11 with Aral Autohof Porta Westfalica, Germany and Circle K Vädermotet, Sweden. In these cases, the LDVs are commonly placed closer to the amenities or have the amenities in between the LDV and HDV parking/charging areas. Further, it can be observed that the traffic safety precautions often are more around the LDV area. In Figure 11a, the pedestrian crosswalk marks are clear, and the area around the corners is restricted from parking to enable a more clear visibility.
- The truck parking bays are often drive-through, however not always.

* Many of the analysed charging stations that exist today are included in category B, some only for HDV and some for both HDV/LDV. However, because the number of electric trucks on the road is currently limited, many of these stations are underutilised. To increase the utilisation, operators allow LDVs to charge at the truck infrastructure. Then the station and the charging bays are designed for HDVs but allow LDVs to charge. However, there are also sites where the charging bays are designed for both LDVs and HDVs. How this dynamic will shift as the electric truck population grows remains an open question, especially as LDV charging demand also rises. It is yet to be seen whether hubs will become HDV-exclusive or if the trend toward mixed-use facilities will accelerate as the demand increase.

Figure 12 DC Handal Mall of Medini EV charging hub, Malaysia, is a site adapted for both LDVs and HDVs such as trucks and buses. One HDV can fit in two charging bays for LDVs. *Image from Kempower.*

B2: Locations not in direct contact with the motorway which allows for only HDV

This is an important deployment scenario, where only HDVs are allowed to stop and charge. Having a charging hub that only allows for HDVs is seen as an important case, as trucks often operate with small time margins and cannot wait for LDVs standing in their way. It is also seen as a good practice for traffic safety not to mix HDVs and LDVs. Moreover, the demand for safe and secure truck parking areas (SSTPAs) that keep both the drivers and the goods safe is one reason for only allowing HDVs at charging stations. In Figure 13, a Milence station that only allows for HDVs can be seen.

Figure 13 An example of a charging hub dedicated to HDV is Milence charging hub in Immingham, United Kingdom. *Image from Milence.*

The following observations have been made:

- Only allowing for HDVs enables the station to have the potential to be a safe and secure charging area, which can be a requirement for some transports to secure the goods.
- Only allowing for HDVs can also be seen as a best practice by logistic actors as there is no risk that LDVs occupy the HDV charging bays. However, this can also be achieved in a shared HDV/LDV hub with separated charging bays.
- If the hub only allows for HDVs, everything can be adapted to the size of an HDV e.g. the manoeuvrability area and the height of signage. See more in Chapter 4.3.
- The sites and services are adapted to the mandatory driving breaks, such as the shorter 45-minute break (which can be divided into 15 + 30 minutes) and the longer overnight stop of at least 9 hours. The same charging bay may be used for both types of stops, to maximise utilisation, but it is not evident that this will be the case. Long breaks, like overnight stops, would certainly increase the utilisation of the space itself but not necessarily the number of kWhs sold. This depends on how many high-power charging sessions would be realised during the same time as the overnight stop lasts. The break point here is probably between 1 and 2 sessions. Today overnight charging is associated with CCS while high power charging during short breaks for long-haul logistics requires MCS. This will lead to a challenge on how to distribute between these two connectors.

  Currently, MCS is primarily associated with high-power charging; however, since MCS is simply a standard, it can be used for both low and high power. Using MCS as the universal standard for all power levels would eliminate the question of how many of each outlet type to install.

General notes

When looking into the aspect of **the associated Vehicle** and its related effects on the charging hub's layout, there have been some observations about best practice at the existing sites and in literature that have not already been taken up, namely:

- It is quite common to have canopies over the chargers for the analysed charging stations, see example in Figure 14b. These can be built both from a customer experience perspective but also from a technical

perspective to shade the chargers in locations where the sun can be very intense, or to reduce the need for manual snow removal around the chargers.
- It is a common practice to use barriers to prevent collisions with chargers; Figure 14 includes different anti-collision solutions in the orange circles. The design of these obstacles varies, and some are specifically engineered to deflect trucks without causing damage, allowing the vehicle to simply slide off.
- The ground at the charging bay is often made of concrete to allow for the static forces from the trucks. Another alternative is Densiphalt which is a semi-flexible pavement that combines the properties of asphalt and concrete, used for example at the Alfredsson Energy site, see Figure 14a. Figure 14b shows the Milence charging station in Ödeshög where it is also clear that the ground at the charging bays is different compared to the surrounding roads. Similar views can be seen in many of the charging sites analysed.
- With the introduction of MCS, which has a left-side standard for the charging inlet, a trend can be observed where CCS chargers are also being installed on the same side. This affect which side the chargers are placed on.
- The length of MCS cables is restricted due to the high-power levels, which will influence the design of the layout.
- Charging units are sometimes installed on elevated platforms to protect them from vehicle impacts. However, ground-level placement is generally preferred for wheelchair accessibility. Even when not elevated, there are advantages to mounting chargers on prefabricated steel foundations rather than casting them directly into concrete (or what pavement is used). This modular approach allows for faster initial installation and provides the flexibility to perform maintenance or upgrades more easily in the future.
- At charging hubs, ensuring seamless manoeuvrability is essential, particularly if a driver must relocate to a different charger e.g. due to equipment malfunction or an initial positioning error. Ideally, the site layout should facilitate this transition without requiring the vehicle to reverse. This "forward-flow" design is more easily achieved at larger sites, where a dedicated bypass or return lane can redirect vehicles back to the entrance point.

Figure 14 a) Charging station Alfredsson Energy, Sweden, where it is clear that they have used another pavement where the chargers are to better adapt to the static force. The orange circles mark their anti-collision solutions. *Image from Alfredsson Energy.* b) Milence station at Ödeshög, Sweden, the surface at the charging bays is different from the surrounding surfaces. The orange circles mark their anti-collision solutions. *Image from Lindholmen Science Park.*

3.2.2 Human related subsystem analysis

The analysis of existing sites included a wide range of scenarios ranging from basic regulatory compliance to award-winning environments.

- **Premium security and amenities:** The OnTurtle station in La Jonquera (Spain) is a primary example of a premium environment, holding the TAPA level 2 certification for security while providing a hotel, a laundry, a supermarket, and even games room.

* **User Centric Excellence:** The Formula Premier Truckstop in UK was named 'Truck Stop of the Year 2023' for its high-end focus on driver well-being, including on-site gym, a self-service kitchen, and a dedicated 'ladies-only' washroom equipped with premium styling tools. TIP Secure Truck Parking Isoparc Sorigny (France) has set a new benchmark for drivers' wellbeing and green parking for the HDVs.
* **Eco-sustainability and Hospitability:** The Seed and Greet hub in Germany integrates an organic bakery concept with sustainable features e.g. an on-site honey production and berry picking, creating a welcoming environment for both LDV and HDV drivers.
* **Operational Efficiency:** The WattHub Geldermalsen in the Netherlands features best practices in logistics by offering guaranteed time-slot reservations eliminating the uncertainty regarding access and waiting times.
* **Design Failures as learnings/lessons:** The OMV eMotion station in Romania, demonstrates how non-drive through design forces trailers to be decoupled and limits charging to only one side of the vehicle, creating significant operational barriers for long-haul trucks.

Best practices for human related subsystem

When planning and developing MCS charging hubs, special attention must be given to the human-related subsystem that directly affect user safety, usability, and overall operational efficiency. These systems play a critical role in ensuring that charging hubs are not only technically functional, but also compliant, intuitive and fit for real-world use by the drivers, operators, and service personnel.

Based on a structured analysis of existing MCS-ready and high-capacity charging sites, the key human centric components have been identified and grouped into four main categories. These categories represent the minimum and best-practice requirements necessary for safe, accessible, and user-friendly hub design. Each component is further described with references to best practices of hub design, providing concrete examples of effective implementation. The locations indicated in brackets represent existing charging hubs or service areas where these features have been observed and successfully implemented, serving as reference examples for current industry practice.

* Core Regulatory Needs (The Must-haves')
* Safety, Security and Physical Environment
* Charging Ergonomic Designs and Accessibility
* Digital interaction and information

Core Regulatory Needs (The Must-haves'): These elements directly address compliance with EU driving and rest time regulations and the driver's basic health. The human related subsystem analysis integrates requirements from the EU Delegated Regulation 2022/1012 which establishes mandatory standards for the SSTPAs. Best practices design must comply with the regulatory services as the baseline for the hub attractiveness. Table 1 lists these regulatory services by categorising the amenities according to HDV and LDV focus.

The amenity requirements for MCS charging hubs differ depending on the primary user group. HDV-focused amenities, aligned with SSTPA Gold and Platinum level requirements, are considered mandatory and address the essential needs of professional drivers during charging stops. LDV-focused amenities, oriented towards convenience and family use, are derived from an extensive analysis of best-in-class hub practices and are presented as recommended features that enhance user comfort and overall hub attractiveness.

Across the four amenity categories—Nutrition, Hygiene, Rest/Waiting, and Experiential features—the identified components reflect both functional necessities and value-added services. For example, nutrition facilities such as convenience stores and restaurants have been observed at sites including Shell Recharge

Bao'an Airport, Östgötaporten, OKQ8, and Ödeshög, while quick grab-and-go food options and vending solutions have been implemented at locations such as Seed and Greet in Germany.

Similarly, 24/7 gender-segregated toilets and showers are standard features at several HDV-oriented sites, while family-friendly sanitary facilities, including baby-changing stations, are incorporated at hubs designed for LDV users. Dedicated rest areas for professional drivers are complemented, in LDV-oriented hubs, by indoor and outdoor seating areas with direct line-of-sight to charging vehicles and access to mobile charging points.

Experiential amenities further enhance the user experience at selected hubs. Free Wi-Fi and power supply for charging personal devices are increasingly common, while more immersive features such as playgrounds, children's corners, and outdoor green zones have been observed at locations including Serways Raststätte Sindelfinger Wald & Schönbuch West, E.ON sites along the E20 in Middelfart, Denmark, and Seed and Greet in Germany. The sites mentioned serve as reference examples where these amenities are already in operation and demonstrate current industry-leading practices.

Table 1 HDV and LDV focused amenities

Amenity Category	HDV Focus (SSTPA Gold/ Platinum Level) (Mandatory)	LDV Focus (Convenience/Family)
Nutrition	Convenience store (restaurant or area for food prep.	Quick grab-and-go snacks, coffee and vending machine with various options.
Hygiene	24/7 gender-split toilets/showers	Clean, family-friendly restrooms with baby-changing stations
Rest/Waiting	Dedicated rest areas	Indoor/outdoor seating and mobile charging points
Experiential	Free Wi-Fi and power supply to charge personal devices	Playgrounds, Kids Corners and outdoor green zones with local fruits.

Safety, Security and Physical Environment: Security is most important at hubs adapted for HDV due to the high value of cargo and vulnerability of drivers during the rest period.

- Site Separation flow: For hubs co-locating HDVs and LDVs, best practice sites like Seed and Greet, Germany and Serways Sindelfinger Wald, Germany show that while LDV and HDV charging points are often co-located for utility, they must be separated to ensure that heavy traffic does not endanger pedestrians or light vehicles. Clearly marked pedestrian walkways should be provided to ensure safety for all users.
- Lighting and shelter: High intensity, glare-free, pedestrian-scale lighting is critical for night safety, while canopies over the charging bays protect both users and equipment from extreme weather.
- Advanced Security: High standard hubs must comply with SSTPA security levels (1-4). Features include ANPR cameras, robust perimeter fencing, 24/7 manned surveillance and bright and bi-directional light which protects drivers and cargo during MCS sessions. Automatic Number Plate Recognition (ANPR) at entry/exit points provides the level of security required by logistic companies. Transported Asset Protection Association (TAPA) - The PSR (Parking Security Requirements) standard was developed by industry stakeholders (manufacturers, logistics providers, and law enforcement) to combat cargo theft, which costs the European economy billions of euros annually. It categorises parking facilities into three formal certification levels based on the intensity of security measures. Level 1: Platinum - Extreme

security measures. Typically requires 24/7 on-site security guards, advanced biometric or ANPR access, and full perimeter physical barriers. Level 2: Gold - High security. Requires robust physical barriers (fencing), 24/7 video surveillance (CCTV), high-intensity lighting, and restricted access controls. Level 3: Silver - Minimum acceptable security. Focuses on basic lighting, some fencing, and documented security procedures. Often involves self-certification.

Charging Ergonomic Designs and Accessibility: This ensures the driver can physically interact with the charging system without any strain. The charging infrastructure should be universally designed to accommodate users with varying physical strengths and mobility needs.

- Interface height: To ensure usability for wheelchair users, screens, buttons, and payment terminals should be set at a maximum height of 120 cm, with a preferred range of 80-100 cm over the parking surface.
- Cable Management: To minimise physical effort (a key ergonomic requirement), best practices require active management to ensure single-handed operations and prevent heavy cables from becoming trip hazards.

Digital interaction and information: These components related to the digital environment that creates trust and reduces the range anxiety.

- Visual Information: Must use high contrast between text and background. Avoid red/green colour combinations.
- Status Indicators: Charger must convey charging status to people with impaired colour vision (i.e., status must be communicated via text/pattern, not just colour).
- Payment/ Code Access: QR codes, tag readers, and payment information should be placed for easy access by both standing and seated persons.

Premium Hubs and services: While regulatory needs provide baseline, premium services significantly increase a hub's attractiveness and the well-being of a driver.

- Comprehensive Services: Extensive catering options, often including multiple branded restaurants and high-quality seating areas, 24/7 kitchens (Formula Premier Truckstop, UK), organic bakeries (Seed & Greet, Germany). Figure 15 illustrates a range of amenities available at designated truck stops. The image on the left highlights the leisure and vending facilities at the TIP Secure Truck Parking (Isoparc Sorigny, France), featuring automated vending, dedicated seating, and television for driver entertainment. In contrast, the image on the right from Alfredsson Energy, (Norrköping, Sweden) showcases kitchen and sanitary facilities, including a kitchenette equipped with a microwave and coffee machines, alongside spacious dining areas and integrated shower/toilet blocks. Figure 16 illustrates the dedicated fitness areas provided for drivers at TIP Secure Truck Parking (Isoparc Sorigny, France). Such facilities are increasingly vital in the logistics industry, as they address the sedentary nature of long-haul driving. By providing accessible exercise equipment, hubs can actively support driver health, reduce fatigue-related risks, and enhance overall occupational well-being.

Figure 15 Examples of drivers lounges at truck stops a) Driver's lounge at TIP Secure Truck Parking Isoparc Sorigny, France. *Image from TIP.* b) Driver's lounge at Alfredsson Energy, Norrköping. *Image from Alfredsson Energy.*

Figure 16 Fitness zone at TIP Secure Truck Parking Isoparc Sorigny, France. *Image from TIP.*

- Time Optimisation: High-quality design incorporates technological solutions to reduce non-rest time, such as reservation applications. This allows drivers to pre-book parking and charging spots, minimising the time wasted searching for available capacity and directly maximising the effective duration of the waiting period.
- Advanced Security: Large Scale, dedicated facilities offering permanently guarded parking. (OnTurtle in La Jonquera), certified by European Secure Parking Organisation (ESPORG) and is the only location in Spain to hold the Transported Asset Protection Association (TAPA) Level 2 certification. Figure 17 shows the monitored gate parking at OnTurtle in La Jonquera)

Figure 17 Advanced security by monitored gated parking at OnTurtle in La Jonquera, Spain. *Image from OnTurtle.*

- Other facilities: Ladies only washrooms with high end and luxury tools (Formula Premier, UK. Quiet zones, nap pods, and trucker lounges with massage chairs (Tiffin River, USA). Hotel, ATM and washing machines (OnTurtle in La Jonquera).

Europe is currently facing a critical shortage of professional drivers. To make the occupation more attractive, there is a clear trend toward providing 'logistic hospitality'. Beyond basic hygiene, hubs are increasingly offering well-being services. Formula Premier (UK), Seed & Greet (Germany) serve as best practice examples where the focus on a premium environment (gyms, organic food, green zones) act as a retention tool for transport companies. By embracing the "Home Away from Home" concept, organisations can enhance the wellbeing and satisfaction of the drivers, ultimately leading to improved productivity and morale.

3.2.3 Supporting information subsystem analysis

To analyse the supporting information subsystem, it has been divided into five different categories:

- Signage
- Road markings
- Surveillance support information
- Authentication
- Digital interface

An analysis has been conducted in each of these categories:

Signage

Signage is an important part of providing users with information and preventing accidents. In general, using pictograms to describe things is a best practice for overcoming language barriers. From the standard "The EU standard for Safe and Secure Truck Parking Areas": *Emergency contacts shall be displayed at the parking facility at least in the national official language and in English. They shall be supported by easily* *understandable pictograms.* Additionally, they state "*Clear signs shall be provided in order to ensure safe traffic movement at the parking facility"* as one of the mandatory services that need to be provided. Another good practice observed at existing sites is adapting the height of signs to truck cabins, particularly at HDV-only sites.

Signage that can be seen from the road are a best practice. Using high signs which also are lighted at night is quite common both on charging stations as well as gas stations. For companies that have multiple stations that serve both LDV and HDV, they sometimes on these signs highlight if the specific site is adapted also for trucks, one example of this is Circle K Vädermotet which has a clear sign about that they have a site that is not only adapted to LDVs but also trucks and that they offer charging. Another example is Einride's sign at their Varberg site which also displays available chargers. An additional example is Plugit's sign in Kotka, Finland, which displays the price for both CCS and MCS charging. These signs are shown in Figure 18.

Figure 18 Examples of signs that can be seen from the road a) Circle K Vädermotet (left picture) *Image from Lindholmen Science Park* b) Einride Varberg (middle picture). *Image from Lindholmen Science Park c)* Plugit Kotka, Finland (Right picture). *Image from Kempower.*

The need for a common standard or harmonisation of signage at charging stations has been raised in the project in relation to best practice. There is an EU standard, EN 17186, that covers the harmonisation of identifiers for the power supply of electric road vehicles (Svenska institutet för standarder, 2019). This standard includes methods for visualising different connectors, which can be used in signage at charging stations. However, there are many other types of signage that are necessary and still require harmonisation.

AFIR also regulates on that the charging hub needs to have an adequately signposted (European Union, 2023). Additionally, it says that member states must ensure that the exact location of alternative fuels infrastructure within TEN-T parking and rest areas is clearly signposted.

Road markings

Road markings are also an important part of providing users with information and accident prevention. A clear pattern that can be seen when analysing existing new built charging stations is that it's very common to use ground-painted arrows to indicate driving direction. This is quite cost effective and easily understandable as it is not limited by language. However, this solution can be problematic if the station is located at a place where snow is common as it can cover the signage, then other solutions might be a better option or is needed as a complement. Wear from studded tyres, winter road maintenance with snow ploughs, also need to be considered when choosing solutions for road markings. A popular choice in cold climates like Scandinavia is thermoplastic road markings applied hot and hardening quickly, with robust retroreflective glass beads to withstand studded tyres and ploughs, ensuring night visibility.

Surveillance support information

CCTV is a common way for both truck stops and charging stations to provide surveillance for their areas. When CCTV is used it is often combined with lights to ensure that it can be used at the dark times of the day as well. Following the EU standard for Safe and Secure Truck Parking Areas there are multiple recommendations on how to place and manage the CCTV. They also recommend that *Physical or remote surveillance checks shall be conducted minimum once every 24 hours.* Both digital and physical attendant surveillance is possible. For example, the Formular premier truck stop in the United Kingdom that have been named "The most secure parking in the North West", *has a* 24/7 Manned Surveillance complemented with digital solutions like CCTV and Automatic Number Plate Recognition (ANPR) (Formula Premier truck stop, 2025).

Beyond security, advanced camera surveillance can also serve as a tool for optimising station logistics and operational flow. On-site personnel can utilise real-time monitoring to identify and resolve immediate obstructions, such as improperly parked trucks that obstruct traffic throughput, which can be difficult to detect early without help from the video, especially at large stations. Furthermore, by integrating AI-driven data processing, the system can analyse vehicle and driver behavioural patterns to enhance both safety and efficiency. This analytical approach is exemplified by the implementation of Viscando's solutions within the E-Charge project, where data is leveraged to refine current operations and inform the design of next-generation infrastructure (E-Charge, 2025).

Authentication

There are multiple ways to authenticate the user that can be used to enter a gated charging station area. For example, Milence Landvetter use an intercom at the entrance gate where there support team will help authenticate the user and let them into the site. ANPR is also a solution that can be used for authentication.

Different solutions have so far been used for authentication/identification of the vehicle related to the charging process, i.e. to enable charging by just connecting the cable:

- VIN (Vehicle Identification Number) number – you typically register it within your charging provider´s app, linking your vehicle for automatic recognition and payment. When the vehicle is connected the charger collects the VIN-number and compares it with the list of approved numbers and starts the charging.
- Autocharge identifies the car via its unique network hardware address (MAC address) linked to a charger account, starts charging automatically.
- Plug & Charge (ISO 15118) uses digital certificates (PKI) for secure, encrypted communication between car and charger, handling authentication and payment automatically.

Digital interface

Many of the charging stations and truck stops have a website where it is possible to find information about the site. The supply of information on the website differs. For some charging sites a website cannot be found.

Some of the stations displays the charger status, whether they are free or not, on their website, for example Alfredsson Energy. There are also third-party companies that can display the charger status at different sites, e.g. The E trucker app, an app that shows many different truck charging stations and displays the status of the chargers at those sites. Third-party companies typically collect the information from the National Access Points (NAP).

NAPs are central platforms in Europe, mandated by the EU, to collect and share real-time and static data not only about electric vehicle charging stations, but also to facilitate access, easy exchange and reuse of transport related data, in order to support the provision of EU-wide interoperable travel and traffic services to end users. AFIR Article 20 mandates CPOs to report data to their country's NAP.

For example, in Sweden, the Swedish Energy Agency is the responsible organisation for the dataset "Charging points for electric vehicles – NOBIL", which is a part of the Swedish NAP trafficdata.se. NOBIL is the database where all the static and dynamic charging infrastructure data is collected for Sweden and Norway, e.g. location of station, operator, connector types, charging capacity, availability status. When you use an EV charging app in Sweden or Norway, real-time information is typically collected from NOBIL, which in turn receives it from CPOs and/or eMSP using standard protocols like OCPI.

3.2.4 Energy supply subsystem analysis

The energy supply subsystem has previously been divided into four elements: **physical backbone**, **physical features, digital features**, **business models.**

Taking a step back to the design phase of a charging station, the available grid connection size becomes crucial. It is also one of the main variables for the physical backbone in the energy supply subsystem. CPOs throughout Europe experience long lead times to get grid connection, which in some countries or specific places are stretching over several years (Macbeth Task 2.1). This is a significant bottleneck today and might worsen with time as significantly increased grid connections will be needed when MCS technology will scale up. A grid capacity map with grid connection cost estimates is a desirable tool for CPOs to soften this bottleneck. Such maps are already available for various countries in Europe, however there are different designs of them including sometimes different functionalities. As a best practice in dealing with several challenges related to grid capacity, the main French DSO, Enedis, provides a grid capacity map with regular updates every six months (Milence, 2024).

Once a grid connection is established, the DSO continues to impact the charging stations electricity management based on the agreement of the specific grid connection or how the local grid tariff is designed. In the constrained European electricity grid, there are surging different flexible grid connection agreements. One example is an obligation to reduce power outtake during grid peak congestion hours; another example is the obligation to reduce power when the grid is extremely constrained based on a steering signal given by DSO. Also, the level and design of grid tariffs can look very different depending on country or between different DSOs in the same country, even if all of them comply with the basic structure dictated by EU. They are a significant cost driver for the charging stations and largely dictates the value of flexibility in form of peak shaving. Depending on the grid connection agreement and grid tariff design, the best practice of the energy supply subsystem could vary. Especially to which extent it is relevant to add load management features such as battery, variable power pricing or booking systems.

When looking into existing charging stations, there is very limited information available from public sources about the station's physical backbone. Some are highlighting their strong grid connections (Kane, 2021, Einride, 2024) while others announcing they have built a micro-grid with virtual power plant capabilities (Miao, 2025). However, it is hard to track down a tangible best practice of these different features.

Currently, available MCS charging stations are installed at a minority of all available public CCS charging stations. Among the few MCS stations installed today, there is a mix between offering a dedicated charging bay for MCS or providing the option to charge with both technologies at the same bay.

The co-existence between MCS and CCS is also present when looking at the hardware, where several charger manufacturers (e.g. Kempower, Alpitronic, Siemens and others) offer power electronics which is compatible to supply both a MCS and CCS charging outlets. Based on the layout of the station, these outlets can be collocated in the same charging bay or supply separate MCS and CCS charging bays. Some manufacturers (Alpitronics, Siemens) offer the two different outlets integrated into a single charging point (see **Error! Reference source not found.**).

Figure 19 Examples of combined CCS and MCS hardware. A Siemens charging point with both MCS and CCS (left) and Shell Amsterdam ETCA charging site with a combined over-head CCS and MCS charger which shares power electronics with MCS charger for ships (right). *Images from Lindholmen Science Park and Shell*.

The question about what is the optimal ratio between CCS and MCS chargers at a single public charging station or how large share of all public charging stations will host MCS remains open as the market has barely started to adopt MCS technology.

As physical features, both battery and solar panel installations are well established components. For some stations also local wind power is accessible. See Table 2 for an overview of how large battery and solar panels (and wind) are installed at existing sites relative to the total size of the charging station. Based on this overview there is no clear correlation between the charging station size to the dimensions of batteries or PVs.

For the majority of sites with batteries listed in Table 2, the battery has a significant share of the total power output from the installed chargers. In some cases, the batteries output power is even larger than the grid connection.

In the locations where PV panels are installed, their theoretical peak power is in general much smaller than the sum of power output from the installed chargers. The exception is when there is an adjacent dedicated area for solar panel (and wind). For example, in WattHub Geldermalsen, the charging station is next to a former landfill which is equipped with a solar panel park and three wind power plants. Another example is Shell Amsterdam ETCA charging station which through a large microgrid is connected to surrounding buildings which has large area of rooftop PV installed.

Table 2 Installed battery and PV sizes for selected charging stations. The charging spots are defined if they are dimensioned for HDVs or LDVs.

Location	Charging spots (#)	Sum inst. Charging capacity (MW)	Grid connection (MW)	Stationary battery (MWh)	PV (MW_p)	Comment
Shell Recharge, Bao'an Airport (China)	258 CCS (LDV)	93	No info	-	0.23	[1]
WattHub Geldermalsen (Netherlands)	42 CCS (HDV)	>3.6	10	-	adjacent PV (9.3MW) and wind (10.8MW)	[2,3,4,5]
DC Handal Mall of Medini EV charging hub, (Malaysia)	28 CCS (LDV & HDV)	No info	1.2	Planned to add	0.37	[6]
Shell Amsterdam ETCA MCS for both marine and heavy-duty road transport (Netherlands)	110 AC, 9 CCS (LDV) and 1 MCS/CCS for trucks and ships	No info	No info	Installed, No info about capacity	~1.4 (3600 solar panels)	Chargers connected to a larger campus microgrid (10kV) [7, 8]
Sichuan supercharging hub (China)	>126 CCS/MCS Mainly HDV	100	No info	0.43	1	For commercial vehicles only [9]
Seed and greet (Germany)	107 CCS (LDV)	>17	No info	2	0.34	[10, 11, 12]
Alfredssons energy (Sweden)	1 MCS 11 CCS (HDV)	4.8	2.4	2.4 (1.2 MW)	0.4	[13,14]
Circle K Flädie (Sweden)	4 CCS (HDV) 10 CCS (LDV)	4.5	0.6	1.6 (0.8 MW)	0.06	[12, 15, personal communication]
Circle K Varberg Nord (Sweden)	8 CCS (HDV) 16 CCS (LDV)	7.3	1.2	1.7 (0.8 MW)	-	[16, personal communication]
OKQ8 Ödeshög (Sweden)	1 MCS 2 CCS (HDV)	1.7	1	0.5 (0.35 MW)	-	There are additional 34 adjacent charge points by other operators [12, personal communication]

[1] https://www.globalconvenience.com/best/entries-25/shell-recharge-shenzhen-china/
[2] https://watthub.nl/locaties-post/watthub-geldermalsen/
[3] https://www.tsg-solutions.com/tsg-delivers-the-worlds-largest-fast-charging-hub-for-heavy-vehicles-in-the-netherlands/
[4] https://avri.nl/nl/over-avri/zonnepark-avri
[5] https://www.thewindpower.net/windfarm_en_30921_avri.php
[6] https://kempower.com/news/kempower-delivers-charging-solutions-to-malaysia-dc-handal/
[7] https://www.shell.com/business-customers/marine/electrification/_jcr_content/root/main/section/simple_96405848_copy/call_to_action/links/item0.stream/1720153806154/e83a617b921d4067515972ec7e545a7d326bf516/shell-marine-mw-charger.pdf
[8] https://www.mobilityplaza.org/news/39472
[9] https://interestingengineering.com/energy/china-huawei-worlds-first-100mw-charging
[10] https://seedandgreet.de/en/welcome/
[11] https://www.energy-storage.news/tesvolt-extremely-proud-to-be-part-of-europes-largest-and-most-innovative-ev-charging-park/
[12] Chargefinder.com
[13] https://alfredssonenergy.se/
[14] https://polarium.com/insights/polarium-and-kempower-enable-megawatt-charging-at-alfredsson-transports-advanced-depot/
[15] https://alltomelbil.se/batterilager-pa-1600-kwh-sakrar-upp-circle-ks-laddstation-i-fladie/
[16] https://www.di.se/nyheter/circle-k-invigde-sin-1-000-e-laddare-fem-ar-for-tidigt/

The charging stations are designed for either LDVs or HDVs or a combination of these vehicle types. The energy infrastructure needs to be dimensioned accordingly as HDVs usually can maintain high charging power over long periods of time, which is distinct to the LDVs. There can be additional adaptation for different end-users, such as at Shell Amsterdam ETCA where the power electronics of an MCS charger provides power to either a truck or a ship.

The digital features are closely connected to manage the grid constraints in form of load balancing as well as providing the best performance from the stationary battery if such exists. References to Chapter 4.8-4.10.

The business model for the CPO could look different regarding power supply to the station. For example, companies might have different strategies to manage peak power, for more information see Chapter 4.8.

The analysis of existing sites and literature shows: It is of clear advantage that DSOs provide grid capacity maps which can help the CPOs in an early stage plan their network expansion and have a more efficient dialog with the DSOs.

Based on review of existing stations with BESS and/or PV, the compilation shows that BESS in general is dimensioned to support charging in a significant manner considering power installed. On the other hand, when PVs are installed within the premises of the charging station, they do not play a significant role to supply power during the time when the sun is shining. The exception is cases when there is in connection to the charging station a large additional area with PV installations.

4 BEST PRACTICES WITHIN SELECTED USE CASES FROM T2.2

This chapter covers the current best practices for the ten use cases selected in task 2.2, for more information see deliverable *D2.2 System-level requirements for the pilot sites*. These practices were identified through a mapping and data collection of existing sites (e.g., charging stations, truck stops, and gas stations) and literature. Moreover, the interviews conducted in T2.1 and the internal expertise within the project group have provided input.

4.1 Dynamic time booking

Use case 1: Dynamic time booking is a use case which is expected to grow in importance in the future, this is especially a need identified from the logistic companies that work on a tight time schedule and will not allow for delays. In Table 3, the use case and its sub-use cases are listed.

Table 3 Use case 1: Dynamic time booking and its sub-use cases from T2.2

Use case 1: Dynamic time booking	
Sub-use case 1.1	Estimated time of arrival is not correct
Sub-use case 1.2	Estimated SoC/Charging need is not the same as communicated (e.g. Detouring)
Sub-use case 1.3	Booked spot not accessible (Infrastructure failure, booked spot blocked)
Sub-use case 1.4	Booking can be cancelled

When analysing the current situation, many imply that booking systems are not needed today since there are almost always free slots available due to the currently low number of electric trucks. However, these systems are seen as an important tool for the future. Consequently, some companies have during the past year put effort into creating reservation systems to be ready for the major transition to truck electrification. Moreover, the extent of their dynamism in practice remains a question to be answered once they have been implemented in reality in large scale. Furthermore, reservation systems also exist for truck parking, a similar use case, but they lack certain components required for a charging hub, such as "energy needed" parameters. The EU standard for Safe and Secure Truck Parking Areas has actually a requirement for the finest level about booking: Secure pre-booking shall be available via phone, contact forms, email, apps or booking platforms. If pre-booking is offered via apps or similar booking systems, data transmission must occur in real time.

From the interviews in T2.1, it is known that logistics companies want a booking system that does more than just hold a time slot, it needs to guarantee that the truck actually fits, that the bay is not blocked by someone else, and that the charger delivers the full power promise. One company has tested switching to power-based booking, which has already been shown to boost usage significantly because it gives drivers the certainty, they need to plan their routes without worrying about delays.

Below is an analysis made of some of the existing reservation systems:

Panion (K2.mobility, 2025) is a software that helps organise fleets and have a function that helps to manage the charging of trucks at a depot (private charging). As the software also is used to plan and follow the routes of the trucks in the fleet, they can use that data to create a dynamic scheme for charging of the fleet. They use real-time data for this retrieved by API from the OEMs. The driver receives the information directly on which charger to use and when to leave the truck and when it is fully charged. Even if this is not a solution for dynamic time booking used at public charging stations, it is a best practice in how to manage dynamic time scheduling at a private charging station.

TRAVIS Road Services operates a platform for parking, cleaning, repairing, which has recently expanded to include booking of charging spots (TRAVIS Road Services, 2025). The Truckstop Shell Eindhoven Acht, located in the Netherlands was the first charging station that was open for pre-booking through the TRAVIS platform. Figure 20 illustrates the station, where barriers are used to prevent the spot from being blocked. The barriers use ANPR to authenticate the trucks. Fryte offers a matchmaking platform connecting fleets with charging infrastructure (Fryte, 2025). The platform was launched in 2025 and can be used to reserve spots if the charging location offers reservation.

Figure 20 Truckstop Eindhoven Acht, Netherlands was TRAVIS platform first bookable spot. Note that they use barriers to prevent the spot from being blocked. *Image from Shell (Shell, 2023).*

E.ON has launched a truck reservation platform for charging stations, which enables truck drivers and dispatchers to book charging slots in advance (E.ON Drive Infrastructure, 2025). Milence has also launched a booking tool for selected stations during 2025 (Milence, 2025). Volvo Trucks has also entered this space through its Volvo Open Charge service, which offers reservation capabilities (Volvo Trucks, 2025). Initially, they allow for booking at the charging stations they have built with OKQ8 and Skellefteå Kraft, but plans to expand to more sites.
Observations that can be made from the above is that the best practice for booking systems includes both booking spots directly of the charging provider as well as using third party platforms to reserve charging spots. However, using reservation system is not seen as current best practice today but it is seen as potential best practice in the future.

Suggestion for implementation of best practices across MACBETH pilot sites- The applicability of dynamic booking for the pilot sites is still unclear. As booking systems are currently not best practice and probably not even needed at the moment, the relevance of introducing a booking system on the pilot sites, and if it will be tested, will depend on how the number of electric trucks develops and the resulting need for it during the pilot testing years.

4.2 Transparent communication of chargers' status and efficient authentication

Transparent and reliable communication of chargers' status, static and dynamic, to avoid any kind of disturbances in the charging process will be essential when planning the charging as well as to act and make adjustments when unexpected events occur. In Table 4, the use case and its sub-use cases are listed.

Table 4: Use case 2: Transparent communication of chargers' status and its sub-use cases from T2.2

Use case 2: Transparent communication of chargers' status	
Sub-use case 2.1	Connection is down
Sub-use case 2.2	Charger is blocked
Sub-use case 2.3	Cost of charging

Furthermore, as part of AFIR (Alternative Fuels Infrastructure Regulation) article 20, all CPOs operating public and semi-public chargers in the EU are required to report both static and dynamic data about their charging infrastructure to their country's National Access Point (NAP). This requirement is valid since April 14th 2025 and must be considered as best practice already now and going forward.

Static data include:

- Location of the charging station
- Number of connectors
- Parking spaces for people with disabilities
- Contact details
- Opening hours
- Operator ID codes
- Connector types
- AC/DC current type
- Maximum power output of charging station
- Maximum power of the individual charging point
- Compatible vehicle types

Dynamic data includes:

- Operational status (e.g. in service/out of order)
- Real-time availability
- Ad hoc price
- Whether electricity is 100% renewable or not

There are two main ways to connect to your NAP, depending on the specific requirements of your country, either through an open API (Application Programming Interface) or through OCPI protocol if that is required. In Sweden OCPI is applied and in Belgium an API is used (see Figure 21 & 22).

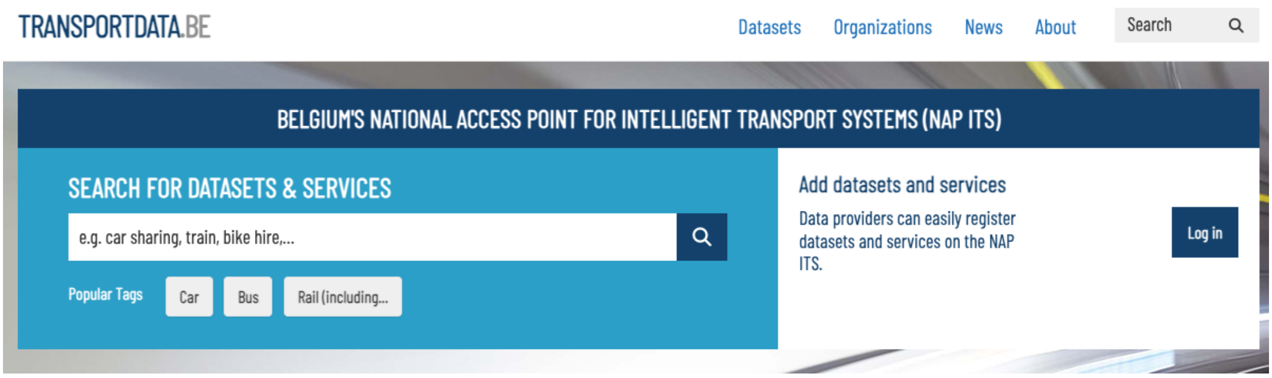

Figure 21 Belgium National Access Point (*Image from https://transportdata.be/en/)*

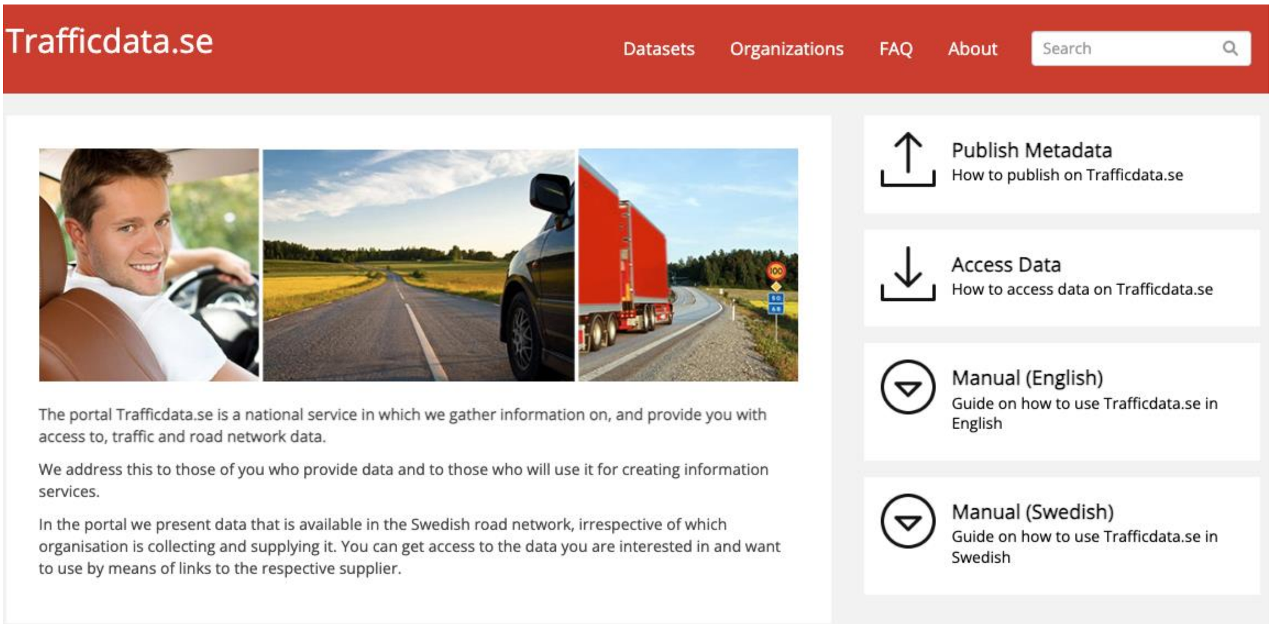

Figure 22 Swedish National Access Point (*Image from https://trafficdata.se/)*

Suggestion for implementation of best practices across MACBETH pilot sites- The best practice to share charging data in order to meet AFIR as well as make it easier to access the data in a conformed way is to go through the NAP:s. In Sweden, this means to share data with NOBIL as part of the Swedish NAP (trafficdata.se), and in Belgium to share the data through the Belgian NAP (transportdata.be).

4.3 Charge without decoupling trailers

Use case 3 is critical for the logistics industry, as it enables trucks to charge without decoupling the trailer, eliminating time-consuming delays to operational schedules. Table 5 displays the main scenario and sub-use cases for use case 3, and below is an analysis made of best practice for the main scenario and sub-use cases.

Table 5 Use case 3: Charge without decoupling trailers and its sub-use cases from T2.2

Use case 3: Charge without decoupling trailers	
Sub-use case 3.1	Charge tractor unit and e-trailer

Sub-use case 3.2	Charge HCT
Sub-use case 3.3	Charge truck carrying dangerous goods
Sub-use case 3.4	Charge tractor unit and refrigerated trailer
Sub-use case 3.5	Charge tractor unit in trailer swapping operation

Insights from T2.1 interviews indicate that many existing public CCS sites are difficult, or even impossible, to use with a tractor-trailer combination because bay geometry, bollards, or cable reach require trailer uncoupling. A clear message from the logistic companies interviewed is that decoupling trailers is perceived as a non-negotiable factor, as decoupling adds 10–15 minutes of work causing driver frustration, and introduces safety risks. Showcasing the importance of this use case.

What is then best practice in order to avoid decoupling of trailers? A clear best practice is to design the charging hub with drive-through and long enough bays for charging of trucks. Furthermore, angled fishbone bays design increases the length of the bay and makes it easier to drive in and out. Another best practice is using flow simulations during the design phase to verify that trucks of various lengths and turning radius can manoeuvre easily on-site. Figure 23 provides an example of a turning circle analysis of various truck configurations made at the Jula Logistics charging site in Falköping, Sweden.

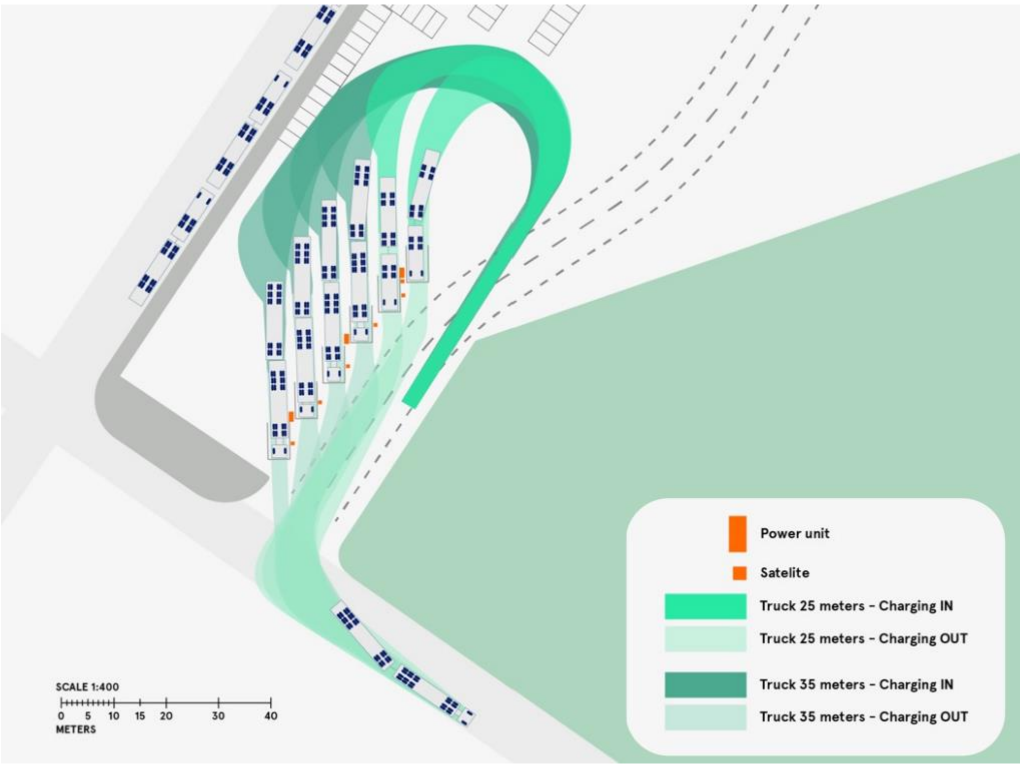

Figure 23 Analysis of turning circles of various truck configuration in design phase can be seen as best practice. This image is from Jula Logistics site in Falköping. *Image from REEL- Charging infrastructure for trucks (CLOSER, 2024).*

The allowed length for truck combinations varies across Europe, and consequently, the required length for charging bays and turning space varies as well. Therefore, best practices regarding truck length also differ. In Finland, progress in High-Capacity Transport (HCT) has moved quickly, making it a valuable case study when setting best practices for HCT-adapted charging stations. Sweden is also a country with HCT progress from which lessons can be learned. Best practices for HCT charging will continue to be investigated during following iterations, as the use of HCT continues to grow. However, it is already clear that the best practices for the main scenario still apply, provided that dimensions are scaled up to accommodate the additional length. In the Nordics, it will certainly be good practice to have long bays. In other countries and where space is limited, it may be rational to have different bay lengths if this may maximise the number of bays.

The current situation for e-trailers is that they are not yet authorised for general use as a common EU regulatory framework for these unique vehicles does not yet exist. Therefore, no current best practice can be identified. However, some tests with e-trailers have been performed and can provide examples of how charging solutions can offer e-trailer charging, for example, in the project REEL in Sweden (CLOSER, 2026). Figure 24 illustrates a dual-charging session where the e-trailer and tractor unit are charged simultaneously. Future iterations of this MACBETH report will continue to define best practices for e-trailer integration as regulatory and technical standards evolve.

Figure 24 Charging session with e-trailer at the Rifil station in Malmö. *Image from CLOSER.*

While ADR regulations now permit electric trucks, they provide no guidance for charging them while carrying hazardous loads. What have been found when looking into this deeper is that uncertainty exists and that for the time being no clear best practice exists regarding charging with dangerous goods as each operator handles it differently. There exist hubs that currently will not allow for charging of trucks carrying dangerous goods. However, looking into other recommendations on the market, the EU standard for Safe and Secure Truck Parking Areas has recommended an optional service namely: Separate dangerous goods parking (European Commission, n.d.).

Trailer swapping is, in some ways, the opposite of both charging with a trailer and long-haul driving. It has the potential to influence the design of charging hubs by removing the need for trailer-attached charging. Currently, trailer swapping is not used to a large extent; however, if it becomes more prevalent, the potential effects could include:

- Hubs must include 'trailer drop-off' zones with additional clearance for vehicle articulation during coupling and decoupling.
- Charging bays would likely not be used with trailers, allowing them to be shorter and designed only for the tractor unit.

Trailer swapping could enable drivers to return home each night rather than taking long-haul trips, as only the trailers travel long distances. Consequently, the need for public overnight charging would potentially decrease.

Suggestion for implementation of best practices across MACBETH pilot sites- The best practice regarding charging without uncoupling will be highly applicable to the pilot sites and are recommended to be implemented. The Swedish pilot site should also investigate the best practices for HCT as Sweden has made significant progress in that field.

4.4 Charging on a highly utilised site with maximised charging infrastructure capacity under spatial limitations

Use Case 4 offers compelling insights into future challenges, particularly the scarcity of available space and existing truck parking along busy highways. In the following section, real-world examples and best practices to achieve a space optimised site are presented, moreover many of the best practices identified for location A in Chapter 3.2.1 are also applicable to this use case.

One way to maximise the number of trucks that can be parked in a rest area has been done in the Kompaktparken or Kollonnenparken project (Die Autobahn, 2016). The basic idea is to park several trucks with the same departure time closely to each other in the longitudinal direction, see Figure 25. Three trucks can park in the same row instead of two, a substantial increase in space utilisation and parking capacity, if it works in the real world. The project was realised in 2016 but whether this solution has been scaled up is not clear.

Figure 25 Photo clip from video available at the (Die Autobahn, 2016).

Since the number of truck parking spaces along busy motorways is already too low, and some must now be converted into charging bays, a question arises: how can this transition be achieved without losing total parking capacity due to the space required for charging equipment?" One solution that has been used in a similar case in bus depot charging is overhead gate charging, for example the Walshaw Street bus Depot in

Oldham, see Figure 26, (Janus Architecture, 2024). However, here it will be a trade-off between the investment for the needed overhead gate infrastructure and the number of parking bays preserved. There is also a challenge related to the thickness of the cable, for high power charging the cable needs to be thick to minimise power loss and that will make it stiff and difficult to roll. Moreover, the cable cannot be too long either which makes this solution difficult, however, if high power is not needed in some of the charging slots, overhead gated charging can be a solution.

Figure 26 Overhead gate charging at the Walshaw Street bus Depot in Oldham, used as a solution to adapt to the current layout of the parking bays for buses. *Image from Janus Architecture*.

Another innovative solution for minimising charging infrastructure around the charging bay is made by Proviridis utilising a patented underground installation of a Kempower solution (Kempower, 2024). In Figure 27, the setup is visible from their multi-energy truck station in Saint-Quentin Fallavier, France. The configuration uses Kempower's Control unit solution which is connected to and receives power from a power unit that is placed above ground. In this specific solution, one handle can deliver up to 240 kW.

Figure 27 A space effective installation of chargers. This is made by Proviridis utilising a Kempower solution. *Image from Kempower.*

Suggestion for implementation of best practices across MACBETH pilot sites- The pilot sites will probably not be highly utilised in the way described in this use case and therefore will not need to maximise the charging infrastructure. However, it is still recommended for the pilot sites to take the best practices into consideration to see if they are relevant and then potentially adapt the layout design to this future scale-up already at this stage.

4.5 Safe LDV charging at an integrated and flexible multipoint truck charge point

Use case 5 is about how to provide safe and secure LDV charging at a charging point mainly built for HDVs. Potential benefits of this concept are to increase utilisation of equipment and space and to increase CPO revenues, making the business case more attractive. The idea is also to increase the number of available chargers for LDVs during times of low or no HDV charging demand. In the case of no HDV charging demand at all, and if the charging bays are not used for HDV parking, LDVs could utilise the chargers without any risk of passengers getting hurt or LDVs getting in the way of HDVs. However, allowing LDVs access at the same time as HDVs raises safety concerns. In Table 6 the use case and its sub-use cases are listed.

Table 6 Use case 5: Safe LDV charging at an integrated and flexible multipoint truck charge point and its sub-use cases from T2.2

Use case 5: Safe LDV charging at an integrated and flexible multipoint truck charge point	
Sub-use case 5.1	A passenger (maybe the driver or a family member, etc.) must go to the toilet, to the restaurant or other areas e.g. for recreation
Sub-use case 5.2	An LDV tries to enter and charge at times when no LDVs are allowed to charge
Sub-use case 5.3	An LDV charges at a charging station with partially integrated and flexible charging infrastructure but with separated LDV and HDV charge points

The number of charging stations for HDVs in Europe is increasing but most of the charging stations have only a small number of chargers installed. One example is the GOFAST station shown in Figure 28 below. The station has two bays with CCS chargers that could be used by HDVs or LDVs.

Figure 28 GOFAST charging station, Oftringen, Switzerland. *Image from (GOFAST, 2021).*

Another example is the Zunder station in Cetina, Spain, shown in Figure 29 below. The station can accommodate HDVs but is maybe more suited for caravans and similar vehicles.

Figure 29 Zunder charging station, Cetina, Spain. *Image from Zunder.*

Typically, the initial network of stations that has been built up til 2026, with just a few chargers at each site, provides CCS charging possibilities that complements depot or terminal charging on a regular basis or at specific occasions. To some extent, the network also makes longer, national or even pan-European, trips possible but more to demonstrate electric trucking than for real logistic flows as CCS charging is not powerful enough for long haul applications.

As described in T2.2, Swedish national funding schemes have supported a nation-wide build-up of some 250 public charging stations, designed and dedicated for truck charging, in line with AFIR. These charging stations are by default also open to LDVs. The stations are attractive to LDV users because they offer high power and are also available most of the time due to the current low number of electric trucks. As long as the HDV charging demand remains low, LDV charging is acceptable but as soon as the HDV demand grows, LDV charging will become a problem. Electrified logistics will be highly dependent on charger availability at the right time and LDVs can neither be prioritised nor allowed to delay the HDVs. This is reflected in Milence's policy not to allow any LDVs into their charging network. The Milence stations are also gated to have full control over which vehicles can access the stations, see Figure 30 below.

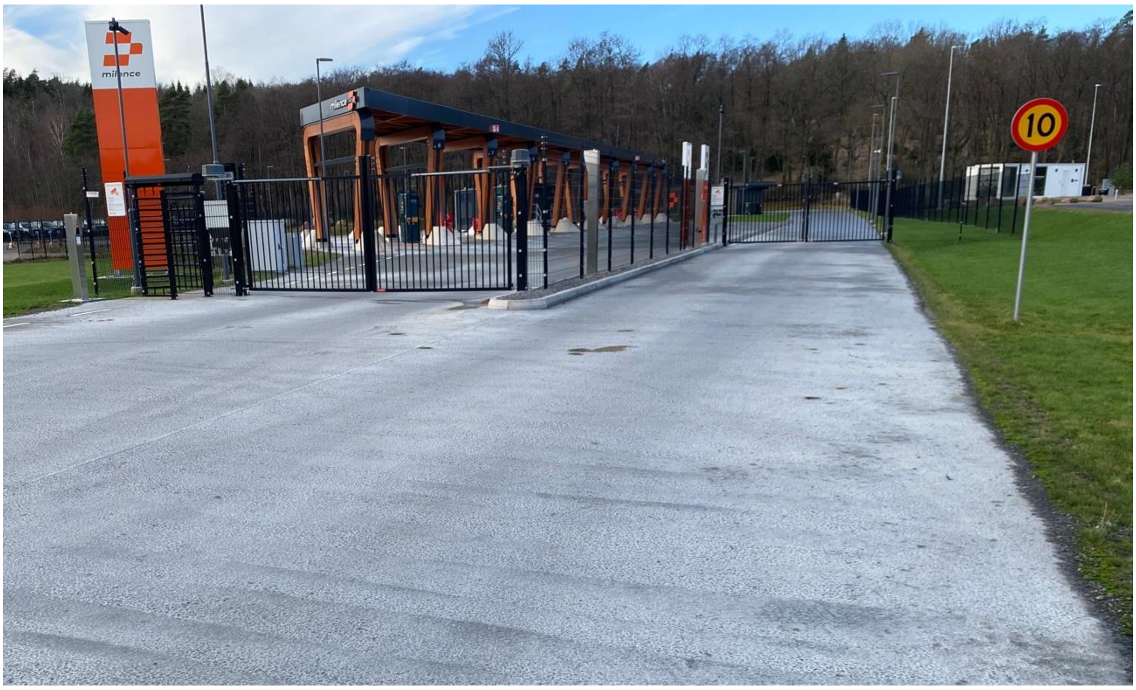

Figure 30 Milence charging station in Varberg Nord, Sweden. The station is gated and dedicated for HDVs. *Image from Lindholmen Science Park*.

Einride is a company within freight mobility also acting as CPO. Like Milence they build charging stations with multiple charging bays dedicated for HDVs. For the time being these stations are also open to LDVs, see one example from the Einride station in Varberg, Sweden in Figure 31. Whether the Einride stations will be open for LDVs in the coming years when more HDVs charge, remains to be seen.

Figure 31 Einride HDV charging station in Varberg Nord, Sweden. A passenger car is about to enter a charging bay. *Image from Lindholmen Science Park.*

Figure 32 shows the Rifil charging station in Malmö which was built with the main purpose to provide HDV charging for Falkenklev, a haulier operating mainly in the south of Sweden, and also the owner of Rifil. The station is in a commercial area close to the E6 motorway and serves both LDVs and HDVs. Some of the bays are used for overnight parking.

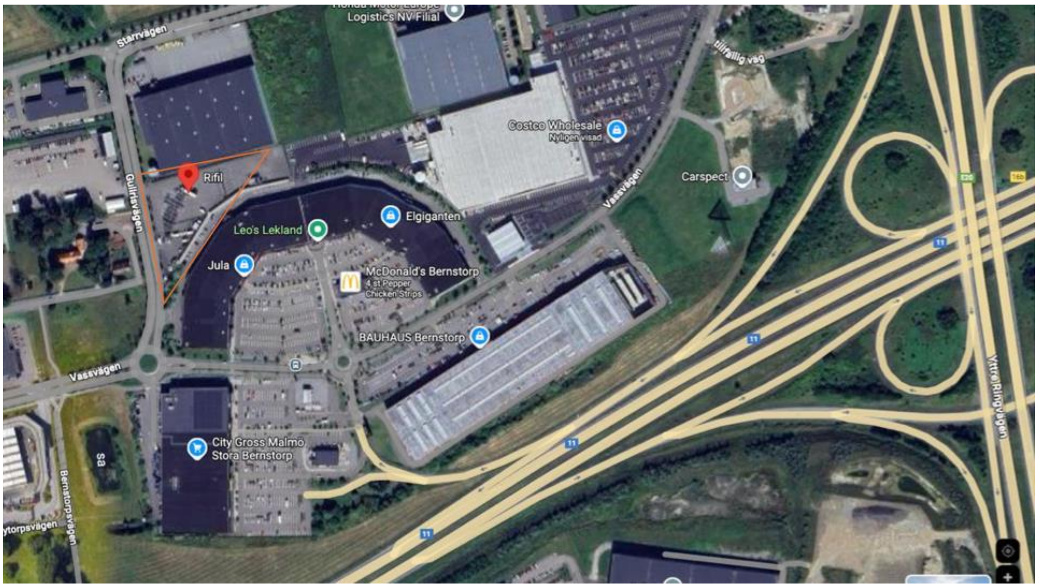

Figure 32 Rifil charging station (orange triangle) for LDVs and HDVs in a commercial area, Malmö, Sweden. *Image from Google Maps*.

The Rifil charging station allows for both LDVs and HDVs and have long charging bays to allow for long truck combinations, see Figure 33. Multiple LDVs can charge in one line to enable a high utilisation of the space. For safety and security, the charging station is well lit up as it operates 24/7. Safety measures that can be seen in many of the other analysed sites, like clearly marked pedestrian walks, is missing here.

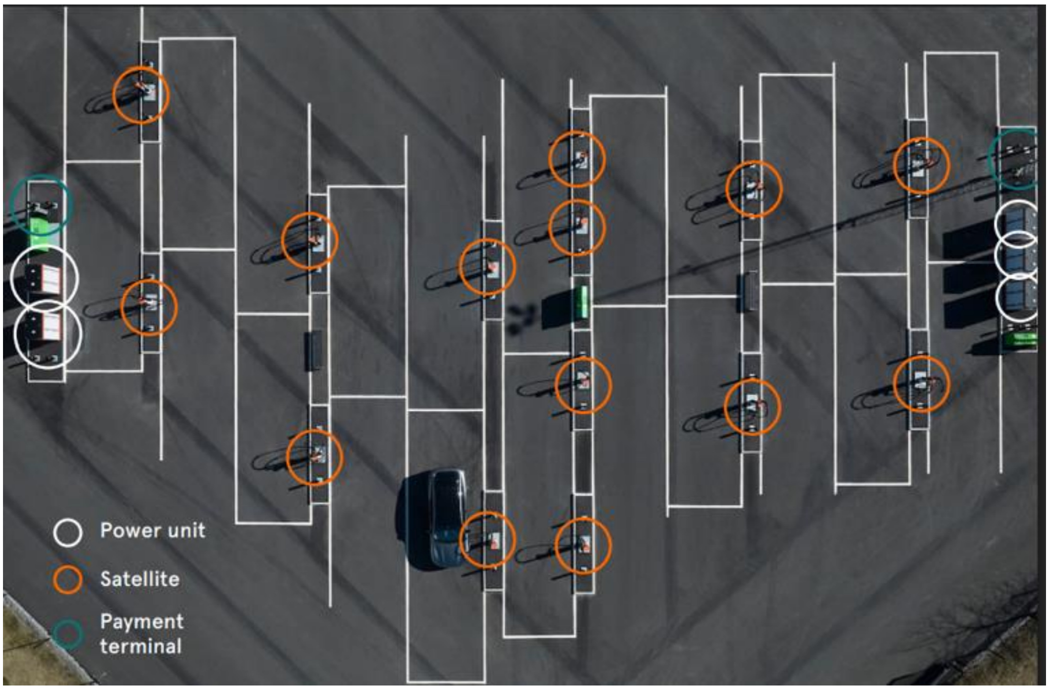

Figure 33 Rifil Malmö, Sweden has a layout for flexible multipoint charging, where one line can allow for either a 34.5 m HCT or two LDVs and HDVs. *Image from REEL- Charging infrastructure for trucks (CLOSER, 2024).*

Another example of a public charging station built for HDVs by the haulier itself but allow for LDVs is the Alfredsson Energy station in Norrköping, Sweden, see Figure 34 below. The station is equipped with an MCS charger and 11 CCS chargers. Anyone can charge and pay with credit card.

Figure 34 Alfredsson Energy, a MCS charging station in Norrköping, Sweden. a) To get a straight angle when entering the charging points even with a HCT (34,5 m), the trucks drive around the terminal house (outside the fenced area). *Image from Alfredsson Energy.* b) The charging point setup. *Image from Kempower.*

Figure 35 below shows the planned layout of an E.ON Drive Infrastructure, EDRI, charging station in Middelfart, Denmark, for both LDVs and HDVs. The vehicle types are clearly separated which reflects current common or best practice.

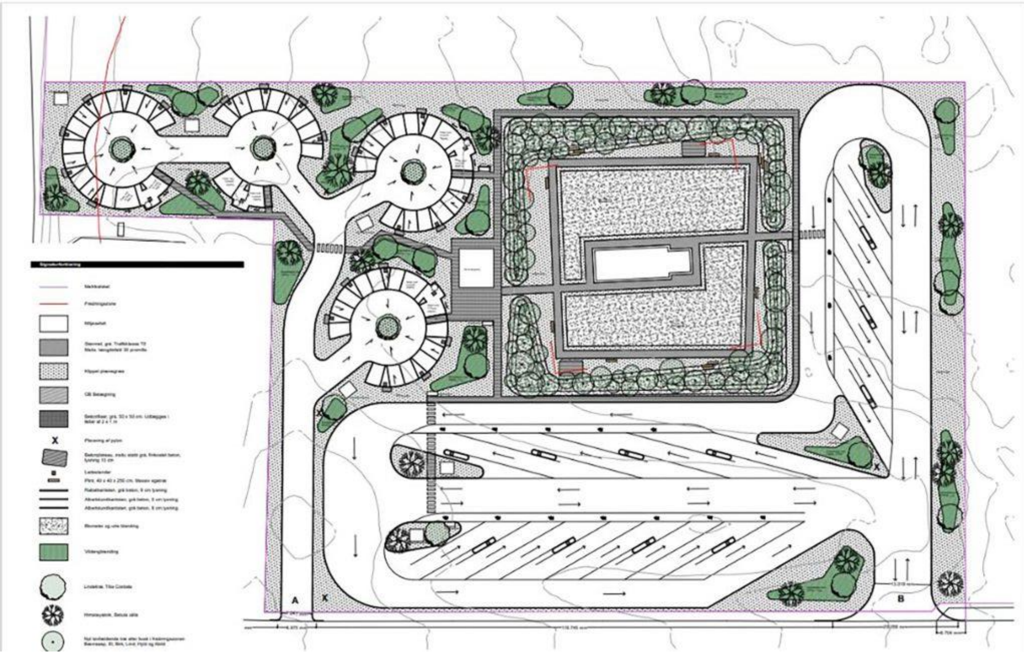

Figure 35 Planned layout of an E.ON Drive Infrastructure in Middelfart, Denmark. *Image from E.ON.*

Practically, all rest areas along or in close connection to the motorways analysed in this report have LDV and HDV parking areas separated from each other. This is both for safety reasons and for physical (geometric) reasons. It is simply more efficient to separate the vehicles. The LDVs need less space per vehicle and do not occupy parking bays dimensioned for HDVs. In addition, the driveways within the LDV area can be made narrower and more space efficient. Figure 36 below shows Steigerwald, a large rest area along the Autobahn in Germany with clearly separated areas for LDVs and HDVs respectively. The shadows in the photo in Google Maps indicate that it is probably taken just before noon. A majority of the HDVs parking bays are occupied compared to the LDV area where just a few LDVs are parked. Moreover, it is shown that the peak times/days of charging/driving vary for the different vehicle types (Enedis et al, 2024). In some European countries, driving bans for trucks on certain weekdays, holidays, or during summer months create potential for LDVs to utilise HDV charging infrastructure that would otherwise remain idle (see more in D2.2).

Figure 36 Rest area Steigerwald, Germany. *Image from Google Maps.*

Figure 37 below shows another example of a similar design, the rest area Oldtimer Pack in Preitenegg, Austria. LDVs and HDVs are clearly separated from each other except for the parking bays for buses which are co-located with the LDVs.

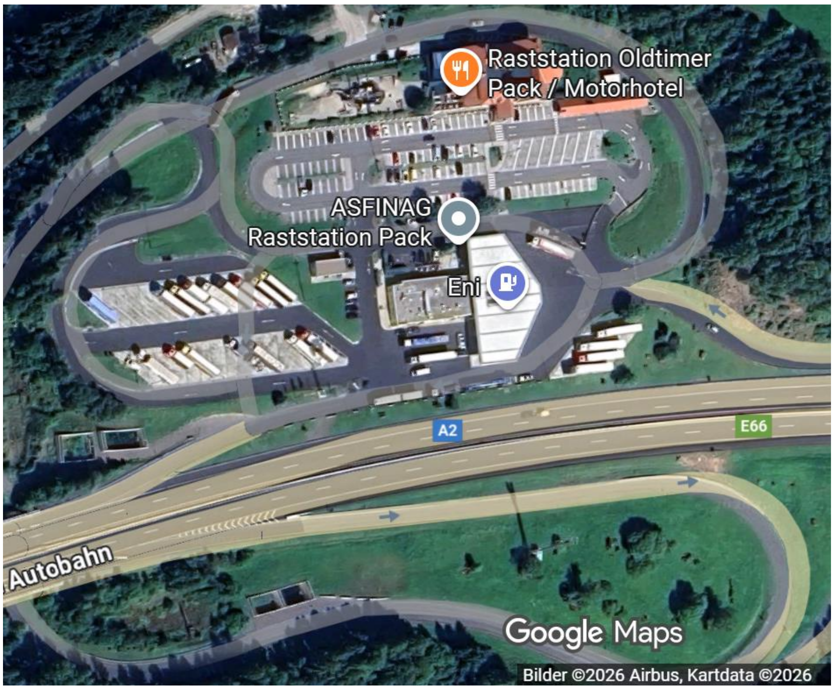

Figure 37 Rest area Oldtimer Pack in Preitenegg, Austria. *Image from Google Maps.*

Suggestion for implementation of best practices across MACBETH pilot sites

Preferably LDVs and HDVs should be kept separated for safety reasons. However, the increased utilisation and additional income that LDV charging could add may be valuable to Plugit, the CPO at the Swedish pilot site, and as well to the LDV drivers along the E6 motorway. There are no driving bans in Sweden and LDVs and HDVs will need to coexist at all times. The design should be made in a way that any LDV charging in the HDV area of the charging station should be positioned as close as possible to the amenities and preferably without having to cross a driveway for HDVs.

4.6 Automatic robot arm plug-in charging

Automatic robot arm plug-in charging is a use case which is expected to grow in importance in the future. It leverages mechanisms to ensure precise connections, and thus enhancing operational efficiency and in addition supports the industry's gradual shift towards automation. In Table 7, the use case and its sub-use case are listed.

Table 7 Use case 6: Automatic robot arm plug-in charging from T2.2

Use case 6: Automatic robot arm plug-in charging	
Sub-use case 6.1	Reservation of Automatic robot arm

Furthermore, the automatic robotic charging system addresses the heavy weight of the cables in an MCS charger which then can eliminate the need for human intervention during the process of coupling and decoupling the charger to and from the vehicle. Figure 38 shows a picture of the ROC-1 from Rocsys.

Figure 38 The automatic robot arm solution ROC-1, from Rocsys. *Image from Rocsys.*

There are several solutions for automated charging, among them are inductive and conductive underbody connections, pantograph charging systems, and battery swapping systems. All these systems require additional expensive parts in the vehicle.

Alternatives, like wireless charging solutions. also have the possibility to simplify the user experience but so far, the power available in these solutions are far from the MCS specifications. Technology providers are working on these issues, and it can be expected to see wireless charging stations capable of increased power transfer rates.

Suggestion for implementation of best practices across MACBETH pilot sites- The automatic robot arm solution from Rocsys is to be installed, tested and in operation at the Belgian site for a limited time. The trial period length is still to be decided. Not relevant for the Swedish site in the project.

4.7 Charging in challenging operational conditions

This use case details MCS charging operations within the challenging environmental conditions typical of Europe's diverse climate zones, ranging from harsh cold to intense heat and heavy precipitation. These climatic differences lead to different requirements depending on the location, for example, managing extreme cold in Northern Europe versus intense heat in Southern Europe. Consequently, CPOs must adapt their hub designs and operational plans to specific local conditions. Table 8 lists the main scenario and respective sub-use cases. The main scenario and the first two sub-use cases will concern challenges related to weather. Additionally, this use case covers challenging conditions like internet failure and vandalism. The primary goal is to ensure the charging station remains fully functional during challenging but operational conditions. For the logistics sector, the downtime due to this is unacceptable as it directly impacts tight business margins. The final sub-use case addresses extreme conditions, focusing on the implementation of safety protocols and the procedures for controlled shutdowns and subsequent system restarts, to minimise downtime.

Table 8 Use case 7: Snow and cold and its sub-use cases from T2.2

Use case 7 main scenario: Snow and cold	
Sub-use case 7.1	Extreme heat and sun
Sub-use case 7.2	Heavy Rainfall and Hail
Sub-use case 7.3	Failure - Internet
Sub-use case 7.4	Vandalism
Sub-use case 7.X	Extreme conditions

The design and operation of MCS hubs must ensure resilience towards the diverse and often harsh climate zones across Europe. Geographic location serves as an important design dimension. Hubs in Northern Europe, such as the Swedish pilot site, can engineer roofs and canopies that withstand heavy winter snow loads and prevent hazardous ice-shedding. A critical best practice for these regions is the implementation of heated charging platforms. By integrating heating element into the pavement, operators ensure that drivers do not struggle with snow and ice removal during the charging process, effectively managing snow clearance without disrupting tight logistic schedule. Efficient snow ploughing can be further enabled by site layouts on the designated snow dumping zones. Hubs in the Southern Europe should address sub-use case 7.1 (extreme heat and sun) to prevent the MCS cables from reaching critical limits and sub-use case 7.2 (heavy rainfall and hail), should include integration of robust drainage systems. Moisture can significantly affect flexible (asphalt) pavement performance. As such, it is important to remove moisture as quickly as possible from such pavements, especially to avoid allowing moisture into the pavement subgrade. Using an appropriate drainage system is one method to remove moisture from pavement structures. Use of densiphalt as a new type of pavement prevents drainage issues by providing a sealed, durable, and jointless surface that forces water to flow off immediately, rather than infiltrating, while resisting the mechanical damage typically caused by heavy rains.

Beyond weather, technical and social resilience are addressed through the sub-use cases 7.3 (Internet failure) and 7.4 (Vandalism). 'Visibility first' design strategy could be adopted against vandalism. This means utilising 24/7 CCTV survey, removing dense bushes to eliminate blind spots, and improving overall sight lighting. This aligns with the 'Premium' security features seen at On Turtle in La Jonquera ,Spain, which utilises fencing, monitored parking, and surveillance to protect high-value cargo and infrastructure. Similarly, Milence hubs emphasise on 'perceived safety' through clear guidance, lighting and video surveillance. These measures, combined with the fire safety emergency response protocols are defined in the CharIn Whitepaper 2025, this makes sure that the hub remains safe, attractive and protected.

Suggestion for implementation of best practices across MACBETH pilot sites - Climate adaptive infrastructure can be adopted for the pilot sites, e.g. the Swedish pilot site can integrate pavement heating in charging bays to maintain ice-free surfaces. Both the sites should utilize robust drainage systems to allow water to drain rapidly during heavy precipitation, preventing pooling around high-voltage equipment and ensuring safe access for vehicles and drivers. Ensure 100% CCTV coverage of both the pilot sites to eliminate blind spots and reduce vandalism. Connect both the site systems directly to emergency services to speed up the response during extreme weather or safety events.

4.8 Managing site power peaks

This use case of managing site power peaks is limited only to the site and how it handles power peaks from charging. The main actor is the CPO, who needs to strike a fine balance between offering attractive service to its customers and handle its grid connection wisely. The main use case contains a Battey Energy storage system (BESS) which the CPO uses to power peak shave towards the DSO and there is also a sub-use which treats load balancing of the chargers as a strategy for peak shaving.

The main use case to use a BESS for peak shaving is a common practice, especially when there is not sufficient available power in the local grid.

There are different strategies to manage load balancing. For example, Milence design system include that each CCS charging point should always be able to provide 400 kW and MCS charging point 800 kW. As a contrast, Circle K with combined passenger vehicle and truck charging station with both CCS and MCS outlets, when needed, handles their restricted grid connection by prioritising truck charging over passenger cars and charging with MCS over charging with CCS.

Several companies (e.g. Panion, Synop, BEV_R) offer data driven load balancing already today for charging at terminals. A core functionality of such service is to simultaneously account for each vehicles unique charging needs to handle planned routes and consider the grid limitations. Such functionality can be further extended by incorporating variable electricity prices, local electricity production, BESS etc. It is implemented through a master algorithm which decides when any plugged-in vehicle will start charging and at what power level the charging will be done. As the algorithm has access to each vehicles planned routes and many other parameters, it can allocate enough energy to the vehicle to ensure that it is sufficiently charged for its upcoming task while keeping the peak power level at a minimum. A relevant case study is the Norwegian food distribution company ASKO's use of the Panion system (K2 Mobility n.d.). Public charging differs from terminal charging by having much more constrained time limits and expectations on high charging powers. However, there is a space to explore if increased data flow between truck and charging stations operators, similar to the case of terminal charging, could offset undesirable load balancing. Such a future functionality for public charging stations is closely coupled with use case 1 of dynamic booking systems.

Suggestion for implementation of best practices across MACBETH pilot sites- BESS is a viable alternative to manage peak shaving instead of obtaining grid capacity which matches charging equipment's maximum capacity.

Load balancing as part of everyday operation is also an option and depends on what kind of product the CPO wants to offer.

4.9 Innovative integration of MCS charging with the grid

The Use case 9, Innovative integration of MCS charging with the grid, takes a broader approach of the transport system and CPO integration with the electricity system, involving more actors and elements compared to UC8. The UC9 suggests how mass deployment of MCS trucks on the road, large MCS charging stations and a high share of intermittent power generation (solar, wind etc) can work effectively together. Even though the use case may become most relevant in a future mass deployment scenario, the proposed solutions may be used and provide value already today. Table 9 lists the main use case and sub-use cases identified for Innovative integration of MCS charging with the grid. Below the identified best practices in the industry related to the use case and sub-use cases are described.

Table 9 Use case 9: Variable charging price and its sub-use cases from T2.2

Use case 9: Variable charging price	
Sub-use case 9.1	Energy community
Sub-use case 9.2	Increased power from nearby renewable energy
Sub-use case 9.3	Self-produced renewable energy
Sub-use case 9.4	BESS for grid support

For the main use case with variable charging prices, there are examples where CPO's charge price is hourly updated e.g. Einride in Sweden. However, it is not a very common pricing strategy by CPOs in Europe.

For best practice related to use case 9.1, there are examples where the charging station is an integral part of a more complex local energy system creating synergies between the different parties. The possibility to participate in an energy community is however very site specific, depending on what adjacent electricity consumers and producers there are and their interest in cooperation. In addition, the possibilities and feasibility for local energy communities are shaped by the national legislation. Below two interesting cases are described.

The WattHub Geldermalsen for example uses wind energy as its primary energy source to power the charging operations. Therefore, the location has a contract with the Betuwewind citizen wind cooperative (officially Burgerwindcoöperatie West-Betuwe a Dutch community-owned energy organisation). A nearby wind park with three wind turbines with a total of ~10 MW provides the energy needed for charging. While the charging station itself does not "own" the turbines, it sits "behind the meter" with them, meaning it uses their power directly before it hits the public grid.

In addition to the described energy elements the Shell Amsterdam ETCA location integrated a hydrogen electrolyser with an approx. capacity of 1 MW as a component of its on-site microgrid. It is physically, including the grid connection, integrated into the same private network that operates the MCS truck/ship loader and uses excess electricity from the campus's 3,600 solar panels (and the power grid) to split water into green hydrogen. The hydrogen produced is not just for research; it is transferred to a hydrogen dispenser located in the campus car park, allowing for the refuelling of hydrogen fuel cell vehicles. Furthermore, waste heat from the electrolysis process can be captured and used to help heat the campus buildings, further increasing the site's overall efficiency.

The summary made of PV installations at charging stations in Chapter 3.2.4 shows that a very limited PV power production capacity is possible to install within the premises of the charging sites relative to the stations charging power capacity. In addition, the only identified site with wind power close by was WattHub Geldermalsen. It concludes that sub-use case 9.3 "Self-produced renewable energy" is closely related to sub-use 9.1 "Energy community" as the identified examples with significant local renewable energy production is dependent of cooperation with nearby located sites.

The sub-use case 9.2 is based on dynamic grid contract between the DSO and CPO to more easily absorb locally produced electricity without putting additional demand on national and regional grids. It is in sharp contrast to current well establish praxis to have a static grid contract with a fixed maximum allowed power withdrawal. An interesting case study is Netherlands whose power grid is highly congested. Their national TSO, TenneT, has started to apply a time of use power contract, where the power withdrawal is restricted during peak hours. The peak hours are predetermined, with advantage to be foreseeable and simpler to handle. However, it does not allow to fully follow the actual grid constrains or synchronise with the renewable energy fed into the regional grid.

The last sub-use case to support grid with a battery is a natural extension of battery used for peak shaving as part of use case 8 "Managing site power peaks". The upside of a battery is its flexibility to provide several different services and provide various savings or revenue streams, usually described as value stacking. It is a common praxis to do value stacking with batteries and should to the largest possible extent also be applied by batteries installed at the charging station.

Suggestion for implementation of best practices across MACBETH pilot sites- There is no well-established practice of using variable charging prices and it is a complex topic. The CPO should explore possible solutions where the grid, CPO and its customers could benefit from variable charging prices based on variations in electricity prices and grid fees. It would be an important step to integrate closer the charging stations with the grid.

Energy community can enable truly local power production, reduction in grid fees and/or access to power, but it is still an immature concept and is highly site specific. The CPO should explore possibilities for cooperation and possibly creation of energy community with the neighbours of its charging stations.

The project should consider installing BESS at the pilot sites to enable participation in grid-supporting services and to optimize operations in response to fluctuating power prices.

4.10 Provide verified emission reductions

The use case 10, Provide verified emission reduction, describes the necessary system functionality to automatically collect, measure, and securely report emissions related to charging events. Such a system enables the CPO to provide additional value for its customers, differentiation of their products as well as additional revenue streams. The identified use case and sub-use cases are summarised in Table 10.

Table 10 Use case 10 Provide verified emission reductions and its sub-use cases from T2.2

Use case 10: Provide verified emission reductions	
Sub-use case 10.1	Sell renewable energy credits within REDIII
Sub-use case 10.2	Spatio-temporal requirements for grid emissions
Sub-use case 10.3	On site Renewable Energy

The main use case is present to some level in the market today as most CPO can offer charging with electricity with known emission intensity, usually renewable electricity according to EU's taxonomy. There are consultancy companies and fleet management companies to provide services of gather and compile emission data from transport activities. The authors could not find any CPO offering such a service and in this iteration of the report no best practices were gathered on how an efficient, standardised and CSRD compliant data gathering and sharing could look like. The lack of identified best practices also applies to account for spatio-temporal production and consumption of low emission electricity (sub-use case 10.2) and verification mechanisms for on-site production (sub-use case 10.3). This remains as future work in the upcoming iteration of this deliverable.

The EU directive to enable sub-use case 10.1 is already in place, however the implementation of these directives into national law varies between the different EU countries. Countries such as Germany, Netherlands, Sweden and France has such mechanisms already in place (Liepold et al. 2024, Nederlandse Emissieautoriteit n.d., Energimyndigheten 2024, Lhyfe Heroes 2024), while many other EU countries do not have the necessary marketplace to sell renewable energy credits to fossil fuel suppliers. For the countries which has system to sell renewable energy credits also has clear national rules how such credits are verified and sold to the fossil fuel suppliers. Between the countries there is some discrepancies how such system is implemented.

Suggestion for implementation of best practices across MACBETH pilot sites- The CPO should follow the national requirements to account for and verify dispensed electricity according to the national law implementation of REDIII. Thereby enable revenue stream by selling the renewable energy dispensed to the companies who sell fossil fuels to the transport sector.

5 DISCUSSION

It is a real challenge to describe or define best practice on how to design, build and operate MCS hubs since they in practice do not exist yet. The MCS technology is still under development and all MCS related standards have not yet been published. Best practice must so far be based on today's system and by early experiences from existing CCS charging infrastructure. It may even be difficult to define best practice for CCS hubs, especially dedicated to HDVs since the number of trucks is still limited and most of them rely on depot charging for their energy supply. Instead, this deliverable involved an extensive analysis of existing CCS hubs, rest stations, truck stops and even premium truck stops. By analysing these sites, Task 5.1 has tried to identify best practices in hub layout, driver amenities, grid integration and more that may be transferable to MCS context. Hopefully, some of these findings may serve as inspiration for the development of the pilot sites in MACBETH.

Best practice is also not a static concept. It depends on geographic location and site conditions including local climate and evolves with changes in user requirements, functional needs, technological development and regulations, and environmental factors. Determining who the primary user is, whether a site serves only HDVs or a mix of LDVs and HDVs, is the first important step. For LDVs, en-route charging is a convenience with a great deal of flexibility in when and where to charge. For the truck driver, the rest time, during which the vehicle should be charged, is a legally mandated operational window which determines different functional needs. This is reflected in the physical layout of the site. In space-constrained locations along motorways, the challenge is to introduce charging infrastructure without reducing the total number of available parking spots, a critical concern given the existing shortage of truck parking in Europe. Solutions such as angled fishbone designs and drive-through bays are no longer optional but essential.

Beyond industry standards, many best practices are mandated by regulation; for example, AFIR requires transparent communication regarding charging, effectively formalising these requirements into operational norms. Furthermore, the "Charge without decoupling" use case highlights a major design challenge, ensuring that the driver can enter, charge, and exit without reversing or detaching cargo. For future MCS hubs, layouts must align with emerging regulatory developments in HDV dimensions. Best practice dictates a "forward-flow" design that can accommodate different truck combinations and changes in this, such as the 34.5m HCT trucks used in the Nordics. The local climate is also an important factor highlighted in use case 7. As the frequency of extreme weather events increases, new best practices will emerge to ensure infrastructure robustness. This includes robust hardware protection, site drainage, and sheltered charging areas to maintain operational uptime in harsh conditions. Furthermore, the specific criteria for obtaining funding incentives heavily influence how stations are designed and operated, further cementing these regulatory standards as industry best practices.

The hub design layout and the best practice is also affected by the charging patterns. It is plausible that battery technology will continue to improve, leading to larger capacities in the future. Simultaneously, maximum charging power is set to increase significantly, reaching well above 1 MW. These advancements will offer drivers greater flexibility regarding where and when to stop and charge. While drivers must still adhere to mandatory rest regulations, they often have some operational flexibility; for example, opting for a 15+30-minute break split rather than a single 45-minute stop. Then some drivers might stop by for a 15 min break and ultra high-power charging to benefit from a low price per kWh or to avoid a longer stay a bit ahead where they know they pay more, where they may have to queue to charge or encounter other difficulties.

Complementing the physical "forward-flow" of the vehicle is the "time-flow" of the driver. If the vehicle subsystem defines how the vehicle can move within the hub, the human related subsystem must fulfil the needs of the drivers during the rest period. By successfully providing the core regulatory amenities (SSTPA-compliant hygiene and nutrition) in the vicinity of the charging bay, the hub directly supports the driver's well-being within the mandatory break window.

While HDV and LDV charging share the same land and grid connection, they should be managed as two distinct operations on the same site. This ensures that a proper recovery environment for HDV drivers (secure parking, quiet zones) is not compromised by LDV users. A hub that is perceived as safe, accessible and resilient to extreme conditions transforms the charging hub from a simple utility into a strategic best hub practice and a preferred destination.

Central to the call and important for the MACBETH project is to find a way to maximise the utilisation of charging infrastructure by designing integrated and flexible charging stations for both LDVs and HDVs. From a traffic safety point of view, mixing the vehicle types is associated with increased risk of accidents. Most rest areas are designed with separated areas for LDVs and HDVs to minimise the risk of people getting hurt. The main cause of accidents is driver fatigue, especially while entering the rest area or truck stop. Another cause is too high speed. Reversing and blind spots are also mentioned as common causes of accidents. In general, and also applicable in areas dedicated to HDVs, it is recommended to go slow, that the parking is well lit and that pedestrian crossings are well marked.

In this report, a few charging stations have been described where both HDVs and LDVs are allowed to charge, and at the same time. The risk of accidents may be lower in a setting where all involved are well aware of that they are in a *shared space*. HDV drivers are aware that LDV drivers and passengers roam in the area and the latter category are aware of the HDVs and the risks associated, specifically with blind spots. Some stations will remain open to both LDVs and HDVs also in the future. But in the long run most stations primarily built for HDVs will probably prioritise HDVs during certain or all hours for logistics customer service and equally or more important for maximising revenues by the number of kWh sold. It remains to be seen how these stations can be built and designed to clearly prioritise HDVs and exclude LDVs during certain hours, to be perceived as a shared space at some times, and finally as a no go zone for HDVs during driving bans. The additional revenues from LDVs will have to be substantial enough to motivate investments in charging adequate charging infrastructure, safety measures, potential design compromises and more.

Regarding the energy supply subsystem, an analysis of public data reveals a significant disparity between visible infrastructure and the more technical aspects of the charging stations. While features such as the number of charging points, maximum charging capacities, and even complementary data for installed photovoltaics (PV) or batteries are frequently communicated and easily accessible, essential 'behind-the-meter' information remains scarce. Critical details, such as grid connection sizes, voltage levels, transformer specifications, switchgear configurations, and bespoke contracts with DSOs are rarely public. Given that these technical aspects are fundamental to the design of future charging hubs, further investigation is required, preferably as part of the ongoing work within MACBETH Work Package 5.

The well-known challenge of DSOs long lead times to provide grid access or an increase in grid connection is closely intertwined with the charging station's design of the local grid (behind the meter). If the slow processes to get a grid access remain, the CPOs run the risk of lagging in building out the charging stations and thereby hinder electrification and especially MCS technology with its high-power requirements. As a measure to mitigate the lack of power grid access, BESS is already today a common solution for peak shaving. If the development of battery technology in terms of performance and cost continues to advance, the role of BESS as an integral part of the charging station will likely grow.

From the analysed stations, a couple of them drew benefits from other nearby assets through shared microgrid, based on the principles of energy communities. Within this report only their mere existence was noted. However, based on interest from Brussels to scale this concept and with chronically long lead times for grid connection, the concept of energy communities creates curiosity. There is a knowledge gap to understand the benefits of energy communities and if they can help to integrate MCS stations into the grid and facilitate the scale up of MCS public charging.

The shift toward integrated supporting systems represents a fundamental transition from passive infrastructure to active operational management. By adopting tools like AI-enhanced surveillance and ANPR, hub operators do more than provide security; they gain the ability to optimise "forward-flow" logistics in real-time, preventing the bottlenecks that often occurs at high-traffic truck stops. Furthermore, the move toward ISO 15118 (Plug & Charge) and automated data reporting via NAPs effectively ensure operational consistency for fleet operators. By removing the friction of manual authentication and providing reliable, real-time availability data, modern stations align with the strict time-margins of the logistics industry. This digital transparency, mandated by AFIR, essentially transforms the charging hub into a reliable node within a global supply chain, where the predictability of the "digital twin" (the data in the app) is just as critical as the physical durability of the concrete charging bay.

The availability and integration of data also impact at which level it can connect the logistic systems' requirements of charging with the charging station's local energy system and even sync with the larger electricity grid. In a sector integrated and data driven future the eMSP could inform the logistic system well in advance which charging station has access to cheap surplus energy and according to this data the routing and charging plan is laid out for the trucks. The planned energy need and time slot is then communicated to the energy management system for the relevant charging stations which accordingly plan the optimal usage of its infrastructure including its stationary battery. Such a data communication across several systems and actors gives a much wider and more advance manners to optimise the transports and charging stations but depends heavily on a well-oiled data exchange structure. The alternative future with barriers and unwillingness of data exchange could keep us in the status quo where the CPO acts as a buffer between the transport- and logistic system. The lack of coordination would maintain a higher level of predictability and maybe robustness, but probably at a higher charging price.

The definition of the best practice for HDV charging is expected to evolve as the technology matures from early adoption of MCS to mass deployment. The current focus (0-5 years) is on interoperability and basic functionality. Best practice currently involves hybrid hubs to support the existing infrastructure and fleets while testing the MCS technology. In future (5-10 years), the focus will shift towards automation and higher efficiency. E.g. Robotic charging arm might eliminate physical strain on drivers and improve overall efficiency. Further trends like urbanisation, goods flows, number of electric trucks, autonomous vehicles and need for secure parking will influence the best practice for MCS hubs forward.

The development of best practices for MCS hubs for EV truck mass deployment will continue. The findings and future progress will be documented in two subsequent iterations of this deliverable.

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7 ANNEX

The annex includes a list of the sites examined as part of the analysis, categorised according to the four subsystems.

7.1 Analysed sites for the vehicle related subsystem

1. Parking JABBEKE Rückweg, Belgum, https://maps.app.goo.gl/FDzVmX1oRsuaLzJEA
2. Raststation Europabrücke, Austria, https://maps.app.goo.gl/dNEhC1ZienKc3jmDA
3. Área de Servicio Itziar La Pausa - Sentido Bilbao, Spain, https://maps.app.goo.gl/34QFnC4Wv1b2De8N6
4. Infoteria Lillebælt Syd - mod Odense, Denmark, https://maps.app.goo.gl/GzYEwFXvvs7gKw9HA
5. Serways Raststätte Neckarburg West, Germany, https://maps.app.goo.gl/W7jojGtPEsKVcQAE7
6. Raststätte Höhenrain W, Germany, https://maps.app.goo.gl/eM2ZJ14oPfNkfwRcA
7. Autogrill Villoresi Est, Italy, https://maps.app.goo.gl/9BgzWrgCaDFDowdm6
8. Serways Raststätte Sindelfinger Wald Süd, Germany, https://maps.app.goo.gl/UnKhFnG9Sby2Z6hF9
9. Eat'n Drive Hylkedal Vest ApS (Sydgående spor), Denmark, https://maps.app.goo.gl/2yF4qLgiGuQLGPnJ6
10. Raststätte Lüneburger Heide, for CAMPINGVOGN, Germany, https://maps.app.goo.gl/imREGZjQDv9if7mv7
11. Serways Raststätte Lichtendorf Süd, Germany, https://maps.app.goo.gl/p9aamcHz13yTf73M7
12. Serways Raststätte Oberlausitz Süd, Germany https://maps.app.goo.gl/412rGFeTTT6cFfTT8
13. Rastplatz Heuchelheim, Germany, https://maps.app.goo.gl/iGyAU7bdL8YU4rYh9
14. Parkplatz Obersambacher Wald, Germany, https://maps.app.goo.gl/3tdr21NuFJmACxQZ9
15. Aire de la Baie de Somme, France, https://maps.app.goo.gl/Gf2FGrLspYTYX98U7
16. BREAK Autohof Hamburg-Nordheide, Germany, https://maps.app.goo.gl/rVsiw4RNhAmxucxv8
17. Aral Autohof Porta Westfalica, Germany, https://maps.app.goo.gl/s65zsDP2UUQoiR6n8
18. Circle K Vädermotet, Sweden, https://maps.app.goo.gl/1wh7cxLrcWD8fkKN8
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