

2025 Voluntary Standards for Battery-Electric Straddle Carriers and Terminal Tractors

ZEPA Zero
Emission
Port Alliance

DECEMBER 2025



2025 Voluntary Standards for Battery-Electric Straddle Carriers and Terminal Tractors

The Zero Emissions Port Alliance (ZEPA) was formed expressly to accelerate port decarbonisation. Decarbonised ports are our vision. Container terminals are our focus, because the electrification of container handling equipment (CHE) is a particularly powerful lever for decarbonising ports. ZEPA aims to accelerate take-up of battery-electric container handling equipment (BE-CHE) among terminal operators by making BE-CHE affordable and accessible by 2030.

This document provides a set of voluntary standards for battery-electric (BE) straddle carriers and terminal tractors. Standardisation is a critical lever of ZEPA's mission to accelerate port decarbonisation, as it addresses key barriers to adoption, such as interoperability, cost efficiency and scalability. The ZEPA 2025 Voluntary Standards represent a foundational step toward aligning industry practices with the vision of decarbonised ports. Developed through co-creation and analysis with ZEPA members and leading experts, these standards also incorporate industry-first insights, supporting all stakeholders in port communities and providing them with a framework to drive meaningful progress.

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About the ZEPA 2025 Voluntary Standards

The ZEPA 2025 Voluntary Standards define key operational and technical dimensions for BE straddle carriers and terminal tractors. The standards were jointly developed by ZEPA members, all of whom are OEMs, terminal operators or port authorities.

Switching from diesel-fuelled to BE-CHE offers significant benefits to container terminal operators. Firstly, it lowers their emissions of greenhouse gases and other air pollutants. Secondly, it reduces noise, which is a valuable advantage in terminals near residential areas. Both these factors make BE-CHE safer, healthier and more comfortable for employees to operate.

Despite these benefits, adoption of certain BE-CHE types remains limited, although initial steps have been taken. One barrier is its affordability: the total cost ownership (TCO) of BE-CHE is still higher than the TCO of its diesel equivalent in most geographies, thanks largely to a combination of higher initial costs for, charging infrastructure costs, additional downtime for charging, and the possible need to replace batteries before BE-CHE reaches its end-of-life.

A second hurdle is accessibility. Consensus among original equipment manufacturers (OEMs) and terminal operators on voluntary technical standards for BE-CHE remains limited. And, until recently, there have been few clear signals to indicate which technologies are preferred by the market. Although improving in the last few years, these issues hold OEMs back from scaling production of BE-CHE, which would, in turn, help to lower its TCO.

History shows that without some convergence on voluntary standards and a shared expectation of the market's general direction, adoption of new technology (in our case BE-CHE) will remain slow: OEMs will have to update their supply chain, production, and assembly, and find scale within to optimise for cost; and individual container terminals will – at first - be able to access only project or custom-made equipment (and components), and thus higher-cost equipment.

By reducing variations on the minimum aspects of batteries and charging equipment and methods (without limiting OEMs' ability to innovate and differentiate on features, performance, design or otherwise), these Voluntary Standards aim to unlock economies of scale in the supply chain and increase the interoperability of vehicles with batteries and charging equipment. Widespread application of the ZEPA 2025 Voluntary Standards shall help to scale benefits and efficiencies in the manufacture as well as the operation of BE-CHE fleets. These developments should, in turn, further reduce the TCO, accelerating the growth of BE-CHE fleets across the port industry and catapulting progress towards decarbonised ports.

Developing the ZEPA Voluntary Standards

Initial standards were jointly developed by ZEPA members, all of whom are OEMs, terminal operators or port authorities. Input and feedback on the standards was provided by several experts beyond ZEPA, including IAV, a leading automotive engineering company active in vehicle development and technology innovation. Systemiq held the secretariat of ZEPA and provided analytical and organizational support throughout this collaborative process of co-development.

Work to develop the ZEPA 2025 Voluntary Standards has focused on standards for terminal tractors and straddle carriers, the priorities defined upfront by ZEPA members. Three main

Affordability remains a barrier to BE-CHE uptake, although adoption momentum has recently increased.

By reducing variations on the minimum aspects of batteries and charging equipment and methods, these Voluntary Standards aim to unlock economies of scale in the supply chain and increase the interoperability of vehicles with batteries and charging equipment.

areas of these two types of equipment have been evaluated to identify opportunities for harmonisation and standardization: charging strategy and method, charger, equipment and software architecture, and battery specifications.

At the outset, four main charging strategies were distinguished, each tailored to different operational approaches that terminal operators can adopt. In practice, at the level of individual terminals one charging strategy is expected to dominate, while globally a mix of approaches may emerge due to differences in specific terminal configurations and operations. The four main charging strategies have been evaluated against multiple criteria, including their TCO, their load profile, adaptability to different terminal and shift configurations, terminal footprint of chargers and the availability of minimum standards and technology.

Formulation of the standards has followed a rigorous process. The data inputs needed to develop potential standards have been crowdsourced from ZEPA members, as well as from several experts in the field, (including research by IAV). Potential Voluntary Standards have been developed, tested and refined through bilateral and multilateral sessions with ZEPA members, crowdsourced comments, expert interviews and comparison with research efforts in similar sectors.

The ZEPA 2025 Voluntary Standards incorporate proven technologies that are currently in use or expected to be in use in the near future. They build on existing standards and experience from adjacent high-volume markets, without limiting further innovation in CHE technology and deployment. ZEPA's goal has been to create a voluntary framework that harmonises certain key operational and technical dimensions of BE-CHE today and can adapt to the key technological advances of tomorrow.

Developing the 2025 update

The ZEPA 2025 Voluntary Standards are an update to the 2024 Voluntary Standards, ensuring the standards reflect the rapid pace of technology advancement in electric BE straddle carriers and terminal tractors. Developed through collaboration between ZEPA members, non-members and industry organizations, the standards are the result of an industry-wide effort.

In 2025, ZEPA members placed particular emphasis on further improving the Voluntary Standards for straddle carriers, driven by updated insights and industry developments. This choice was made as at the beginning of 2025, standardisation was still very limited for electric straddle carriers, preventing interoperability of chargers, batteries and vehicles, and delaying deployment of electric straddle carriers at the commercial scale.

Key changes in the 2025 Voluntary Standards update include significant revisions to standards SC.1 through SC.12, the addition of new interoperability standards (e.g., OCPP), updated charging infrastructure requirements and enhanced battery safety standards. The TCO model for straddle carriers has also been refined using updated, and additional expert-backed assumptions.

For terminal tractors, changes are more limited. Most updates stem from improvements originally developed for straddle carriers, which were then applied to terminal tractors where relevant. Overall, the 2025 update reflects strengthened evaluation criteria for charging strategies, an improved TCO model, new technology watchpoints, and updated Voluntary Standards. With these changes, no further major revision is expected in the near term.

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Using the ZEPA 2025 Voluntary Standards

The ZEPA 2025 Voluntary Standards are:

- **open standards**¹, meaning they are open to anyone to use and share, free of charge, under an open source license;
- **voluntary standards**, meaning that whilst ZEPA hopes they shall be widely adopted by the industry due to the benefits they intend to deliver, they are not mandatory; and
- **minimum standards**, meaning that they provide baseline expectations but industry members remain free to innovate and develop further.

The ZEPA 2025 Voluntary Standards are specifically developed for BE-CHE procedures. They can help with the choice of charging strategy for terminal operators and point to the appropriate charging infrastructure. They also inform minimum technical specifications for several types of CHE, batteries and chargers during the development of procurement documents.

ZEPA encourages port industry members — terminal operators, OEMs, port authorities and grid operators — to refer to the ZEPA 2025 Voluntary Standards in any discussions concerning the electrification of CHE fleets and of port operations in general.

ZEPA also urges port industry members and global standards organizations to collaborate on ensuring future standards are aligned and consistent with the ZEPA 2025 Voluntary Standards. This will avoid the emergence of small divergences between standards, which could reverse the benefits that these Voluntary Standards aim to deliver, in particular, lower TCO for BE-CHE and greater interoperability, performance, safety and efficiency.

The ZEPA 2025 Voluntary Standards are 'open' standards, meaning they are available to anyone to use and share, free of charge.



The ZEPA 2025 Voluntary Standards aim to harmonize industry practice based on current and anticipated technologies

¹ This work (excluding photo rights) is made available under the Creative Commons Attribution 4.0 International license (CC BY 4.0) <https://creativecommons.org/licenses/by/4.0>.

Scope and Limitations of the ZEPA 2025 Voluntary Standards

The ZEPA 2025 Voluntary Standards apply only to BE-CHE and do not cover hydrogen-electric container handling equipment (HE-CHE) at this stage. Research² indicates that, when compared to HE-CHE, BE-CHE is the more accessible, attractive and affordable choice today for terminal operators as it is more competitive in most use cases. Both technologies eliminate CO₂-related tailpipe emissions, are quiet and generate low levels of vibration. However, analysis of HE-CHE shows that, on average, it has a significantly higher TCO than BE-CHE and is unlikely to be accessible to terminal operators at scale in time for their net zero targets. Hydrogen also presents particular fuel-handling challenges and complexities arising from health and safety considerations (e.g., flammability, high-pressure requirements). Accordingly, the 2025 ZEPA initiatives (including these Voluntary Standards) were focused on BE-CHE as the more realistic technology to achieve affordability and accessibility relative to diesel-CHE by 2030.



Research² indicates BE-CHE is the more realistic choice for terminal operators in the short to medium term

Further, for 2025, ZEPA and its members chose to concentrate on developing Voluntary Standards for terminal tractors and straddle carriers, as noted above. terminal tractors are the most numerous vehicles in the fleet and produce the largest share of emissions, so their electrification would have the largest decarbonising impact. straddle carriers, on the other hand, have the biggest TCO difference with diesel-CHE and are the most challenging to electrify due to their high load and run time. For these two types of equipment, the ZEPA 2025 Voluntary Standards are grouped under three topics:

- charging strategy and method;
- "Charger, equipment & software architecture; and
- battery specifications.

Development of voluntary standards for other equipment types and other topics can be addressed at a later stage.

Some of the ZEPA 2025 Voluntary Standards describe physical aspects of the equipment. Others focus on factors such as charging strategies and communication protocols that

2. Systemiq (2023), Reaching a tipping point in Battery-Electric Container Handling Equipment

operators and OEMs also need to consider when deciding the design, procurement and operation of BE-CHE.

Some of these Voluntary Standards are deliberately more prescriptive than others. For interoperability and safety reasons, the standards which define physical dimensions and safety protocols are highly prescriptive and provide clear, specific requirements. Other standards that offer guidance on issues related to design, procurement and operational practices are less prescriptive.

The ZEPA 2025 Voluntary Standards aim to introduce certain minimum technical specifications and protocols based on current and anticipated technologies and experience, while preserving OEMs' freedom to improve and differentiate on these, innovate further and explore new solutions and terminal operators' freedom to adopt new deployment strategies. ZEPA members acknowledge that BE technologies are evolving and anticipate that the equipment itself, its deployment, and adoption rates will all change: new battery chemistries (e.g., solid state) are on the horizon; new business models (e.g., battery-as-a-service) are emerging; and adoption rates are climbing in adjacent high-volume segments (e.g., passenger cars). Through our various initiatives, we specifically intend to help make BE-CHE more attractive, accessible and affordable to implement. Therefore, the ZEPA 2025 Voluntary Standards support and anticipate further relevant technology development by highlighting 'technology watchpoints' on pages 28 and 42.

In the process of defining the ZEPA 2025 Voluntary Standards, several emerging technology developments were identified that could impact the Voluntary Standards in the future. To facilitate a discussion on the existing technology (including the short-term outlook), and limit speculation these emerging, longer-term developments are considered as 'technology watchpoints'.

The ZEPA 2025 Voluntary Standards aim to introduce certain minimum technical specifications and protocols based on current and anticipated technologies and experience, while preserving stakeholders' freedom to improve and innovate further.



The successful deployment of battery-electric container handling equipment (BE-CHE) in terminal operations relies on system interoperability and standardized data exchange. ZEPA and the Terminal Industry Committee 4.0 (TIC4.0) share the objective of advancing interoperability and data standards to enable efficient integration of emerging technologies. For further details, refer to TIC4.0 - www.tic40.org

The ZEPA 2025 Voluntary Standards for terminal tractors

The ZEPA 2025 Voluntary Standards for terminal tractors are shown in the table below. In the chapters following this table, the methodology, the technology watchpoints, the rationale and additional remarks for the ZEPA 2025 Voluntary Standards are discussed in more detail. Note that some Voluntary Standards are prescriptive for interoperability or safety reasons, while others merely highlight suggested considerations.

Charging Strategy & Method *(see overview of strategies on page 12)*

- TT.1** **Ensure rotational charging, with depot-style charging as a flexible complement:** rotational charging is assumed to be the main charging mode, whereas depot charging is additionally used to provide complementarity in accommodating local shift and break schedules as well as daily and weekly terminal demand fluctuations.
- TT.2** **Ensure consistency with regional adoption of international standards for charging and communication protocols:** NACS/CCS1 (North America), CCS2 (APAC and EMEA), GB/T (China), CHAdeMO (Japan) and emerging MCS (Global).

Charger, Equipment & Software Architecture

- TT.3** **Assume charger lay-out considerations:** keep trailer attached to tractor, assume no reversing is needed, allow for drive through, maintain minimum cable length of 5 meters, minimise space required, minimise distance to charging spots by having multiple charging spots in the port (charging strategy dependent), maintain 'safety margin standard' (e.g. 1 meter around truck), accommodate demand shifts in job types at port level and adhere to regional safety regulations.
- TT.4** **Assume inlet location and charge cable design considerations:** assume an ergonomic and safe solution (i.e., maximum cable length of 15 meters), limit carrying weight, assume driver can enter/exit vehicle, assume the charge cable is retractable and cannot lie on the ground, assume the inlet is located at the left side of the vehicle.
- TT.5** **Ensure compatibility with hands-free charging solutions by adhering to the Mating Space Medium High and Obstacle-Free Space Standards, specifically for the connector described under TT.2** (i.e., the charge inlet location should be located at a height level of 60-120 cm measured from the ground and have a width and inlet depth of 40 cm).
- TT.6** **For non-battery swapping solutions, assume battery pack location(s) considerations:** battery system location(s) should not change turning radius, increase wheelbase, exceed footprint of tractor, create collision risks (e.g., include a safety bumper) or limit driver's vision compared to Internal Combustion Engine (ICE) terminal truck designs.
- TT.7** **For battery swapping solutions, assume solution considerations for interoperability (including 'behind the cabin' as starting point for open standard).** In addition to the battery pack location, other features need to be agreed on in order to arrive at a workable open standard, e.g., (non-exhaustive): mechanical plugs with HV safety strategy (i.e., touch protection, mechanical electric disconnection), communication bus interface, signal connector interface, battery box size and functional sequences for (dis)connection.
- TT.8** **Ensure each vehicle complies with the ISO 26262 functional safety requirements series:** a clearly marked safety switch should be included to manually disconnect all power electronics in an emergency or during maintenance. Additionally, when a fault occurs, it should first be indicated on the dashboard, followed by power limitation and a delayed shutdown. Moreover, proper grounding, isolation monitoring, and battery separation during charging should be in place to prevent electrocution.
- TT.9** **Ensure adherence to the existing automotive Open Charge Point Protocol (OCPP) specifications.**

Battery Specifications

- TT.10** Ensure that batteries are equipped with a certified BMS, overcurrent and short-circuit protection, thermal management, and safe battery placement: measures should be included to avoid exposure to explosive atmospheres and ensure electrical components are adequately isolated. These provisions are essential to maintain vehicle stability, safety, and optimal battery operation.
- TT.11** Ensure battery system allows for ~1 C-rate charging (i.e., battery can be charged from 0% to 100% in maximum one hour).
- TT.12** For non-battery swapping equipment setup, assume no voluntary standard or solution for battery specifications.
- TT.13** Assume battery packs that are used in commercial heavy-duty road trucking and/or passenger vehicle designs.

The ZEPA 2025 Voluntary Standards for straddle carriers

The ZEPA 2025 Voluntary Standards for straddle carriers are shown in the table below. In the chapters following this table, the methodology, the technology watchpoints, the rationale and additional remarks for the ZEPA 2025 Voluntary Standards are discussed in more detail. Note that, as for terminal tractors, some Voluntary Standards are prescriptive to preserve interoperability and safety, while others merely highlight considerations.

Charging Strategy & Method *(see overview of strategies on page 12)*

- SC.1** **Ensure rotational charging, with depot-style charging as a flexible complement:** rotational charging is assumed to be the main charging mode, whereas depot charging is additionally used to provide complementarity in accommodating local shift and break schedules as well as daily and weekly terminal demand fluctuations.
- SC.2** **Ensure consistency with regional adoption of international standards for charging and communication protocols:** NACS/CCS1 (North America), CCS2 (APAC and EMEA), GB/T (China), CHAdeMO (Japan) and emerging MCS (Global).

Charger & Equipment Architecture

- SC.3** **Assume charger lay-out considerations:** allow for drive through, maintain minimum cable length of 5 meters, minimise space required, minimise travel distance to charging spots by having multiple charging spots in the port (charging strategy dependent), maintain 'safety margin standard' (e.g. 1 meter) around straddle carrier, accommodate for different container job types at terminal level and adhere to regional safety regulations.
- SC.4** **Assume three options for inlet location and charge cable design considerations:** (1) platform level, (2) above the drive unit, and 3) in the space between the wheels at ground level. Generally, assume an ergonomic and safe solution (i.e., minimum cable length of 5 meter and maximum of 15 meters, limited carrying weight, driver can enter/exit vehicle, and the charge cable is retractable and cannot lie on the ground).
- SC.5** **Ensure compatibility with hands-free charging solutions by adhering to the Mating space Medium High and Obstacle-Free Space Standards, specifically for the connector described under SC.2** (i.e., the charge inlet location should be located at a height level of 60-120 cm measured from the ground).
- SC.6** **For non-battery swapping equipment setup, assume battery pack location(s) considerations:** battery system location(s) should stay within footprint of straddle carrier, limit collision risks (e.g., include a safety bumper), optimise driver's vision, reduce tipping risk, ensure safe maintenance/service, allow easy replacement, and be positioned to allow quick access for fire response teams in case of an accident.
- SC.7** **Ensure each vehicle complies with the ISO 26262 functional safety requirements series:** a clearly marked safety switch should be included to manually disconnect all power electronics in an emergency or during maintenance. Additionally, when a fault occurs, it should first be indicated on the dashboard, followed by power limitation and a delayed shutdown. Moreover, proper grounding, isolation monitoring, and battery separation during charging should be in place to prevent electrocution.
- SC.8** **Ensure adherence to the existing automotive Open Charge Point Protocol (OCPP) specifications.**

Battery Specifications

- SC.9** Ensure that batteries are equipped with a certified BMS, overcurrent and short-circuit protection, thermal management, and safe battery placement: measures should be included to avoid exposure to explosive atmospheres and ensure electrical components are adequately isolated. These provisions are essential to maintain vehicle stability, safety, and optimal battery operation.
- SC.10** Ensure the battery system supports a minimum charging rate of ~1C (i.e., battery can be charged from 0% to 100% in maximum one hour), and, where required, allows higher charging rates >2C, as different charging strategies may benefit from increased C-rates.
- SC.11** For non-battery swapping equipment setup, assume no voluntary standard or solution for battery specifications.
- SC.12** Assume battery packs that are used in commercial heavy-duty road trucking and/or passenger vehicle designs.

A closer look at charging strategies

The setup that terminal operators chose for their BE-CHE fleet highly influences their day-to-day operations, the required charging equipment, the peak power demand, and ultimately the TCO for the equipment. ZEPA has therefore defined four charging archetypes for BE-CHE that are used and referenced in the ZEPA 2025 Voluntary Standards. These four charging archetypes are: depot charging, vehicle rotation, fast opportunity charging and battery swapping. The specific application and customer preferences define the operational specifications, including charge rate and ratio of chargers to equipment. Combinations of archetypes can be pursued.

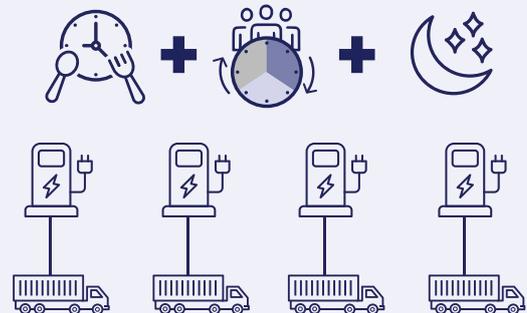
Vehicle rotation (continuous operation)

Equipment operators begin charging their BE-CHE unit when the battery reaches a low level during their shift and rotate to a charged BE-CHE vehicle to continue working their shift without significant downtime, while their original vehicle charges. Each charger can support approximately 10 CHE (in case of SC) to 17 CHE (in case of TT). This means terminals – at full adoption – may need to purchase more BE-CHE units than the number of ICE units they replace. As battery capacity increases and charge rates improve, the ratio of extra equipment shall reduce. Chargers serving a few units are strategically located throughout the terminal to ensure easy access. This strategy generally leads to a relatively flat electricity demand profile without major peaks, using grid capacity most efficiently. Exhibit A shows a rotational charging setup for a BE terminal tractor fleet.



Depot charging (during fixed breaks)

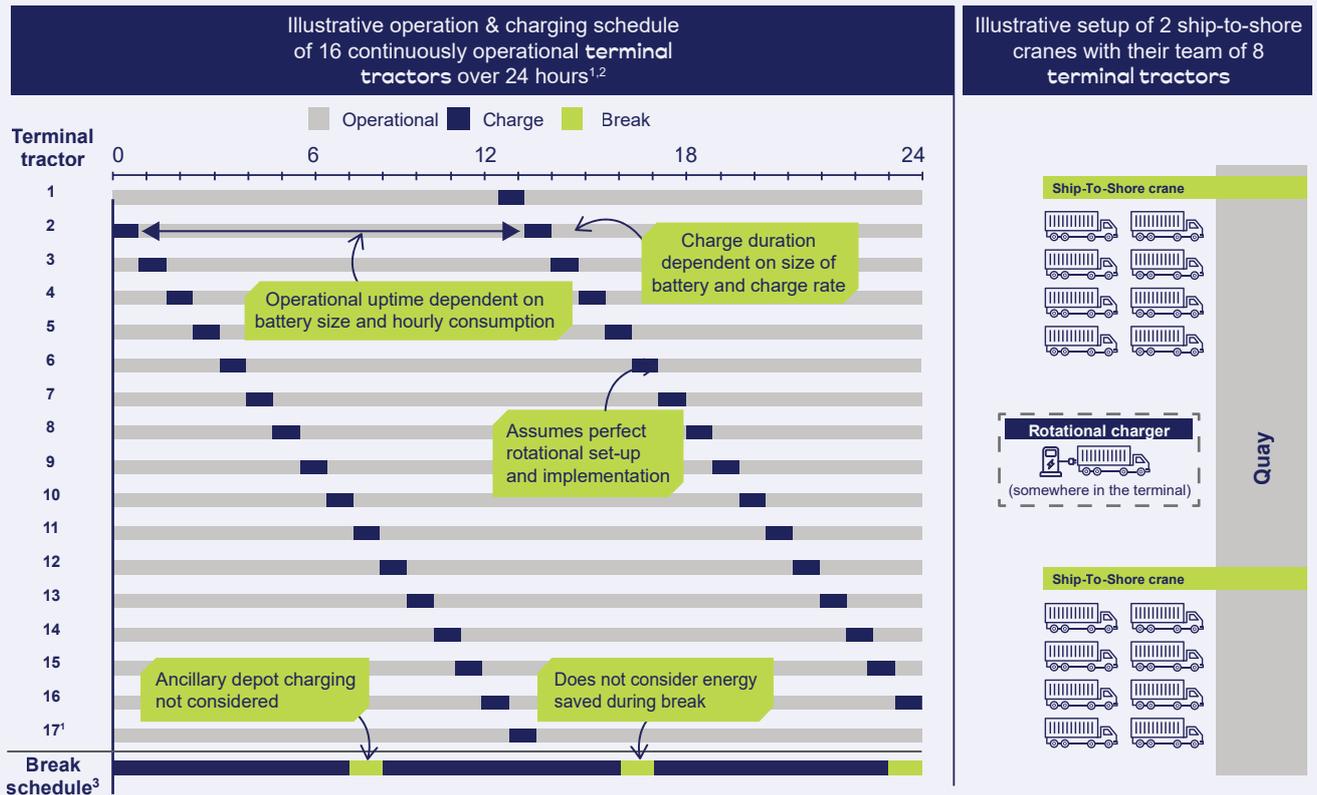
All BE-CHE units charge simultaneously either overnight (for non-24-hour shifts) or during scheduled breaks (for 24-hour shifts). Each unit of BE-CHE has a dedicated charger, allowing equipment operators to use the same unit of equipment throughout their shifts without terminals needing to purchase additional units. Chargers are centrally located in areas such as break zones, parking's or maintenance facilities. Terminals can have multiple charging locations across the site to maximise accessibility and efficiency. This strategy generally leads to an electricity demand profile with very high peaks due to simultaneous charging.



Depot charging (staggered breaks)

BE-CHE units charge during operators' breaks, which are staggered across shifts to smooth electricity demand and avoid load peaks. This may enable more efficient use of chargers and grid capacity. It may also reduce the number of chargers needed, as charging is spread over a longer time window. However, this approach depends on such scheduling being permitted under applicable regulations and union agreements.

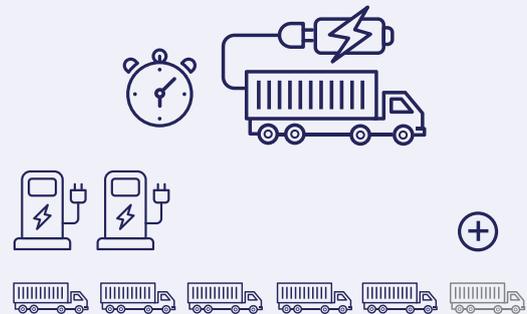
Illustrative vehicle rotation charging set-up for terminal tractors



(1) One additional terminal tractor estimated for a fleet of 16 full-time operational vehicles (2) ~50-minute charging + travel/set-up time estimated, effective battery use of 188 kWh per discharge cycle (total battery size 250kWh), charge rate of 250 kW (3) Based on 8-hour shifts including 1-hour breaks

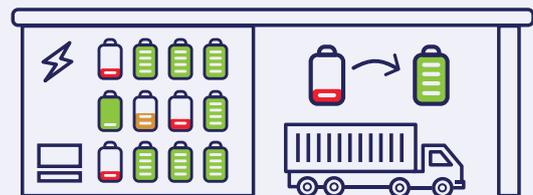
Fast opportunity charging (during operation)

BE-CHE charges quickly and frequently throughout operations, ideally during random periods of inactivity as well as scheduled breaks. Chargers are positioned at strategic decentralized locations where units of CHE have short breaks, such as loading zones, to maximize efficiency and minimize downtime. Converting idle time to charge time is especially challenging since exact location and duration of idling varies and is hard to predict. This strategy generally leads to a relatively flat electricity demand profile without major peaks.



Battery swapping (continuous operation)

BE-CHE units swap batteries when the battery reaches a low state of charge during shifts. Operators maintain the same CHE throughout their shifts, eliminating the need for additional BE-CHE. Each swapping station can charge approximately 6 to 12 batteries simultaneously and serve around 20 to 70 CHE units in continuous operation. Swapping stations are typically located in central areas of the terminal, although there may be multiple locations to enhance accessibility and efficiency. Additional batteries are required to make battery swapping possible. This strategy generally leads to a relatively flat electricity demand profile without major peaks.



The vehicle rotation strategy for BE-CHE has the most alignment potential, meaning the ease of implementation and ability to work seamlessly across different operational setups, systems and environments (See Exhibit B). Vehicle rotation, opportunity charging and battery swapping all have flat loads and have a lower TCO. Battery swapping, however, uses technologies that are not yet available for straddle carriers, has limited adoption to date and lacks currently available standards, limiting its interoperability. Vehicle rotation and depot charging rely most on technologies that are widely used in high-volume segments, such as passenger cars. Depot charging does not provide a flat load unless staggered breaks are implemented. It does, however, fit well in terminal operations, as scheduling with charges during breaks is easier. This is in contrast to opportunity charging, which often involves unpredictable waiting times.

The vehicle rotation strategy for battery-electric container handling equipment seems to have the most alignment potential across charging strategies

EXHIBIT B

Evaluation criteria for charging strategies (evaluated as stand-alone)

■ Medium potential
 ■ High potential
 ■ Very high potential

	Load profile	Adaptability to different terminal & shift configurations	Total Cost of Ownership (<i>deep-dive next pages</i>)	Technology & standard availability	Terminal footprint for chargers
Charging strategies	<i>Distribution of charging demand over time</i>	<i>Robust and reliable performances under different terminal schedules</i>	<i>Expected total ownership cost</i>	<i>Maturity and standardization of technology needed for strategy</i>	<i>Space needed for charger installation</i>
Vehicle Rotation (continuous operation)	Even load profile, as charging demand is distributed steadily	Highly adaptable to different operating schedules, terminal configurations, and equipment setup patterns	Relatively low costs: despite needing extra vehicles, charging infrastructure requirements are minimal	Mature, used in high-volume segments, standards available	Limited number of chargers at flexible locations, but additional parking required for extra vehicles
Depot Charging (during fixed breaks)	Concentrated peak load as charging is clustered during fixed breaks ¹	Depending on break duration and charging rate, charging during breaks may be insufficient for straddles ²	High costs due to 1:1 charging equipment and peak power premium ¹	Mature, used in high-volume segments, standards available	1:1 charger-to-vehicle ratio requires significant space, can use existing parking areas where possible
Opportunity Charging (during operations)	Even load depending on effective scheduling. Although short bursts may arise as charging happens 'randomly'	High risk of impact to operations in case waiting time is not sufficiently available during operations	Relatively low costs: despite needing extra vehicles, charging infrastructure requirements are minimal.	Mostly mature, but adoption of hands-free connection technology remains lower in high-volume market vs manual connection	Use of valuable space nearby operations (e.g., near quayside for sea-side operating equipment)
Battery Swapping (continuous operations)	Even load profile, as charging demand is distributed steadily	Same as vehicle rotation, though failure risk is higher because a single station outage affects entire system	Relatively low cost, actual costs uncertain due to early-stage maturity (for straddle carriers)	Technology not available for SC's; Limited adoption so far for TT's	Requires dedicated swap bays, a battery storage facility, and appropriate safety measures

Note: [1] If staggered breaks are used in the operational schedule this could reduce the number of chargers needed and the peak load during break charging, reducing costs [2] The orange/light green box shows that depot poses challenges related to break charging for straddles, unlike for terminal tractors.

Source: ZEPA member working sessions, Systemiq analysis

CHAPTER 2

**Terminal Tractors -
Analyses and discussions
underlying the
Voluntary Standards**



Terminal Tractors - Analyses and Discussions underlying the Voluntary Standards

The ZEPA 2025 Voluntary Standards have been co-developed in a collaborative process of extensive analysis and discussion by ZEPA members, non-members and industry organisations. This chapter shares analysis and discussion supporting the Voluntary Standards for terminal tractors: the TCO analyses; the rationale and related remarks for each Voluntary Standard; and the technology watchpoints to consider.

The Total Cost of Ownership (TCO) calculations differ from the 2024 Voluntary Design Standards and 2023 white paper Reaching a Tipping Point in Battery-Electric Container Handling Equipment due to updates and variations in key inputs and assumptions such as cost of charging solutions, energy consumption, downtime, battery salvage value, and forecasted energy costs. Refined insights and updated market data also contribute to these differences. The ZEPA analysis explores multiple charging strategies in greater depth, though the assumed technical setups may not fully reflect market availability. As a result, the TCO numbers are indicative, with actual TCO varying based on company terms, business and fleet sizes, availability, order sizes modes of operation, local energy costs, and labor agreements, and Weighted Average Cost of Capital, among others.



The conclusion remains:
BE terminal tractors are approaching the TCO of their diesel counterparts in some specific regions

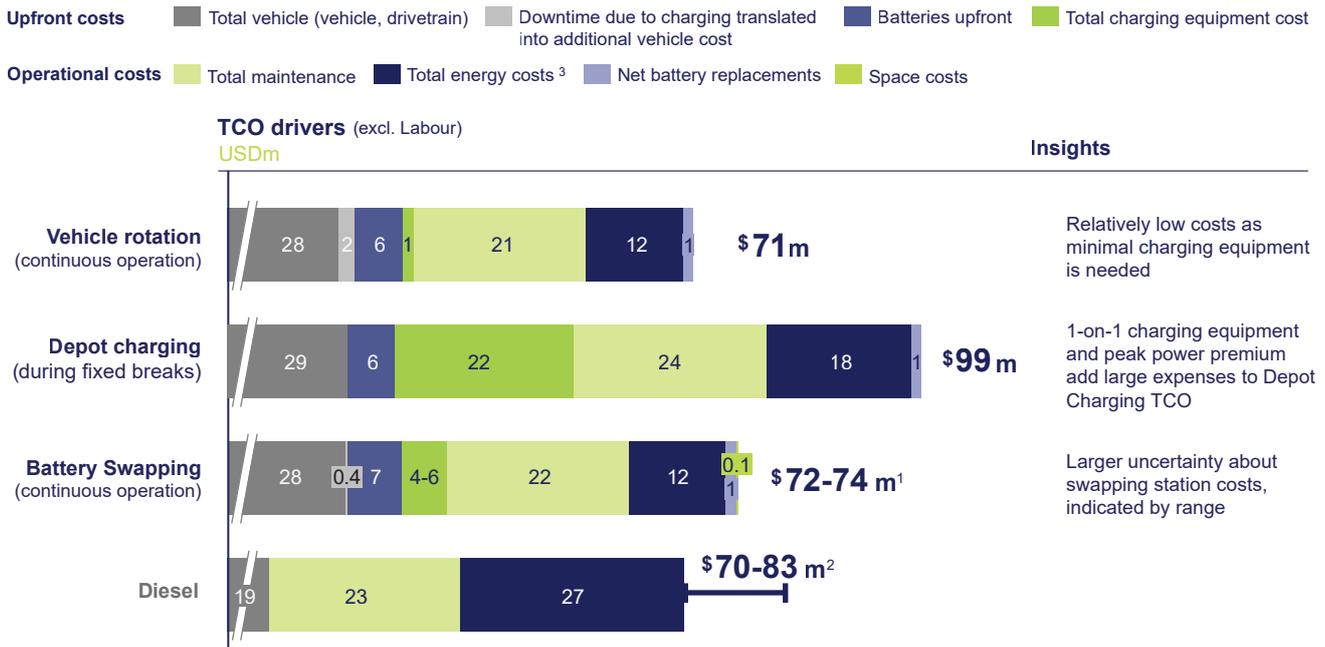
A Total Cost of Ownership for terminal tractors analyses

The TCO analyses calculate the indicative net present value of the lifetime costs of both diesel-powered and BE terminal tractors. The TCO for BE-terminal tractors is evaluated for the three charging strategies, since each strategy affects the cost drivers of the TCO differently. Opportunity charging is not considered for terminal tractors, since this is not feasible at this point as operational constraints leave little (reliable) time to stop and charge at fixed locations (with STS at different positions). The inputs required to develop the TCO model have been crowdsourced from ZEPA members, as well as from several experts in the field, such as IAV, and supplemented with publicly available data.

The analyses indicate that vehicle rotation is the most cost-effective charging strategy for BE-terminal tractors, followed by battery swapping (See Exhibit C). Vehicle rotation has the lowest upfront costs for charging equipment and the lowest maintenance costs. The cost for the total vehicle is lower for the vehicle rotation strategy, as the vehicle is used less intensively compared to other charging strategies and therefore has a longer lifetime. While battery swapping has higher charging equipment and maintenance costs, it offsets these by avoiding the costs of additional vehicles needed for vehicle rotation. Notably, the indicative TCO for vehicle rotation, battery swapping, and diesel strategies is already within ~2% difference of each other.

Opportunity charging is not considered for terminal tractors, since this is not feasible at this point as operational constraints leave little (reliable) time to stop and charge at fixed locations.

EXHIBIT C Vehicle rotation results in the lowest TCO for BE terminal tractors, followed by battery swapping



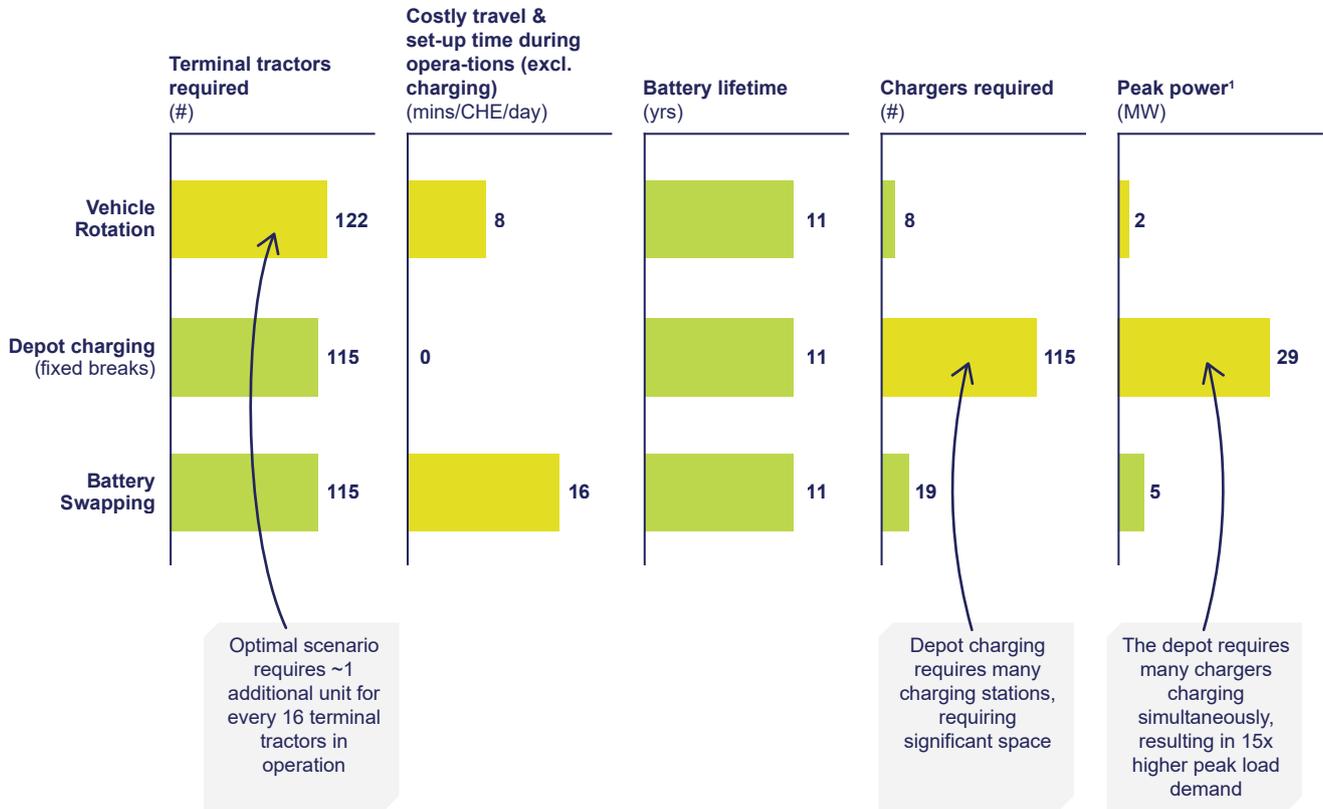
Note: Exact TCO by company will differ based on variables stated above NPV for total vehicle lifetime of 12 years (depot, swapping) and 12.8 (Vehicle Rotation). (1) Upper end of range shown for +\$100k battery swapping hub costs (\$120k-200k) due to large uncertainty in costs (2) Range illustrates a 50% increase in diesel costs from 1 to 1.5 \$ (3) High peak demand in depot charging punished with +50% in energy costs and grid fees. Source: ZEPA work, TO operational requirement survey, Systemiq analysis

The main driver of the higher TCO for depot charging is the number of chargers needed to charge all the equipment simultaneously (See Exhibit D). In addition, this strategy results in a peak power demand approximately 15 times higher than the peak power demand of vehicle rotation.

EXHIBIT D

Overview of the main TCO drivers for each charging strategy for Terminal Tractors

■ Cost-effective ■ Less cost-effective



Note: No redundancy assumed for any charging strategy. Modelled as stand-alone strategy (1) Assumes no peak shaving during shift breaks. Source: ZEPA member working sessions, TO operational requirement survey, Systemiq analysis



Terminal Tractor Methodology

The main assumptions for modelling the TCO of terminal tractors (similar to the straddle carrier model) are:

- **Throughput:** The terminal completes 4 million container moves per year.
- **Operating Schedule:** The terminal operates continuously on a 24/7 schedule, consisting of three shifts of 8 hours, with a 45-minute break per shift and 15-minute shift change. This results in 21 moving hours per day.
- **Peak capacity:** The terminal is expected to be operating at peak terminal capacity 50% of the year.
- **Off-peak terminal demand:** The percentage of off-peak versus peak demand is approximately 67%.

Other modelling assumptions can be found in the Annex: *TCO Modelling Assumptions*.

Based on these assumptions, the model calculates the average number of moves per hour needed at the terminal and derives the fleet size needed for 4 million moves per year. The model then assesses the cost implications of various factors for a fleet of this size to derive the TCO for terminal tractors for each of the four charging strategies. The TCO calculations are based on average operational utilisation, while the total fleet size is determined by peak capacity requirements. The factors assessed include:

- **Battery and charging**, such as battery capacity, effective battery use and required charging time.
- **Shift schedule**, including details of required breaks and operating time.
- **Lifetime** of batteries and vehicles.
- **Maintenance** required on batteries and vehicles.

Based on these details, the model considers the cashflows for a 12-year period for the four charging strategies and the diesel alternative. The cost components of the TCO are equipment CapEx, comprising vehicle, battery and charging equipment costs, and OpEx costs, comprising the costs of energy, maintenance, labour and end-of-life replacement.

Discussion for each Voluntary Standard for Terminal Tractors

TERMINAL TRACTORS Charging Strategy & Method

TT.1 Ensure rotational charging, with depot-style charging as a flexible complement: rotational charging is assumed to be the main charging mode, whereas depot charging is additionally used to provide complementarity in accommodating local shift and break schedules as well as daily and weekly terminal demand fluctuations.

Rationale

- **Rotational charging** has a favourable TCO outlook (driven by reduced waiting time, fewer chargers and space requirements, as well as lower peak power loads), is most adaptable to different terminal & shift configurations, distributes charging load steadily over time, builds on technology that is already widely adopted in adjacent sectors, and is more likely to create (potential) interoperability with other equipment types.
- **Depot charging** during shift breaks and on non-operational fleet (during off-peak periods) minimises the need for additional vehicles. When complementing a rotational charging strategy, depot charging increases operational flexibility by adding additional chargers. However, it is constrained by a higher TCO (e.g., a 1:1 charger-to-vehicle ratio is needed to maintain operational continuity) and high peak loads during charging windows. Staggered breaks could improve TCO outlook of depot charging, however most terminals do not operate with staggered breaks, or this may not be feasible to implement.
- The equipment setup for **rotational charging complemented by depot charging** is more likely to be interoperable with other BE-CHE (e.g., reach stackers).
- **Opportunity charging and battery swapping technology** are not mentioned in Voluntary Standard TT.1 as they are considered less suitable charging strategies for terminal tractors at this point.
 - Terminal tractors have significant waiting time during operations that could be used for opportunity charging; however, the variation in the location and duration of such waiting time (e.g., at berth waiting for ship-to-shore crane) makes it difficult to utilise the time for charging.
 - Battery swapping technology at present is often tailored to the specific vehicle and/or battery, as no formal open standards exist. It may add additional requirements (and constraints) to the vehicle design and is yet to scale in adjacent high-volume sectors. In addition, battery pack locations differ for different vehicle designs, and many technology and vendor lock-in risks are not yet resolved.

Remarks

- An additional 5-10% units of BE-CHE are assumed to be required for the rotational charging strategy to ensure there is always a vehicle that is being charged and enough charged vehicles available to maintain continuous operations without downtime.
- According to the TCO calculations, depot charging is already (partially) obsolete and shall be increasingly outperformed by other strategies as the batteries and power electronics required for higher charging rates become more affordable, allowing rotational charging facilities to cover all terminal tractor charging needs.

TERMINAL TRACTORS Charging Strategy & Method

TT.2 **Ensure consistency with regional adoption of international standards for charging and communication protocols:** NACS/CCS1 (North America), CCS2 (APAC and EMEA), GB/T (China), CHAdeMO (Japan) and emerging MCS (Global).

Rationale

- Follow existing standards from adjacent high-volume sectors, such as passenger vehicles and heavy-duty trucking, that follow NACS, CCS2, GB/T, CHAdeMO and emerging MCS standards.
- Follow prevalent adoption of connector standards in local regions to increase likelihood of interoperability, availability and access to maintenance, service and parts.

Remarks

- Regions where (presently) there is no clearly dominant charging method (e.g., South America) are not included.
- If harmonisation takes place in an adjacent high-volume sector, this standard needs to be updated.
- MCS charging is emerging as a globally accepted standard for high charge rates, with most use cases in Europe and focused on heavy-duty trucks. Adoption remains limited for now, but is expected to grow^{3,4,5}.
- Eventually North America shall follow CCS2/MCS in case of high-power charging with 500 kW.

TERMINAL TRACTORS Charger, Equipment & Software Architecture

TT.3 **Assume charger lay-out considerations:** keep trailer attached to tractor, assume no reversing is needed, allow for drive through, maintain minimum cable length of 5 meter, minimize space required, minimize distance to charging spots by having multiple charging spots in the port (charging strategy dependent), maintain 'safety margin standard' (e.g. 1 meter around truck), accommodate demand shifts in job types at port level and adhere to regional safety regulations

Rationale

- The considerations ensure operational safety and cost-optimal charging (i.e., time- and space-efficient) Demand for terminal job types (shore-yard, yard-yard, yard-rail, yard-road, yard-ship) may vary over time, causing a shift in vehicle charging demand across the terminal yard.
- Regulation on safety margins surrounding the vehicle varies regionally, and master yard planners will want to optimize yard space.

Remarks

- A voluntary standard for charging lay-out would be highly dependent on the terminal and the charging strategy, and did not emerge from the ZEPA working sessions.

3. The Liquid Grid (2024), Charging Ahead: Megawatt Charging for Maritime Electrification - <https://theliquidgrid.com/megawatt-charging-for-maritime>
Scania (2025), CharIN White Paper Megawatt Charging System (MCS) - https://www.charin.global/media/pages/technology/knowledge-base/0c2cc2c8da-1747654352/250508_whitepaper_megawatt_charging_system_2.0.pdf
4. Scania (2025), Megawatt charging – all you need to know about MCS - <https://www.scania.com/group/en/home/electrification/e-mobility-hub/megawatt-charging-all-you-need-to-know-about-mcs.html>

TERMINAL TRACTORS Charger, Equipment & Software Architecture

TT.4 Assume inlet location and charge cable design considerations: assume an ergonomic and safe solution (i.e., maximum cable length of 15 meters), limit carrying weight, assume driver can enter/exit vehicle, assume the charge cable is retractable and cannot lie on the ground, assume the inlet is located at the left side of the vehicle.

Rationale

- The considerations ensure operational safety and time- and space-efficient charging
- The CharIN MCS Whitepaper⁶ has advised on trucking standards for charge inlet location (left side of the vehicle) and cable length for MCS in trucking (maximum 15 meters).
- Cables longer than 5 meters require the use of cable reels or other management systems to prevent tangling, wear, and safety issues.

Remarks

- No clear charging inlet location emerged from the ZEPA working sessions, although near the driver door has been mentioned most often. CharIN Megawatt Charging System (MCS) Whitepaper suggests behind the foremost axle.
- Some terminal operators favouring a depot strategy setup prefer to have the inlet location on the front to optimize use of space.

TERMINAL TRACTORS Charger, Equipment & Software Architecture

TT.5 Ensure compatibility with hands-free charging solutions by adhering to the Mating Space Medium High⁷ and Obstacle-Free Space Standards, specifically for the connector described under TT.2 (i.e., the charge inlet location should be located at a height level of 60-120 cm measured from the ground and have a width and inlet depth of 40 cm).

Rationale

- Certain terminal-specific operations may require automated charging solutions, and terminal operators should be able to acquire equipment compatible with automated charging.
- Follow existing standards from adjacent high-volume sectors such as passenger vehicles and heavy-duty trucking.

Remarks

- Other hands-free technologies, like QCC (Quick Charging Connections), pantograph (up or down), busbar, and induction, should also be considered as solutions.

6. CharIN (2022), CharIN Whitepaper Megawatt Charging System (MCS) (with title hyperlinked https://www.charin.global/media/pages/technology/knowledge-base/c708ba3361-1670238823/whitepaper_megawatt_charging_system_1.0.pdf)

7. ISO 3874:2017 - Series 1 freight containers—Handling and securing, provides detailed guidelines on the necessary clearances and alignment features to ensure safe and efficient container handling

TERMINAL TRACTORS Charger, Equipment & Software Architecture

TT.6 For non-battery swapping solutions, assume battery pack location(s) considerations: battery system location(s) should not change turning radius, increase wheelbase, exceed footprint of tractor, create collision risks (e.g., include a safety bumper) or limit driver's vision compared to Internal Combustion Engine (ICE) terminal truck designs.

Rationale

- When the vehicle does not use a battery swapping strategy, there is no need to prescribe the location(s) of the battery pack(s).
- The location(s) of the battery pack(s) should not limit or change the (safe) operation of the vehicle.

Remarks

- There is currently no standard location for the battery pack in different terminal tractor designs.

TERMINAL TRACTORS Charger, Equipment & Software Architecture

TT.7 For battery swapping solutions, assume solution considerations for interoperability (including 'behind the cabin' as starting point for open standard). In addition to the battery pack location, other features need to be agreed on in order to arrive at a workable open standard, e.g., (non-exhaustive): mechanical plugs with HV safety strategy (i.e., touch protection, mechanical electric disconnection), communication bus interface, signal connector interface, battery box size and functional sequences for (dis)connection.

Rationale

- The considerations ensure interoperability between battery swapping technologies and battery pack designs. Some testing of the interoperability of equipment from different providers for behind-the-cabin swapping is currently being done.
- Standardizing battery swapping solutions is challenging, as many may have individual Intellectual Property and design rights attached.
- Placing the swappable battery pack behind the cabin appears to be the most likely positioning to achieve open standardization based on existing solutions and OEM input.

Remarks

- More standardization of battery swapping solutions is needed.
- Battery packs behind the cabin limit the driver's view (although mirrors and cameras can accommodate) and may raise the vehicle's centre of gravity for the vehicle.
- Battery swapping technology at this point is often tailored to the specific vehicle and/or battery, as no open standards exist, and is yet to scale in adjacent high-volume sectors. Battery pack locations differ in different vehicle designs and many technology and vendor lock-in risks are not yet resolved.
- Designs that do not accommodate battery swapping allow for more design flexibility (i.e., multiple battery packs located in different parts of the truck).

TERMINAL TRACTORS Charger, Equipment & Software Architecture

- TT.8** Ensure each vehicle complies with the ISO 26262 functional safety requirements series: a clearly marked safety switch should be included to manually disconnect all power electronics in an emergency or during maintenance. Additionally, when a fault occurs, it should first be indicated on the dashboard, followed by power limitation and a delayed shutdown. Moreover, proper grounding, isolation monitoring, and battery separation during charging should be in place to prevent electrocution.

Rationale

- In an emergency situation the operator and/ or emergency response team should be able to easily identify and disconnect the batteries from the rest of the vehicle to reduce safety hazards.
- A fault indication must alert operators via the dashboard when a system malfunction is detected. The system must then limit power and initiate a delayed shutdown to protect components. Fault response must align with the ISO 26262 series for functional safety.
- During charging, terminal tractors must be grounded to mitigate electric shock risk. Ground connection must comply with IEC 61936-1 for high-voltage installations, and isolation of the high voltage system must meet ISO 6469-3 safety requirements. Continuous insulation monitoring is required to detect faults, and the battery must remain galvanically isolated from the vehicle body under all conditions. Further standards related to vehicle functional safety may be applicable beyond those referenced here.

TERMINAL TRACTORS Charger, Equipment & Software Architecture

- TT.9** Ensure adherence to the existing automotive Open Charge Point Protocol (OCPP) specifications.

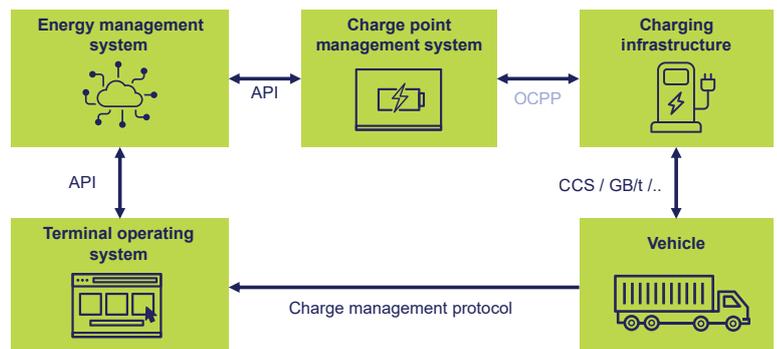
Rationale

- Together, this standard supports scalability, secure communication, and interoperability across suppliers and systems in the charging ecosystem. This includes a focus on interoperability between Charge Point Management Systems (CPMS), charging infrastructure, energy management systems, terminal operating systems and vehicles.
- Applying OCPP enables standardised data exchange and coordinated operations, including load balancing, remote monitoring, and integration of smart charging features. This supports scalability and compatibility across suppliers and systems.

Remarks

- Without standardized protocols, integration across CPMS and charging infrastructure requires custom interfaces.
- Additional standards may be explored as relevant (e.g. ISO 15118 for plug-and-charge functionality or IEC 61851 for conductive charging systems).

The OCPP sits between the Charging Infrastructure and Charge Point Management System and enables interoperability⁸. Costly bespoke interfaces are required to ensure communication between CPMS and charging infrastructure if no standard protocol is followed



8. Open Charge Alliance (2025), Open Charge Point Protocol - <https://openchargealliance.org/protocols/open-charge-point-protocol/#OCPP2.1>

TERMINAL TRACTORS Battery Specifications

TT.10 Ensure that batteries are equipped with a certified BMS, overcurrent and short-circuit protection, thermal management, and safe battery placement: measures should be included to avoid exposure to explosive atmospheres and ensure electrical components are adequately isolated. These provisions are essential to maintain vehicle stability, safety, and optimal battery operation.

Rationale

- Aligning battery-related measures with these standards ensures a minimum level of protection against risks such as thermal runaway, electrical faults, or mechanical impact
- These provisions are essential to maintain vehicle stability, safety, and optimal battery operation.

Remarks

- For a deeper explanation of battery fire and safety requirements, you can refer to the **ZEPA Battery Fire Risk and Safety**⁹ document. It provides guidance and technical background behind these recommendations.
- **BMS (Battery Management System):** A BMS is required to monitor temperature, voltage, state of charge, and state of health, and to detect unsafe conditions such as overtemperature or cell imbalance. Backed by ISO 12405, the ISO 26262 series, and UNECE R100.
- **Protection devices:** The battery and charging circuits must be protected with fuses or circuit breakers rated for the battery's short-circuit current. This prevents overheating of cables and ensures electrical isolation during faults (UNECE R100, ISO 26262 series).
- **Thermal management:** An active or passive cooling system must be present to maintain safe battery temperature ranges and reduce the risk of thermal runaway, in line with safety testing under the ISO 12405 series and control system design under the ISO 26262 series.
- **Safe placement:** Batteries must be located to preserve vehicle stability and be mechanically secured to prevent displacement or injury risk during collisions. This reflects requirements in SAE J1766 and vibration/load testing in the ISO 16750 series.
- **Explosion protection:** Components that generate heat or sparks (e.g., contactors, connectors) must not be placed in zones where flammable gas mixtures may be present. Based on design principles from IEC 60079-0 for explosive atmospheres.



9. ZEPA (2025), Battery-Electric Container Handling Equipment Fire Risk and Safety - <https://www.zepalliance.com/publications-tools>

TERMINAL TRACTORS Battery Specifications

TT.11 Ensure battery system allows for ~1 C-rate charging (i.e., battery can be charged from 0% to 100% in maximum one hour).

Rationale

- High C-rate batteries (i.e., >2C) today come at a higher TCO compared to lower C-rate batteries, because of the different cost and battery lifetime for the chemistries involved.
- Higher C-rate charging (i.e., >2C) reduces the need for extra equipment in the rotational strategy (extra vehicles) and the swapping strategy (extra batteries). The percentage of extra vehicles needed is logarithmic to the charging rate, since it is calculated by dividing charging time by operating time (and independent of the battery size). Therefore, charging rates higher than 500 kW produce marginal improvements in that percentage, i.e., 3.2% for 500kW and 2.1% for 750 kW charging (assuming a consumption of 16 kWh/h).
- Operational requirement can be met by ~1C-rate charging in the charging strategy as described in TT.1.

Remarks

- Terminals that have a potential to deploy the depot charging strategy (all except for those with 24/7 schedules) could operate with even lower C-rates.

TERMINAL TRACTORS Battery Specifications

TT.12 For non-battery swapping equipment setup, assume no voluntary standard or solution for battery specifications.

Rationale

- Standards for battery pack dimensions have not emerged across adjacent high-volume sectors such as commercial heavy-duty trucking and passenger vehicles.
- When the vehicle does not use a battery swapping strategy, the dimensions of the battery pack do not need to be prescribed.
- As battery chemistries are still under much development, both in CHE and adjacent sectors, standardising at this point may limit innovation

Remarks

- Applying current high-volume battery modules and battery packs results in sub-optimal battery capacity (i.e., kWh) for terminal tractors because they are not optimized for current terminal tractor chassis designs and battery platforms.
- ZEPA members agreed that the battery specifications do not have to be prescribed but should be at the discretion of the OEM (taking requirements from terminal operators, service/maintenance providers, battery manufacturers, and battery recyclers).

TERMINAL TRACTORS Battery Specifications

TT.13 Assume battery packs that are used in commercial heavy-duty road trucking and/or passenger vehicle designs.

Rationale

- Benefit from economies of scale in adjacent high-volume sectors.
- Using battery packs from adjacent high-volume sectors comes with higher local availability of spare parts, and maintenance/service knowledge.
- The Internal Combustion Engine (ICE) -CHE segment OEMs typically sources critical components (e.g., engines) from OEMs in the high-volume segments.

Remarks

- Assumes that currently available mass-produced battery packs can accommodate terminal tractor load profile requirements.
- Assumes sufficient availability of battery packs for BE-CHE.
- Rectangle 618, TextboxGroup 572, Grouped objectThere is a need for reliability engineering efforts to ensure battery solutions from adjacent high-volume sectors can withstand the BE-CHE use case.
- Consideration should be given to re-use, repair, and recycling of battery packs to extend the lifecycle of battery solutions used in straddle carriers.



C Technology watchpoints for terminal tractors

In the process of defining the ZEPA 2025 Voluntary Standards, several emerging technology developments were identified that could impact the Voluntary Standards in the future (See Exhibit E). To facilitate a discussion on the existing technology (including the short-term outlook), and limit speculation these emerging, longer-term developments are considered as ‘technology watchpoints’. For each technology watchpoint, we explain the milestone that the technology needs to hit, indicate which voluntary standard it may influence, and describe its potential impact. The three main developments are charging standards, charging methods and battery technology evolution.

EXHIBIT E

Technology watchpoints for terminal tractors

Indicative size of impact on standard: Low     High

	 Watchpoint		 Indicative potential impact on the voluntary standards ¹	
Charging standards	<p>Increasing charge capability of MCS: Commercially available MCS technology expands beyond the current 1.2 MW (assuming the application of 800V). This could occur faster than expected, with 3.5 MW MCS currently being developed by the industry and already deployed in projects in the marine and mining sector. Additionally, the rated current could also increase further to 500 Amp with a passive cooled cable system. Such liquid-cooled cables are being developed to reduce the need for external cooling systems, reducing the overall costs.</p> <p>Increased charging capability of CCS: Commercially available CCS technologies expand beyond the current 560 kW maximum, and CCS standards expand beyond the current 400kW (continuous charge) maximum (assuming the application of 800V). This could lead to an increased charge capability for CCS, leading to it becoming more widely adopted in adjacent high-volume sectors</p>	TT.1	Charging strategy	With rotational charging as main strategy, less extra vehicles are required with higher charging rates. This may also remove the need for ancillary depot charging equipment. 
		TT.11	Minimum battery performance	Consider higher C-rate standards to accommodate higher kW charge rate standards. 
		TT.2	Charging connector standards	Suggested to update connector standards, calibrate on-board and power electronics. 
Charging methods	<p>Battery swapping: solutions and business models develop in adjacent sectors, leading to lower TCO, reduced vendor lock-in, higher technology readiness, better standardization across suppliers, and better interoperability between equipment types.</p>	TT.1	Charging strategy	Consider battery swapping as main charging strategy. 
		TT.3	Charging layout	Charging and terminal layout may now include swapping stations. 
		TT.11	Minimum battery performance	Battery size can be optimised with battery swapping strategy. 
		TT.3	Charging layout	Consider to include hands-free charging solution(s) in charging layout (potentially quay area). 
Battery technology	<p>Battery chemistries: the charging capability of battery chemistries associated with long lifetime and high safety increases because of ongoing R&D efforts in adjacent high-volume sectors including LFP (lithium iron phosphate) and NMC (nickel manganese cobalt) chemistries, which are now emerging for terminal applications.</p>	TT.1	Charging strategy	Less depot charging may be required if you charge at higher charge rates under rotational charging. 
		TT.11	Minimum battery performance	Consider higher C-rate standards to follow upward trend of batteries' (affordable) increasing charge capability. 

1. This view represents the state of technology and development as of December 2025

Sources: Bilateral & multilateral working sessions with ZEPA members and experts and Systemiq analysis

CHAPTER 3

**Straddle Carriers -
Analyses and discussions
underlying the
Voluntary Standards**



Straddle Carriers - Analyses and Discussions Underlying the Voluntary Standards

The ZEPA 2025 Voluntary Standards have been co-developed in a collaborative process of extensive analysis and discussion by ZEPA members, non-members and industry organisations. This chapter shares the analysis and discussion supporting the Voluntary Standards for straddle carriers: the TCO analysis, the rationale and related remarks for each Voluntary Standard, and the relevant technology watchpoints to consider.

The TCO calculations differ from the 2024 Voluntary Design Standards and 2023 white paper Reaching a Tipping Point in Battery-Electric Container Handling Equipment due to updates and variations in key inputs and assumptions such as cost of charging solutions, energy consumption, downtime, battery salvage value, and forecasted energy costs. Refined insights and updated market data also contribute to these differences. The ZEPA analysis explores multiple charging strategies in greater depth, though the assumed technical setups may not fully reflect market availability. As a result, the TCO estimates are indicative only, with actual TCO varying based on company terms, business and fleet sizes, availability, order sizes modes of operation, local energy costs, labor agreements, and Weighted Average Cost of Capital, among others.



The conclusion remains:
BE straddle carriers are approaching the TCO of their diesel counterparts in some specific regions

A Total Cost of Ownership for Straddle Carrier Analyses

The TCO analyses calculate the indicative net present value of the lifetime costs of both diesel-powered and BE straddle carriers. The TCO for BE straddle carriers is evaluated for the four charging strategies, since each strategy affects the cost drivers of the TCO differently. The inputs required to develop the TCO model have been crowdsourced from ZEPA members, as well as from several experts in the field, such as IAV, and supplemented with publicly available data.

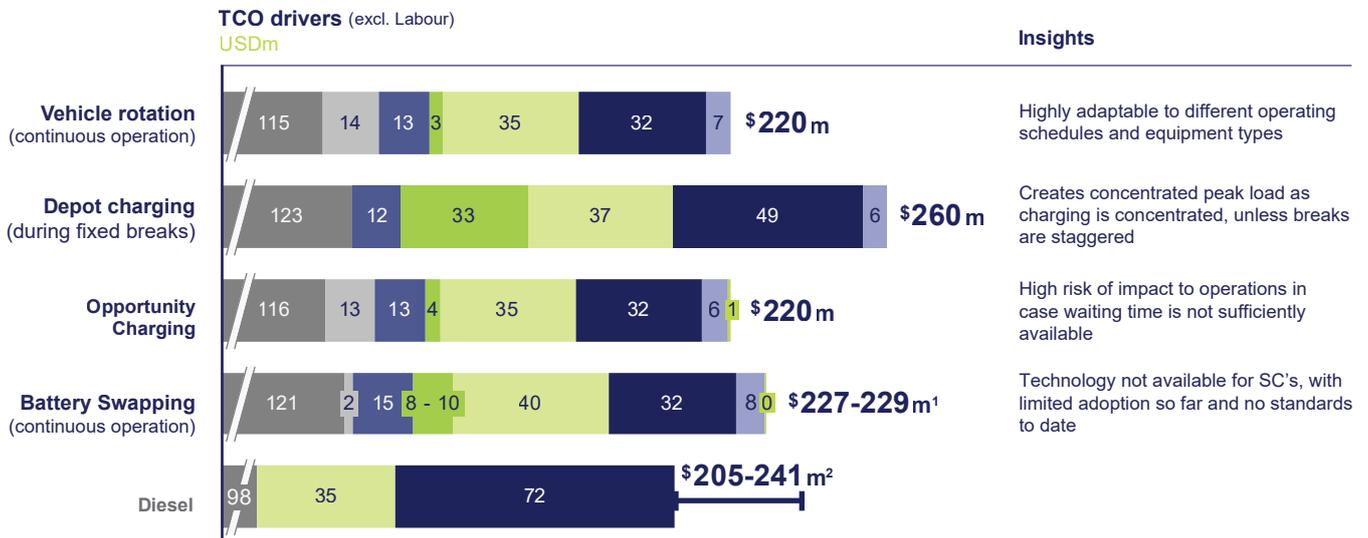
For straddle carriers, vehicle rotation, opportunity charging and battery swapping all show relatively similar TCO outcomes (See Exhibit F). Vehicle rotation remains the lowest-cost option together with opportunity charging, requiring more additional vehicles but the least charging equipment. The costs for opportunity charging – as standalone charging strategy – are driven by additional chargers and more expensive terminal space. Opportunity charging also required extra operators (which are not included in TCO) as the high charging frequency and unpredictability required additional vehicles to be used simultaneously. Battery swapping has higher upfront battery costs but avoids the need for additional vehicles, keeping its TCO close to the other strategies. However, this approach is based on a technology that is not yet commercially available for straddle carriers, creating uncertainty in both feasibility and cost estimates. Depot charging has the highest TCO due to 'high' peak load and the large number of chargers required. On its own, it often cannot deliver enough energy during standard operator breaks, limiting vehicle availability. With staggered breaks, however, the charging and energy costs of depot charging can be reduced to achieve a lower overall TCO (see Appendix).

The ZEPA 2025 Voluntary Standards aim to introduce certain minimum technical specifications and protocols based on current and anticipated technologies and experience, while preserving stakeholders' freedom to improve and innovate further.

EXHIBIT F Vehicle rotation results in the lowest TCO for BE Straddle Carriers, followed by opportunity charging

Total Cost of Ownership (TCO) for straddle carrier

Upfront costs ■ Total vehicle (vehicle, drivetrain) ■ Downtime due to charging translated into additional vehicle cost ■ Batteries upfront ■ Total charging equipment cost
Operational costs ■ Total maintenance ■ Total energy costs³ ■ Net battery replacements ■ Space costs



Note: Exact TCO by company will differ based on variables stated above. NPV calculated for vehicle lifetime of 15 years (1) Upper end of range shown for +\$100k per battery slot battery swapping hub costs (range \$240k-\$340k per battery slot) due to large uncertainty in costs (2) Range captures uncertainty in diesel costs (1\$-1.5\$) (3) Lower end of range excludes CO2 costs.

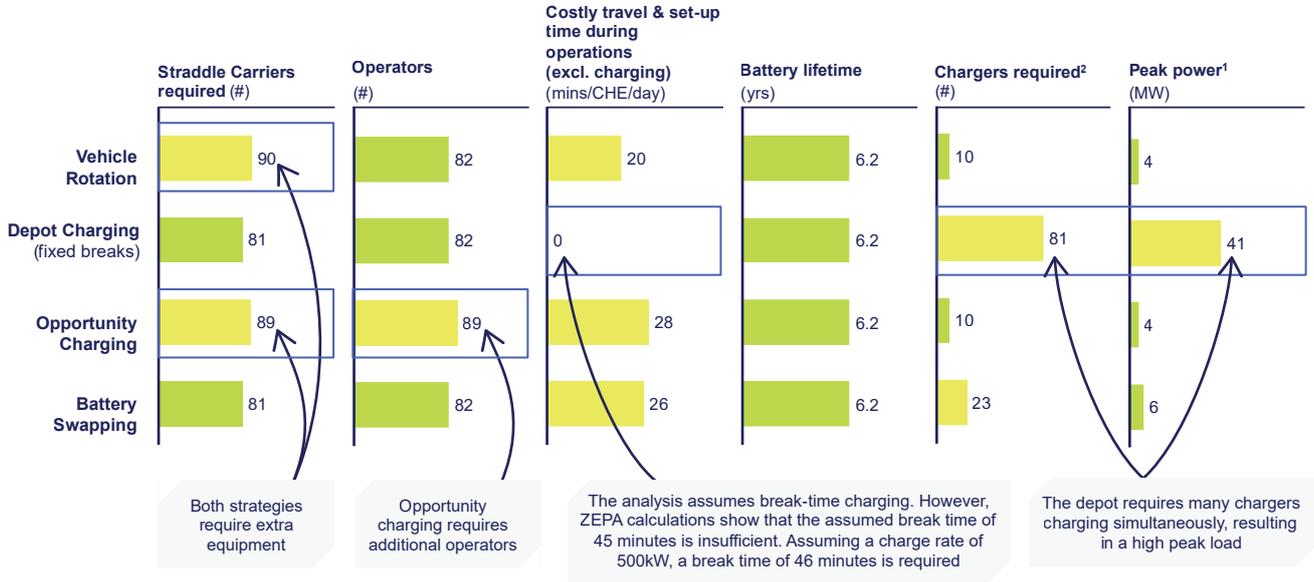
Source: ZEPA work, TO operational requirement survey, Systemiq analysis.

The main driver of the TCO for opportunity charging is the higher number of operators required due to high charge, travel and set-up time (see Exhibit G).

EXHIBIT G

Overview of the main TCO drivers for each charging strategy for straddle carriers

■ Cost-effective ■ Less cost-effective



Note: No redundancy assumed for any charging strategy. Modelled as stand-alone strategy (1) Assumes no peak shaving during shift breaks .
 Source: ZEPA member working sessions, TO operational requirement survey, Systemiq analysis

Straddle Carrier Methodology

Similar to the terminal tractor model, the main assumptions for modelling the TCO of straddle carriers are:

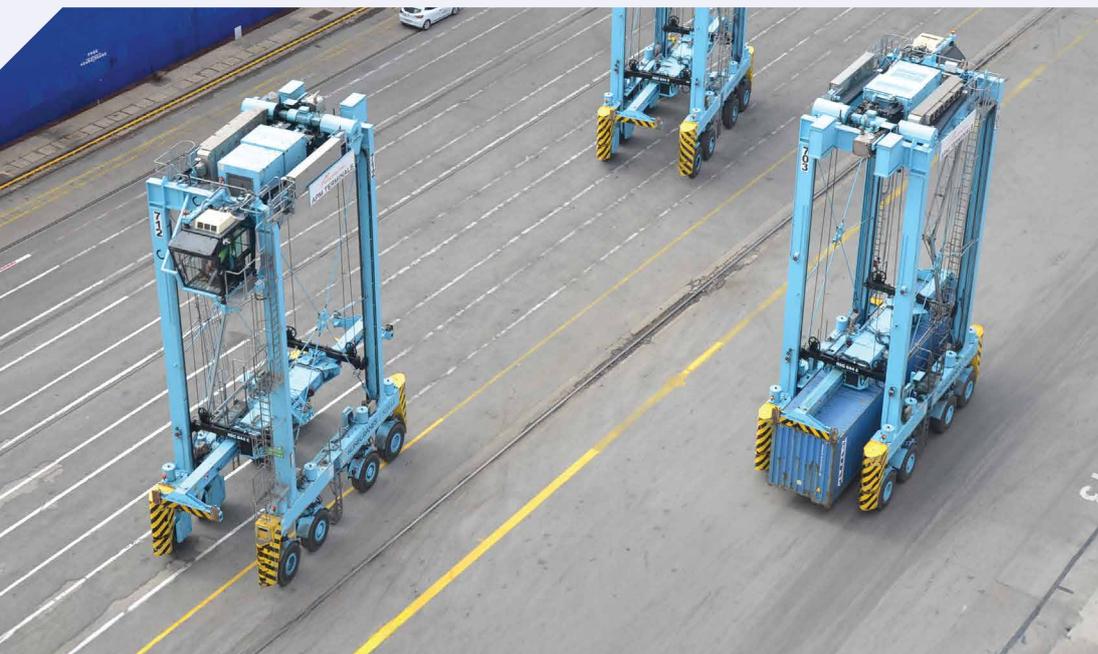
- **Throughput:** The terminal completes 4 million container moves per year.
- **Operating Schedule:** The terminal operates continuously on a 24/7 schedule, consisting of three shifts of 8 hours, with a 45-minute break per shift and 15-minutes shift change. This results in 21 moving hours per day.
- **Peak capacity:** The terminal is expected to be operating at peak terminal capacity 50% of the year.
- **Off-peak terminal demand:** The percentage of off-peak versus peak demand is approximately 67%.

Other modelling assumptions can be found in the Annex: *TCO Modelling Assumptions*.

Based on these starting assumptions, the model calculates the average moves per hour needed at the terminal and derives the fleet size needed for 4 million moves per year. The model then assesses the cost implications of various factors for a fleet of this size to derive the TCO for straddle carriers for the four charging strategies. The TCO calculations are based on average operational utilisation, while the total fleet size is determined by peak capacity requirements across the full fleet. The factors include details of:

- **Battery and charging**, such as battery capacity, effective battery use and required charging time.
- **Shift schedule**, including required breaks and operating time.
- **Lifetime** of batteries and vehicles.
- **Maintenance** required on batteries and vehicles.

Based on these details, the model considers the cashflows for a 15-year period for the three charging strategies and the diesel alternative. The cost components of TCO are equipment CapEx, comprising space, vehicle, battery and charging equipment costs, and OpEx costs, comprising the costs of energy, maintenance, labour and end-of-life replacement.



Discussion for each Voluntary Standard for straddle carriers

STRADDLE CARRIERS Charging Strategy & Method

SC.1 Ensure rotational charging, with depot-style charging as a flexible complement: rotational charging is assumed to be the main charging mode, whereas depot charging is additionally used to provide complementarity in accommodating local shift and break schedules as well as daily and weekly terminal demand fluctuations.

Rationale

- **Rotational charging** has a favourable TCO outlook (driven by reduced waiting time, fewer chargers and space requirements, as well as lower peak power loads), is most adaptable to different terminal & shift configurations, distributes charging load steadily over time, builds on technology that is already widely adopted in adjacent sectors, and is more likely to create (potential) interoperability with other equipment types.
- **Depot charging** during shift breaks and on non-operational fleet (during off-peak periods) minimises the need for additional vehicles. When complementing a rotational charging strategy, depot charging increases operational flexibility by adding additional chargers. However, depot charging on its own is less adaptable to different terminal and shift configurations, as break durations may not always enable full recharging. Additionally, it is constrained by a higher TCO (e.g., a 1:1 charger-to-vehicle ratio is needed to maintain operational continuity) and high peak loads during charging windows. Staggered breaks could improve TCO outlook of depot charging, however most terminals do not operate with staggered breaks, or this may not be feasible to implement.
- The equipment setup for **rotational charging complemented by depot charging** is more likely to be interoperable with other BE-CHE (e.g., reach stackers).
- **Opportunity charging** can improve TCO when complementing rotational charging, making use of the available waiting time of vehicles. On its own, this approach may still face challenges due to the unpredictable timing, availability, and duration of waiting time, particularly in manual settings. Additional constraints include the need for customised hands-free chargers, extra operators to accommodate for waiting time, and charger placement close to operations.
- **Battery swapping** technology for straddle carriers does not exist (at this point), thus adding much uncertainty to operational and fleet planning. Its TCO outlook does seem to be comparable to that of the vehicle rotation and opportunity charging strategies. However, battery swapping may add additional requirements (and constraints) to the straddle carrier design, the technology has no synergy with other charging strategies and their equipment set-up, and battery swapping experience from terminal tractors and road trucks may not be transferable.

Remarks

- An additional 8-12% BE-CHE is assumed to be required for a pure rotational charging strategy. As batteries and power electronics required for higher charging rates are becoming more affordable, charge rates can be increased, and BE-CHE fleet size requirements can be reduced.
- While faster charge rates do not reduce the number of vehicles or chargers required for depot charging (as each vehicle still needs a dedicated charging point), it could enable depot charging by allowing a full recharge within available break times (something the TCO analysis shows is currently a tight).

STRADDLE CARRIERS Charging Strategy & Method

SC.2 Ensure consistency with regional adoption of international standards for charging and communication protocols: NACS/CCS1 (North America), CCS2 (APAC and EMEA), GB/T (China), CHAdeMO (Japan) and emerging MCS (Global).

Rationale

- Follow existing standards from adjacent high-volume sectors, such as passenger vehicles and heavy-duty trucking, that follow NACS, CCS2, GB/T, CHAdeMO, NACS and emerging MCS standards.
- Follow prevalent adoption of connector standards in local regions to increase likelihood of interoperability, availability and access to maintenance, service and parts.

Remarks

- ZEPA's TCO model assumes charge rates of up to 500 kW to meet the operational requirements of straddle carriers; however, this remains below the charging power range defined under MCS, which can reach up to 1.2 MW.
- Regions where (presently) there is no clear dominant charging method (e.g., South America) are not included.
- In case a harmonisation of charging protocols across regions takes place in an adjacent high-volume sector such as heavy-duty trucks, this standard needs to be updated.
- North America is shifting predominantly to NACS, or CCS2/MCS in case of high-power charging with 500 kW¹⁰.
- MCS charging is emerging as a globally accepted standard for high charge rates, with most use cases in Europe and focused on heavy-duty trucks. Adoption remains limited for now, but is expected to grow^{10,11,12}.
- Each of the named charging protocols is defined with reference to specific international or industry standards (e.g. IEC, ISO, or SAE). Accordingly, reference to a given protocol implicitly refers to the relevant underlying standards applicable to that protocol.

STRADDLE CARRIERS Charger Equipment & Architecture

SC.3 Assume charger lay-out considerations: allow for drive through, maintain minimum cable length of 5 meters, minimise space required, minimise travel distance to charging spots by having multiple charging spots in the port (charging strategy dependent), maintain 'safety margin standard' (e.g. 1 meter) around straddle carrier, accommodate for different container job types at terminal level and adhere to regional safety regulations.

Rationale

- The considerations ensure operational safety and cost-optimal (i.e., time- and space-efficient) charging.
- Demand for terminal job types (shore-yard, yard-yard, yard-rail, yard-road, yard-ship) may vary over time, causing a shift in vehicle charging demand across the terminal yard.
- Regulation on safety margins surrounding the vehicle varies regionally, and master yard planners will want to optimise yard space.

10. The Liquid Grid (2024), Charging Ahead: Megawatt Charging for Maritime Electrification (with the title hyperlinked to Charging Ahead: Megawatt

11. Charging for Maritime Electrification)

Scania (2025), CharIN White Paper Megawatt Charging System (MCS) (title hyperlinked to

12. chrome-extension://efaidnbmnnnibpcajpcglclefindmkaj/https://www.charin.global/media/pages/technology/knowledge-base/0c2cc2c8da-1747654352/250508_whitepaper_megawatt_charging_system_2.0.pdf)

Scania (2025), Megawatt charging – all you need to know about MCS. (title hyperlinked to

https://www.scania.com/group/en/home/electrification/e-mobility-hub/megawatt-charging-all-you-need-to-know-about-mcs.html)

Remarks

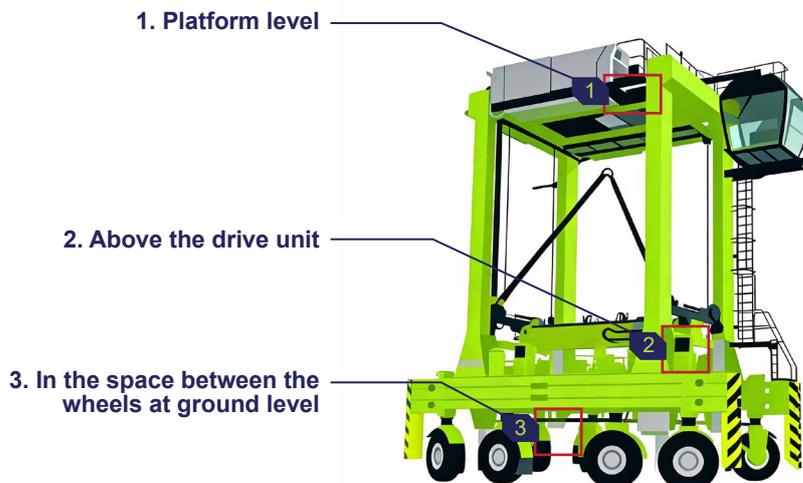
- A charging layout is highly dependent on the terminal type & lay-out and the charging strategy (mix) and did not emerge from the ZEPA working sessions. For instance, to allow for drive through (where frequent operator changes are required), platform-level charging with bridge connections can support faster transitions between vehicles. This way operators could stay on the same level of the platform of the straddle carrier (also for charging).

STRADDLE CARRIERS Charger Equipment & Architecture

SC.4 Assume three options for inlet location and charge cable design considerations: (1) platform level, (2) above the drive unit, and (3) in the space between the wheels at ground level. Generally, assume an ergonomic and safe solution (i.e., minimum cable length of 5 meter and maximum of 15 meters, limited carrying weight, driver can enter/exit vehicle, and the charge cable is retractable and cannot lie on the ground).

Rationale

- The considerations ensure operational safety and time- and space-efficient charging.
- CharIN MCS Whitepaper¹³ has advised on trucking standards for charge inlet location (left side of the vehicle) and cable length for MCS in trucking (maximum 15 meters).
- Cables longer than 5 meters require the use of cable reels or other management systems to prevent tangling, wear, and safety issues.
- To enhance interoperability and provide guidance, three inlet positions have been identified:



- These affect the different charging positions and operational layouts across terminals and ensure the Voluntary Standards accommodate common variations in equipment design and site configuration.

Remarks

- Given variations in ways of mounting and dismounting a single standardised inlet location could not be established.
- A dual-port configuration may be considered to accommodate different charging needs. This could include both (1) a high-power inlet for daily use and (2) an optional low-power port for overnight or maintenance charging.

13 CharIN (2025), CharIN White Paper Megawatt Charging System (MCS) (with title hyperlinked CharIN White Paper Megawatt Charging System (MCS)). 2025. CharIN.
https://www.charin.global/media/pages/technology/knowledge-base/0c2cc2c8da-1747654352/250508_whitepaper_megawatt_charging_system_2.0.pdf

STRADDLE CARRIERS Charger Equipment & Architecture

SC.5 Ensure compatibility with hands-free charging solutions by adhering to the Mating space Medium High¹⁴ and Obstacle-Free Space Standards, specifically for the connector described under SC.2 (i.e., the charge inlet location should be located at a height level of 60-120 cm measured from the ground).

Rationale

- Certain terminal specific operations may require hands-free charging solutions, and terminal operators should be able to acquire equipment that is compatible with that.
- Follow existing standards from adjacent high-volume sectors such as passenger vehicles and heavy-duty trucking.

Remarks

- Other technology solutions like QCC (Quick Charging Connections), pantograph (upward-acting or downward-acting, and following OppCharge specifications), busbar, and inductive charging should also be considered as a solution for hands-free charging. The standardisation landscape for these technology solutions differ, with differing levels of maturity and applicability in/out-side the terminal environment.

STRADDLE CARRIERS Charger Equipment & Architecture

SC.6 For non-battery swapping equipment setup, assume battery pack location(s) **considerations:** battery system location(s) should stay within footprint of straddle carrier, limit collision risks (e.g., include a safety bumper), optimise driver's vision, reduce tipping risk, ensure safe maintenance/service, allow easy replacement, and be positioned to allow quick access for fire response teams in case of an accident.

Rationale

- The location(s) of the battery pack(s) should not limit or change (ideally improve) the (safe) operations & maintenance of the vehicle.
- Significant weight increase on top of the straddle carrier can increase tipping hazard.

Remarks

- ZEPA members agreed that the battery pack(s) location(s) does not have to be prescribed but should be at discretion of the OEM (taking requirements from terminal operators, service/maintenance providers, battery manufacturers, and battery recyclers)
- Different locations for SC battery packs are currently being explored: e.g., on the platform and on the sides.
- Interoperability is an important consideration in case of battery swapping, especially between battery pack and swapping systems.

14. ISO 3874:2017 - Series 1 freight containers—Handling and securing, provides detailed guidelines on the necessary clearances and alignment features to ensure safe and efficient container handling.

STRADDLE CARRIERS Charger Equipment & Architecture

- SC.7** Ensure each vehicle complies with the ISO 26262 functional safety requirements series: a clearly marked safety switch should be included to manually disconnect all power electronics in an emergency or during maintenance. Additionally, when a fault occurs, it should first be indicated on the dashboard, followed by power limitation and a delayed shutdown. Moreover, proper grounding, isolation monitoring, and battery separation during charging should be in place to prevent electrocution.

Rationale

- In an emergency situation the operator and/ or emergency response team should be able to easily identify and disconnect the batteries from the rest of the vehicle to reduce safety hazards.
- A fault indication must alert operators via the dashboard when a system malfunction is detected. The system must then limit power and initiate a delayed shutdown to protect components. Fault response must align with the ISO 26262 series for functional safety.
- During charging, BE CHE must be grounded to mitigate electric shock risk. Ground connection must comply with IEC 61936-1 for high-voltage installations, and isolation of the high voltage system must meet ISO 6469-3 safety requirements. Continuous insulation monitoring is required to detect faults, and the battery must remain galvanically isolated from the vehicle body under all conditions. Further standards related to vehicle functional safety may be applicable beyond those referenced here.

STRADDLE CARRIERS Charger Equipment & Architecture

- SC.8** Ensure adherence to the existing automotive Open Charge Point Protocol (OCPP) specifications.

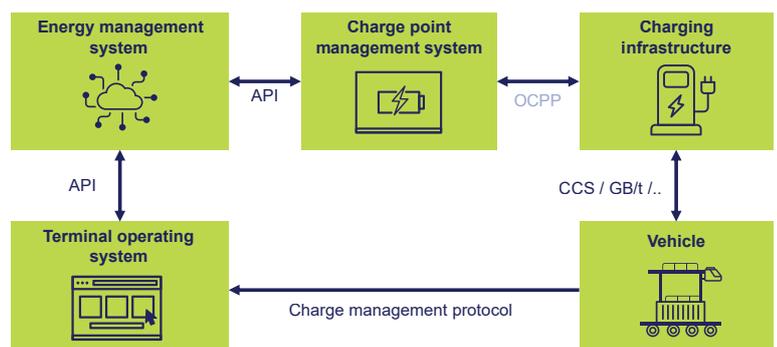
Rationale

- Together, these standards support scalability, secure communication, and interoperability across suppliers and systems in the charging ecosystem. This includes interoperability between Charge Point Management Systems (CPMS), charging infrastructure, energy management systems, terminal operating systems and vehicles.
- Applying OCPP enables standardised data exchange and coordinated operations, including load balancing, remote monitoring, and integration of smart charging features. This supports scalability and compatibility across suppliers and systems.¹

Remarks

- Without standardised protocols, integration across CPMS and charging infrastructure requires custom interfaces.
- Additional standards may be explored as relevant (e.g. ISO 15118 for plug-and-charge functionality or IEC 61851 for conductive charging systems).

The OCPP sits between the Charging Infrastructure and Charge Point Management System and enables interoperability. Costly bespoke interfaces are required to ensure communication between CPMS and charging infrastructure if no standard protocol is followed.



15. Open Charge Alliance (2025), Open Charge Point Protocol - <https://openchargealliance.org/protocols/open-charge-point-protocol/#OCPP2.1>

STRADDLE CARRIERS Battery Specifications

SC.9 Ensure that batteries are equipped with a certified BMS, overcurrent and short-circuit protection, thermal management, and safe battery placement: measures should be included to avoid exposure to explosive atmospheres and ensure electrical components are adequately isolated. These provisions are essential to maintain vehicle stability, safety, and optimal battery operation.

Rationale

- Aligning battery-related measures with these standards ensures a minimum level of protection against risks such as thermal runaway, electrical faults, or mechanical impact.
- These provisions are essential to maintain vehicle stability, safety, and optimal battery operation.

Remarks

- For a deeper explanation of battery fire and safety requirements, you can refer to the **ZEPA Battery Fire Risk and Safety document**⁹. It provides guidance and technical background behind these recommendations.
- **Battery Management System (BMS):** A BMS is required to monitor temperature, voltage, state of charge, and state of health, and to detect unsafe conditions such as overtemperature or cell imbalance. Backed by ISO 12405, the ISO 26262 series, and UNECE R100.
- **Protection devices:** The battery and charging circuits must be protected with fuses or circuit breakers rated for the battery's short-circuit current. This prevents overheating of cables and ensures electrical isolation during faults (UNECE R100, ISO 26262 series).
- **Thermal management:** An active or passive cooling system must be present to maintain safe battery temperature ranges and reduce the risk of thermal runaway, in line with safety testing under the ISO 12405 series and control system design under the ISO 26262 series.
- **Safe placement:** Batteries must be located to preserve vehicle stability and be mechanically secured to prevent displacement or injury risk during collisions. This reflects requirements in SAE J1766 and vibration/load testing in the ISO 16750 series.
- **Explosion protection:** Components that generate heat or sparks (e.g., contactors, connectors) must not be placed in zones where flammable gas mixtures may be present. Based on design principles from IEC 60079-0 for explosive atmospheres.



9. ZEPA (2025), Battery-Electric Container Handling Equipment Fire Risk and Safety - <https://www.zepalliance.com/publications-tools>

STRADDLE CARRIERS Battery Specifications

SC.10 Ensure the battery system supports a minimum charging rate of ~1C (i.e., battery can be charged from 0% to 100% in maximum one hour), and, where required, allows higher charging rates >2C, as different charging strategies may benefit from increased C-rates.

Rationale

- Operational requirement can be met by ~1C-rate charging in the charging strategy as described in SC.1.
- Faster charging can reduce the need for extra equipment in the rotational, opportunity (extra vehicles) or swapping (extra batteries) strategies. Fast-charging components still come at a premium due to higher power and thermal requirements, though this premium is falling with scale and standardisation of adjacent high-volume markets.
- The intent of this Voluntary Standard is to provide a general minimum requirement and to indicate a performance range that could be feasible and desirable under certain circumstances.

Remarks

- The percentage of extra equipment required has logarithmic relation to the charging rate since it is calculated by charging time divided by operating time (and independent from the battery size). Therefore, there is a marginal improvement by pursuing charging rates higher than 500 kW, i.e., 10% for 500kW and 7% for 750 kW charging (assuming a consumption of 55 kWh/h).
- For strategies involving overnight charging and/or battery swapping, charging rates in the range of ~0.5-1 C are sufficient as charging at around 0.5C can extend battery lifetime and reduce purchase cost.

STRADDLE CARRIERS Battery Specifications

SC.11 For non-battery swapping equipment setup, assume no voluntary standard or solution for battery specifications.

Rationale

- Standards for battery pack dimensions are at this point not prevalent in adjacent high-volume sectors, such as commercial heavy-duty trucking and passenger vehicles.
- When the vehicle does not use a battery swapping strategy, the dimensions of the battery pack do not need to be prescribed.
- As battery chemistries are still under much development, both in CHE and adjacent sectors, standardising at this point may limit innovation.

Remarks

- Current high-volume battery modules and battery packs may not be optimised for straddle carrier chassis designs and battery platforms requirements.
- ZEPA members agreed that the battery specifications do not have to be prescribed but should be at discretion of OEM (taking requirements from terminal operators, service/maintenance providers, battery manufacturers, and battery recyclers).

STRADDLE CARRIERS Battery Specifications

SC.12 Assume battery packs that are used in commercial heavy-duty road trucking and/or passenger vehicle designs.

Rationale

- Benefit from economies of scale in adjacent high-volume sectors.
- Using battery packs from adjacent high-volume sectors comes with higher local availability of spare parts, and maintenance/service knowledge.
- The Internal Combustion Engine (ICE) -CHE segment OEMs typically sources critical components (e.g., engines) from OEMs in the high-volume segments.

Remarks

- Assumes that currently available mass-produced battery packs can accommodate straddle carrier load profile requirements.
- Assumes sufficient availability of battery packs for BE-CHE.
- There is a need for reliability engineering efforts to ensure battery solutions from adjacent high-volume sectors can withstand the BE-CHE use case.
- Consideration should be given to re-use, repair, and recycling of battery packs to extend the lifecycle of battery solutions used in straddle carriers.



carriers

In the process of defining the ZEPA 2025 Voluntary Standards, several emerging technology developments were identified that could impact the Voluntary Standards in the future (See Exhibit H). To facilitate a discussion on the currently existing technology (including short-term outlook), and limit speculation, the longer-term developments are considered as technology watchpoints. For each technology watchpoint we explain the milestone that the technology needs to hit, indicate which voluntary standard it may influence, and describe its potential impact. The three main developments are charging standards, charging methods and battery technology evolution.

EXHIBIT H Technology watchpoints for straddle carriers

Indicative size of impact on standard: Low High

	Watchpoint	Indicative potential impact on the voluntary standards¹			
Charging standards	Increasing charge capability of MCS: Commercially available MCS technology expands beyond the current 1.2 MW (assuming the application of 800V). This could occur faster than expected, with 3.5 MW MCS currently being developed by the industry and already deployed in projects in the marine and mining sector. Additionally, the rated current could also increase further to 500 Amp with a passive cooled cable system. Such liquid-cooled cables are being developed to reduce the need for external cooling systems, reducing the overall costs.	SC.1	Charging strategy	With rotational charging as main strategy, less extra vehicles are required with higher charging rates. This may also remove the need for ancillary depot charging equipment.	
		SC.10	Minimum battery performance	Consider higher C-rate standards to accommodate higher kW charge rate standards.	
	Increased charging capability of CCS: Commercially available CCS technologies expand beyond the current 560 kW maximum, and CCS standards expand beyond the current 400kW (continuous charge) maximum (assuming the application of 800V). This could lead to an increased charge capability for CCS, leading to it becoming more widely adopted in adjacent high-volume sectors.	SC.2	Charging connector standards	Suggested to update connector standards, calibrate on-board and power electronics.	
Charging methods	Battery swapping: solutions and business models develop in adjacent sectors, leading to lower TCO, reduced vendor lock-in, higher technology readiness, better standardisation across suppliers, and better interoperability between equipment types ² .	SC.1	Charging strategy	Consider battery swapping as main charging strategy.	
		SC.3	Charging layout	Charging and terminal layout may now include swapping stations.	
	QCC, pantograph (upward or downward-acting), busbar, and induction: technical solutions (some are currently in pilot phase) demonstrate a robust charging system for terminal operational settings, exhibiting a high utilisation rate of operational waiting time compared to other charging strategies.	SC.3	Charging layout	Consider to include hands-free charging solution(s) in charging layout (potentially quay area).	
Battery technology	Battery chemistries: the charging capability of battery chemistries associated with long lifetime and high safety increases because of ongoing R&D efforts in adjacent high-volume sectors including LFP (lithium iron phosphate) and NMC (nickel manganese cobalt) chemistries, which are now emerging for terminal applications.	SC.1	Charging strategy	Less depot charging may be required when charging at higher charge rates under rotational charging.	
		SC.10	Minimum battery performance	Consider higher C-rate standards to follow upward trend of batteries' (affordable) increasing charge capability.	

1. This view represents the state of technology and development as of December 2025
 Sources: Bilateral & multilateral working sessions with ZEPA members and experts and Systemiq analysis

Conclusion and Outlook

By forming a dedicated alliance and fostering industry-wide collaboration, ZEPA has taken a crucial step in driving the decarbonisation of port operations. Through raising awareness, facilitating a structured co-creation process, and delivering the ZEPA 2025 Voluntary Standards (an update on the 2024 version), ZEPA underscores the commitment of the CHE ecosystem to accelerate the transition to sustainable practices.

These standards build upon established frameworks from adjacent high-volume sectors and extend them by introducing new, CHE-specific guidance. This targeted enhancement is designed to improve the accessibility, affordability, and attractiveness of BE-CHE, while addressing key interoperability and safety challenges. In doing so, ZEPA not only strengthens the business case for electrification but also lays the groundwork for broader formalisation, should regulatory alignment or sector-wide consensus call for it.

Ultimately, by promoting harmonisation, innovation, and shared expectations, the ZEPA Voluntary Standards aim to catalyse emissions reductions across global ports—delivering cleaner air, improved working environments, and long-term benefits for the entire maritime logistics ecosystem.

While this report touches on technology watchpoints related to areas such as battery swapping, circularity, other equipment types and software topics, there is still much to explore. Readers are encouraged to stay informed on developments in these domains as the industry continues to evolve.



These Voluntary Standards are designed to improve accessibility, affordability and attractiveness of battery-electric CHE, while addressing key interoperability and safety challenges.

The co-creation process for the ZEPA 2025 Voluntary Standards has been open to any industry stakeholders to participate in, including non-ZEPA members. To encourage wide adoption of the Voluntary Standards, ZEPA would urge more industry stakeholders to consider participating in research exercises and discussions regarding future iterations and developments of the Voluntary Standards, to ensure these continually incorporate a wide diversity of perspectives, address evolving needs across the industry, and provide the flexibility needed to keep pace with future technological advancements and offer a strong minimum foundation for further innovation and improvements by industry members.

General word about ZEPA and its members

The Zero Emissions Port Alliance (ZEPA) is a cross-value-chain port alliance set up by its members to tackle BE-CHE adoption challenges together. Specifically, ZEPA aims to accelerate port decarbonisation by making BE-CHE affordable and accessible, and therefore implementable, within the next ten years.

Systemiq held the secretariat of ZEPA and provided analytical and organisational support throughout the development of this document.



Affordability

Challenge: BE-CHE is currently more expensive than diesel CHE.



Accessibility

Challenge: BE-CHE value chain does not have the scale required for a large roll-out, implementation is often complex.



Attractiveness

Immediate benefits: BE-CHE immediately eliminates tailpipe emissions.

LEVERS TO IMPROVE COMPETITIVENESS (FOCUS OF ZEPA)

- Technology learning effects
- Reduced charging downtime
- Standardisation & decoupling
- Scaled production capacity
- Power purchase agreements
- Workforce training

BENEFITS

- No scope 1 emissions
- Lower scope 2 emissions
- No air pollutants
- Lower levels of vibration & noise

ZEPA has 13 members whose activities span the container handling sector.



In 2024, ZEPA counted 11 members, all of whom also actively contributed to the development of the first edition of the Voluntary Standards.

AARHUS HAVN

APM TERMINALS
Lifting Global Trade

CATL


DP WORLD

INDUCTEV 

 KEMPOWER



 Port of
Rotterdam

ROCSYS 

 SANY

 SSAMarine
A Carrix Enterprise

Acknowledgements

This report has been developed by Systemiq and constitutes a collective view of participating organisations in the Zero Emissions Port Alliance. ZEPA members have supported and validated the underlying analyses, and have agreed to endorse the findings as presented in this report. The Voluntary Standards have also been endorsed by EUROGATE.



We would like to thank other collaborators for providing valuable contributions to this report, both in 2024 and in 2025. Specifically, we would want to highlight:

- International Association of Ports and Harbors (IAPH)
- C40 Ports & Shipping Cities Group
- Port of Antwerp-Bruges
- Smart Freight Centre
- Portwise
- IAV
- K&L Gates

Disclaimer

The ZEPA Secretariat provides this report for informational purposes only. The data and comprehensive analysis it contains reflect our commitment to delivering accurate, insightful findings. While we have worked diligently to make sure the report is reliable and clear, we recognise it may have areas needing further refinement. Information contained in this report is made as at the date of publication. The ZEPA Secretariat does not have any obligation to update or otherwise revise any information reflecting circumstances arising after the date of publication.

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Citation

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ZEPA Alliance (2025). 2025 Voluntary Standards for Battery-Electric Straddle Carriers and Terminal Tractors.

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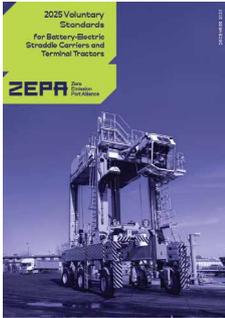
<https://creativecommons.org/licenses/by/4.0>. If you adapt this work, please include the following disclaimer along with the attribution: *“This is an adaptation of ‘ZEPA Alliance (2025). 2025 Voluntary Standards for Battery-Electric Straddle Carriers and Terminal Tractors.’ The views and opinions in this adaptation have not been reviewed or approved by ZEPA Alliance.”*

Further Reading

This report is part of a broader series of publications by the Zero Emission Port Alliance, dedicated to making untethered BE-CHE affordable and accessible by 2030. Together, these publications tackle key adoption challenges to accelerate port decarbonisation and drive industry-wide innovation.

For further reading please see the other publications or see www.zepalliance.com

Latest Publications



2025 update to the Voluntary Standards for battery-electric straddle carriers and terminal tractors (this document)



Battery-Electric Container Handling Equipment Battery Fire Risk and Safety - A transitioning fire risk profile



Strategic Pathways for Battery-Electric Container Handling Equipment Battery Circularity - Value add versus compliance risks



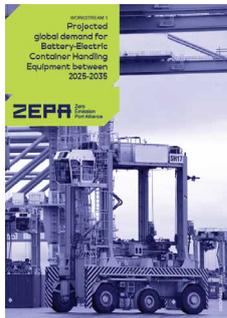
Load Profile Scenario Explorer



Workforce implications - How investing in a green, future-proof workforce can enable the transition towards BE-CHE



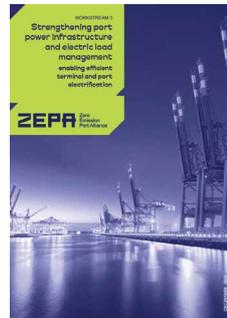
Transition plan towards electric fleets - Structured steps for coordinated action



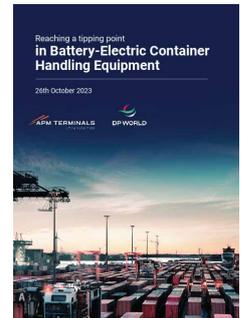
Expected purchases for battery-electric container-handling equipment 2025-2035



2024 Voluntary Standards for battery-electric straddle carriers and terminal tractors



Strengthening port power infrastructure and electric load management so container terminals and ports electrify efficiently



Reaching a tipping point in Battery-Electric Container Handling Equipment

TCO Modelling Assumptions

General assumptions

Input	Figure
Power price [\$/kWh]	0.10
Grid fees [\$/kWh]	0.05
Diesel price [\$/L]	1.00
Discount rate	10%
CO2 price (Diesel vehicles) [t/CO2]	100
Moves per hour	6
Battery lifetime (cycles)	7000

Terminal tractor Assumptions

	Depot (fixed breaks)	Vehicle Rotation	Battery Swapping
Moves per hour		6	
Minimum charge rate [kW]		250	
Minimum battery capacity [kWh]		250	
Modelled vehicle lifetime [years]	12	12.8 (new)	12
Maintenance reduction (vs Diesel)		20%	

Straddle carrier Assumptions

	Depot (fixed breaks)	Vehicle Rotation	Opportunity Charging	Battery Swapping
Moves per hour		8.5		
Minimum charge rate [kW]	500	500	500	250
Minimum battery capacity [kWh]	500	500	500	500
Modelled vehicle lifetime [years]	15	16.5	16.3	15
Maintenance reduction (vs Diesel)		15%		

Additional materials on charging

EXHIBIT A1

Overview of complementing charging strategies next to vehicle rotation

Depot charging for Straddle Carriers complements vehicle rotation; opportunity charging can as well, but requires a different interface and location, making it less straightforward. Battery swapping is impossible to combine with vehicle rotation.

✓ Mixing of charging strategy possible ✓ Mixing of charging less likely ✗ Mixing of charging impossible

	Potential complementing charging strategies next to vehicle rotational			Insight
	Depot (during fixed breaks)	Opportunity (during operation)	Battery swapping (continuous operation)	
MCS charger set-up (or another method)	✓	✓	✗	Depot and opportunity charging complement vehicle rotation. All combinations of charging strategies are feasible with an MCS (or similar) setup, except battery swapping, which is not possible.
Location of chargers that is optimal for terminal (and low cost)	✓	✓	✗	Depot charging complements operations easily, while opportunity charging is more challenging. Charger location is less critical for depot or rotational charging but essential for opportunity charging due to short waiting times. At terminals with well-located chargers and predictable longer waits, occasional opportunity charging can be added. Battery swapping requires a separate swapping station.
Manual charging interface (as opposed to hands-free connection)	✓	✓	✗	Depot charging complements operations easily, while opportunity charging is more challenging. Hands-free charging is essential for opportunity charging, while manual charging is sufficient for depot and rotational charging. Battery swapping cannot be done manually.
Recommendation	Combine <i>rotational</i> with <i>depot</i> to increase operational flexibility and balance peak load	Complement <i>rotational</i> with <i>opportunity</i> charges at the rotational/depot charger location in case a terminal has long and predictable waiting times	Battery swapping uses a different technology, making it impossible to combine with other strategies.	

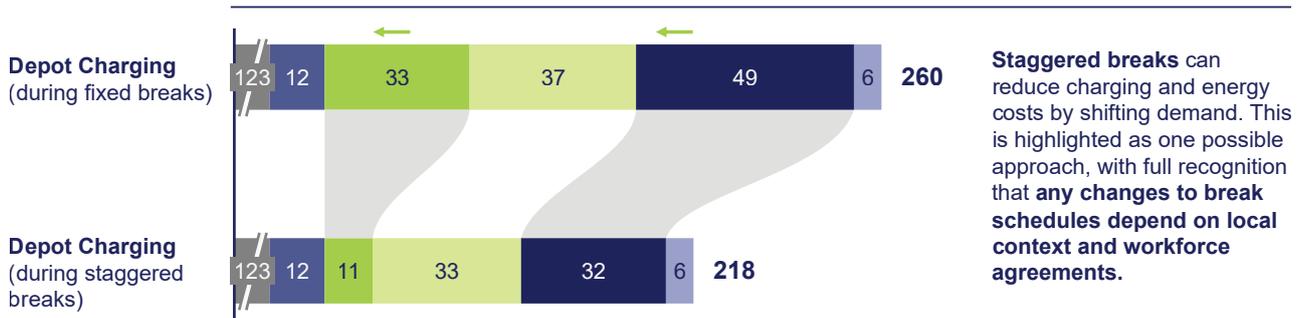
Total cost of Ownership comparison for depot charging with fixed breaks and with staggered breaks

Staggered breaks could reduce overall TCO of Depot Charging through reduced charging and energy costs, but implementation depends on local context and work-force agreements.

- Total vehicle (vehicle, drivetrain)
- Downtime due to charging translated into additional vehicle cost
- Batteries upfront
- Total charging equipment cost
- Total maintenance
- Total energy costs
- Net battery replacements
- Space costs

NPV drivers (ex. Labor)

\$m USD



Note:

- 1 All specific changes highlighted in next slides, pending further member feedback. Other changed assumptions include the **SC energy consumption** slightly increased from **53 kWh/h to 55 kWh/h**.
- 2 Assumption pending member discussion, as there are different perspectives on these assumptions.
- 3 All outputs are indicative as they are based on theoretical/ projected future costs. Additionally, actual TCO also varies on specific local variables.
- 4 High peak demand in depot charging punished with +50% in energy costs and grid fees. The cost for the total vehicle is lower for the vehicle rotation and opportunity charging strategy, as the vehicle is used less intensively compared to other charging strategies and therefore has a longer lifetime.

Abbreviation	Explainer
BE-CHE	Battery-Electric Container Handling Equipment
BMS	Battery Management System
CAPEX	Capital Expenditure
CCS	Combined Charging System
CHAdEMO	Charge de Move
CPMS	Charge Point Management System
C-rate	Battery charge/discharge rate relative to capacity
Diesel-CHE	Diesel Container Handling Equipment
eSC	Electric Straddle Carrier
eTT	Electric Terminal Tractor
GB/T	Guobiao Recommended
HE-CHE	Hydrogen Electric Container Handling Equipment
HV	High Voltage
ICE	Internal Combustion Engine
ISO	International Organisation for Standardisation
kW	Kilowatt
kWh	Kilowatt-hour
MCS	Megawatt Charging System
MW	Megawatt
NACS	North American Charging Standard
NPV	Net Present Value
OCPP	Open Charge Point Protocol
OEM	Original Equipment Manufacturer
OPEX	Operational Expenditure
QCC	Quick Charging Connections
RTG	Rubber Tyred Gantry
TCO	Total Cost of Ownership
ZEPA	Zero Emission Port Alliance

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