Reaching a tipping point
in Battery-Electric Container Handling Equipment

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APM TERMINALS
Lifting Global Trade

DP WORLD

Preface

Container Handling Equipment (CHE), which is used to load and unload containers on and off maritime transport ships, is a vital cog in the logistics of international trade. When untethered, it is typically powered by diesel which emits greenhouse gases and particulate matter. Terminal operators, original equipment manufacturers (OEMs), port authorities and shipping line operators have a shared interest in abating these emissions.

History suggests that the exponential adoption of a new technology, such as Battery-Electric CHE, can happen after a 'tipping point' is reached. A tipping point is a moment in time when a new technology becomes more affordable, attractive, and accessible than the incumbent technology.

This white paper is a call to action for the entire port ecosystem and Container Handling Equipment (CHE) value chain to accelerate towards a tipping point for BE-CHE. It presents the challenges faced in the market, identifies levers that can make BE-CHE competitive with diesel CHE, and lays out the actions stakeholders should take to enable a tipping point.

The results are the following:

A tipping point for Battery-Electric CHE (BE-CHE) can be reached within 2-8 years, if all stakeholders take the right actions. Analysis suggests that by then the TCO of BE-CHE can become less than diesel CHE.

Four levers can close the existing TCO gap: scale, standardisation & modularisation, reducing charging downtime, and incentives from the public sector & customers.

Collective action by the entire ecosystem (i.e., operators, OEMs, port authorities, policy makers and customers) is required to bring the tipping point forward and capture the value at stake.

The global shipping industry has a shared interest in reaching zero-emission CHE

Container Handling Equipment (CHE) is a critical enabler of seaborne transport, which has a lower carbon footprint than land or airborne transport[1] and accounts for 90% of global trade[2]. It is used to (un)load containers (off) on maritime transport ships across the world's 940 container ports[3]. In 2020, the global fleet of CHE enabled the transportation of ~815 million twenty-foot equivalent units, or TEUs[4], with a total value of USD 8.1 trillion[5]. Estimated at 100,000-120,000 units, it is responsible for ~10-15 MtCO2e per annum (scope 1 and scope 2), which is equivalent to the annual emissions of a country such as Slovenia.

- For terminal operators, meeting emission reduction targets requires the decarbonisation of CHE, which accounts for ~50-60% of scope 1 and scope 2 emissions.
- For port authorities, zero-emission CHE is essential to meet emission reduction targets (both at port- and national level) and to deliver environmental & social benefits (e.g. better air quality, lower healthcare costs).
- For shipping line operators, zero-emission CHE is required to abate scope 3 emissions and to meet growing demand from beneficial cargo owners for end-to-end low-carbon supply chains.
- For OEMs, meeting terminal operators' transition requirements is a clear commercial incentive to develop low-emission CHE. Additionally, it reduces their downstream scope 3 emissions from equipment use.

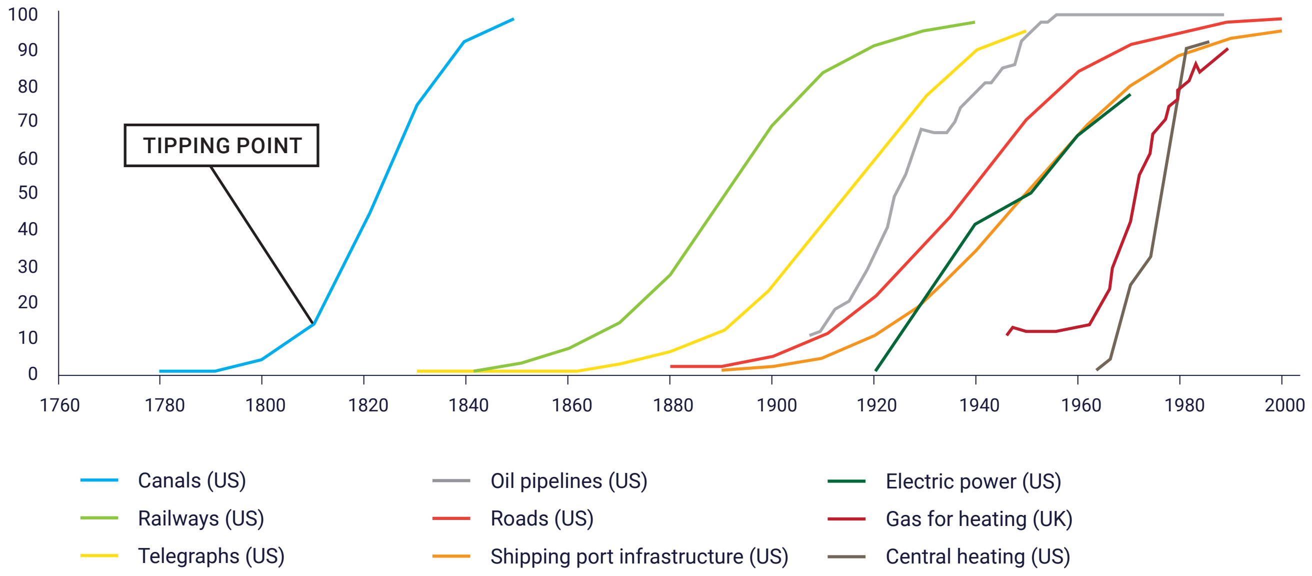
CHE comes in two forms: ~30% of units are tethered, ~70% of units are untethered. Tethered CHE can either be stationary (e.g. ship-to-shore cranes) or operate in predictable limited movements (e.g. rubber tyre gantry cranes). These are typically used to move containers from ship to shore or to stack containers in terminal yards. Tethered CHE can be powered by direct electricity supply, which can be switched to a renewable power source to achieve zero-emissions.

Untethered CHE is typically used for bidirectional quay-to-yard moves (e.g. straddle carriers, terminal tractors) or to perform terminal housekeeping (e.g. reach stackers). Untethered CHE today mostly relies on engines running on diesel, resulting in emission of greenhouse gases and particulate matter[6]. Only a few zero-emission untethered CHE are currently in operation and there are challenges to be overcome before a 'tipping point' can accelerate a rapid decarbonisation of this type of CHE (see Box 1).

LINK [1]**Source:** International Chamber of Shipping, Environmental Performance: Comparison of CO2 Emissions by Different Modes of Transport
LINK [2]**Source:** OECD, Ocean Shipping and Shipbuilding
LINK [3]**Source:** UNCTAD (2020), Ports in the global liner shipping network: Understanding their position, connectivity, and changes over time
LINK [4]**Source:** UNCTAD (2021), Review of Maritime Transport
LINK [5]**Source:** Port Economics, Management and Policy (2020), Value of Containerized Trade
[6]The main greenhouse gases emitted during the combustion of diesel include carbon dioxide (CO2), nitrogen oxides (NOx) and hydrocarbons (HC). Diesel combustion also generates a complex mixture of solid, mostly small carbon, particles known as diesel particulate matter (DPM).

Box 1: Tipping points

A new technology can reach a 'tipping point' when it becomes more competitive than the conventional technology in three dimensions: affordability, attractiveness and accessibility. Historical examples indicate that when a tipping point is reached for a new technology, its adoption switches from a linear to an exponential pace as consumers, producers and investors decisively adopt it. Parallels in the infrastructure and energy spaces show that S-curve adoption post tipping point.



Historical examples of infrastructure and energy technology adoptions.
(see: The Breakthrough Effect, Systemiq 2023)

Battery-electric will become the standard for decarbonising CHE

Zero-emission untethered Container Handling Equipment (CHE) are either Battery-Electric CHE (BE-CHE) or Hydrogen-Electric CHE (HE-CHE)[7]. Both options eliminate tailpipe emissions, are quiet and generate low levels of vibration. However, BE-CHE will be the preferred solution because it is equally or more competitive than HE-CHE in the vast majority of use cases:

- **BE-CHE is more affordable than HE-CHE:** The total cost of ownership (TCO) of HE-CHE is, on average, analysed to be 47% higher than that of BE-CHE, even when taking into account the effects of a lower charging downtime (see Box 2). This affordability gap is expected to remain as the technology develops. HE-CHE requires 3-4 times more electricity than BE-CHE[8] and expensive equipment is needed to turn that electricity into hydrogen, which results in sustained higher fuel costs. In addition, equipment prices for HE-CHE are expected to be 25-45% higher than for BE-CHE because of greater equipment and material complexity.
- **BE-CHE is more accessible than HE-CHE:** HE-CHE will not be accessible to terminal operators at scale in the coming years for two reasons. First, OEMs do not expect the first prototypes before 2025 and the first commercially viable products before 2030. Second, the supply of green hydrogen, which today is estimated to represent less than 1% of total hydrogen supply[9] and which lacks the support of a hydrogen grid, will remain in the long-term many orders of magnitude smaller than that of renewable power.

[7]While biofuels are often heralded as an easy fix, the scarcity of feedstock required for their production means supply is limited and must be reserved for highest-value use cases where alternatives are not available, such as in aviation.

[8]Hydrogen-electric CHE running on green hydrogen has a well-to-wheel efficiency of less than 25%, because electricity is first used to produce hydrogen before the latter is converted back to electricity in the fuel cell, which creates unavoidable efficiency losses. Comparatively, battery-electric CHE has a well-to-wheel efficiency of 75-80%. It is expected that imported hydrogen cannot overcome such a significant cost gap.

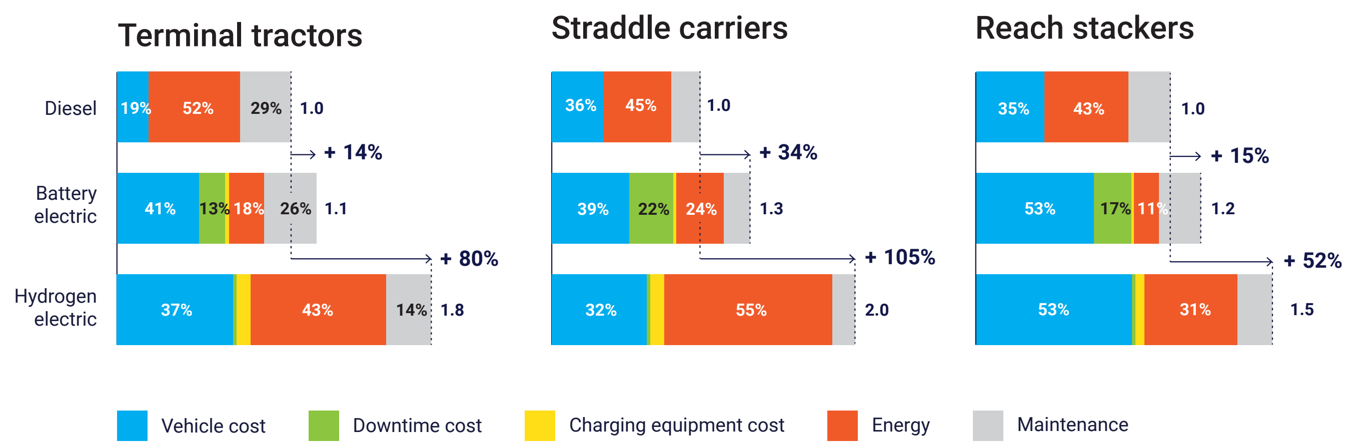
LINK [9]**Source:** IEA, Hydrogen Portal

Hydrogen-Electric Container Handling Equipment (HE-CHE) will only be desirable in specific instances, such as in extreme cold environments or in locations where the grid is not sufficiently reliable to meet the increase in electricity demand associated with using BE-CHE.

Using HE-CHE will, nonetheless, come with heightened healthy and safety concerns associated with the inherent challenges of hydrogen handling and utilisation (e.g. flammability, high-pressure requirements).

Box 2: TCO comparison across diesel, battery-electric and hydrogen-electric CHE

TCO, M USD, normalised for each CHE type to diesel in year 2023 = 1.0



Outside-in TCO assessment of selected CHE in 2023 in M USD. All values are global averages. Equipment costs are based on prices observed across a range of OEMs; energy costs assume a diesel price of USD 1/litre, an electricity price of USD 0.14/kWh, and a hydrogen price of USD 10/kg.

Action is needed to pull the tipping point of BE-CHE forward

Battery-Electric Container Handling Equipment (BE-CHE) has started to be deployed in recent years. BE-CHE are already more attractive than diesel CHE as they do not generate scope 1 greenhouse gas emissions, nor scope 2 emissions when charged with renewable electricity. BE-CHE are also quiet, produce low levels of vibration, and do not emit air pollutants, which presents significant benefits for operators' and local communities' health and safety.

However, challenges in affordability and accessibility require action to reach a tipping point in this decade. These challenges differ depending on the type of CHE[10].

Affordability challenge: BE-CHE is currently more expensive than diesel CHE

Today, the TCO of BE-CHE is higher than that of diesel CHE (see Box 2). This is the major barrier to overcome in order to reach a tipping point. Despite OPEX savings of more than 50% on energy, the TCO of BE-CHE is on average 1.2-1.43 times higher today than that of diesel CHE, because of:

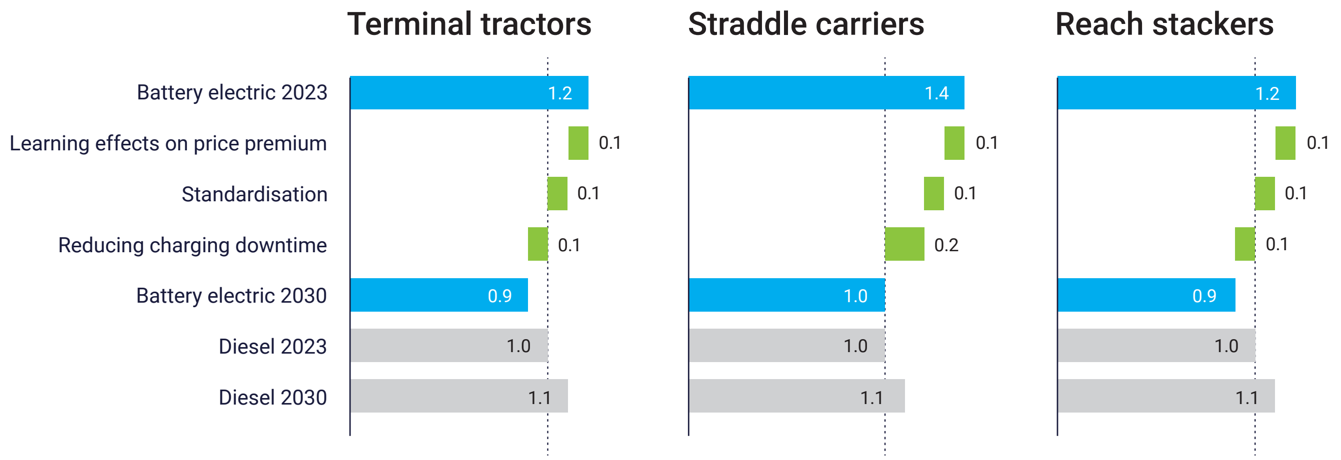
- **Higher equipment prices** of an estimated +50% for straddle carriers, +70% for reach stackers, and +150% for terminal tractors, because of battery costs and a lack of manufacturing scale.
- **Charging infrastructure costs** of on average above USD 40k per unit employed.
- **Additional downtime for charging,** translating in full fleet conversion factors from diesel to battery-electric of about 1.3 for reach stackers and straddle carriers and about 1.2 for terminal tractors. While early pilot data suggests batteries have capacity for a full shift, CHE is typically used for several shifts in a row (e.g., 3-4 for straddle carriers).
- **Battery replacement before end of life,** as battery lifetime can be less than 50% of asset lifetime for most equipment categories (with the exception of terminal tractors).

Nevertheless, BE-CHE can quickly become a financially attractive option (well) before 2030. Battery-electric terminal tractors and reach stackers can achieve TCO parity within five years, while straddle carriers within this decade. However, this does require immediate action by terminal operators, OEMs of CHE, and public authorities (notably port authorities). Box 3 shows the effects of three key cost trends that terminal operators can activate: reducing prices through increased demand signals and therefore scale, standardising and modularising batteries and charging technology, and reducing charging downtime.

[10] Not all types of equipment are as conducive to electrification as others. For example, terminal tractors, which are simpler by design and have lower energy requirements on average, are easier to electrify than straddle carriers, which are heavier and more complex machines capable of moving containers horizontally as well as vertically.

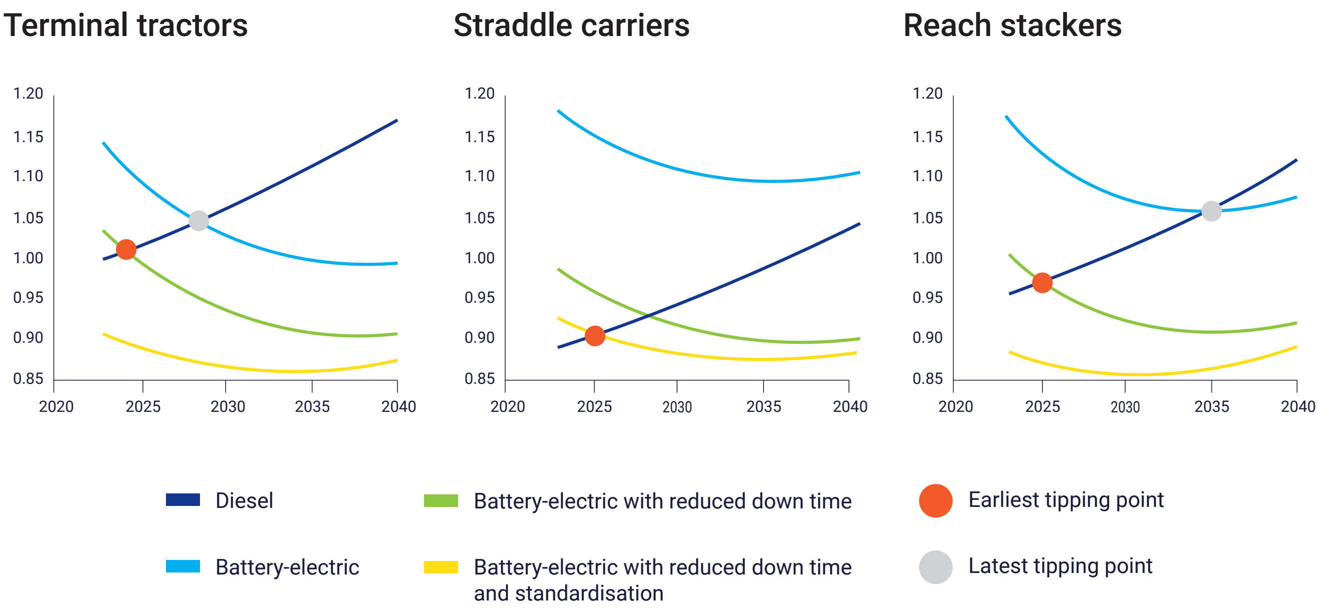
Box 3: Closing the gap to TCO cost parity between diesel and Battery-Electric CHE

TCO, M USD, normalised for each CHE type to diesel in year 2023 = 1.0



Assessment of the potential evolution of BE-CHE's TCO. The calculations assume annual 1) learning effects on battery-electric price premiums 2) annual decreases of 0.25% for diesel prices and of 1% for electricity prices.

TCO, M USD, normalised for each CHE type to diesel in year 2023 = 1.0



Evolution of TCO for selected CHE between 2023 and 2040 under three scenarios: BE-CHE alone, with reduced charging downtime, and with both reduced charging downtime and standards for key technology components.

First, a major decrease in the TCO of BE-CHE (of close to ~10% on average) can come from technology learning effects, lowering capex.

Riding on the coattails of the automotive industry, developments in battery cells, battery packs, electric drivetrains, and charging solutions will bring down equipment prices. Taking automotive battery packs as a benchmark, costs fell year-on-year by an average of 11% from over $2000/kWh in 2000 to $150/kWh in 2022. Forecasts anticipate that battery packs will be available to car manufacturers for below $75/kWh by 2030. Since Battery-Electric Container Handling Equipment (BE-CHE) uses the same component base as electric vehicles, it will benefit from similar price decreases. Also, as pilots and first full-terminal deployments drive early-stage market growth, OEM batch sizes will increase, which will lower the design cost per vehicle, increase the buying discount on batteries, and reduce the delay in accessing the latest technological innovations.

Second, the introduction of technology standards for battery packs, management systems and charging solutions, notably to decouple battery procurement from equipment production, could bring down the TCO of BE-CHE by 7% on average.

This is achieved through shortening innovation cycles and streamlining both production and deployment processes. Moreover, decoupling batteries would allow both terminal operators and OEMs to make use of standard battery packs, instead of bespoke battery packs, and would therefore allow the industry to tap into lower battery market prices

Third, re-thinking the way terminals are operated can optimise for charging and reduce downtime.

This can bring down the TCO of Battery-Electric Container Handling Equipment (BE-CHE) by at least 9% on average. There are three main options that terminal operators can consider to reduce downtime. Ultra-fast chargers, with an output of 600 kW, are already commercially available. If positioned in optimal locations (eg. close to operators' rest area), these chargers can reduce downtime from 20-35% to 10-15%. Though ultra-fast chargers are more expensive than regular chargers, savings on downtime costs would outweigh the upfront price premium.

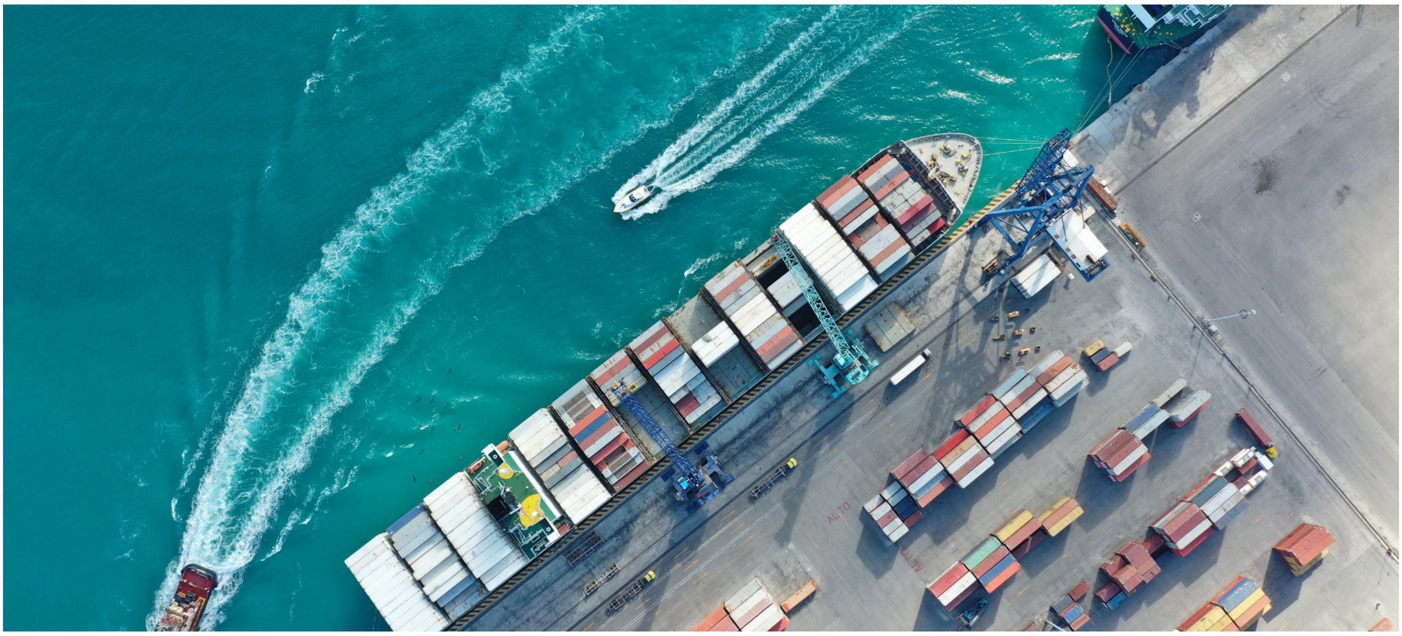
Battery swapping stations are capable of changing batteries in time frames that are competitive with diesel re-fuelling. For example, some eTT models already on sale can have their batteries swapped in 6 minutes. The technology could reduce downtime to 5%, which would outweigh the costs associated with the extra batteries.

Wireless power supply (WPS) has the potential to eliminate downtime completely, by utilising asset idle time to re-charge the equipment battery without creating additional downtime. Asset idle time can occur on a recurring basis and at predictable locations, which creates repeated windows of opportunity for charging. TTs, notably, tend to be idle for 40-60% of their operating time at the quay or in the yard either in a queue or while a container is (un)loaded. Frequent charging windows between move orders can also be introduced by switching from a gang system to a pool system. Though the technology is still early-stage, it has demonstrated its potential. Ideanomics, for example, recently tested successfully a 500 kW wireless charger capable of charging class 8 electric trucks in under 15 minutes.

Accessibility challenge: The BE-CHE value chain does not have the scale required for a large rollout

BE-CHE are commercially available and already being employed. Even if BE-CHE would be more affordable than diesel CHE, several value chain hurdles should – and can – be overcome before exponential rollout can commence:

- **OEM production capacity is insufficient,** with lead times for initial deliveries around ~12 months or more.
- **A lack of standardisation across OEMs** prevents terminal operators from streamlining the rollout of BE-CHE. Variations in battery sizes mean terminal operators have to make different operational adjustments based on the supplier, while differences in charging solutions prevent terminal operators from building a one-size-fit-all charging infrastructure.
- **Access to sufficient power supply can be challenging** in some geographies. Though BE-CHE can enable emission reductions even if the grid it is connected to is not zero-emission, net-zero operations can only be achieved if it is paired with renewable electricity, which can be difficult to access in geographies with low renewable penetration and/or inappropriate market design and/or in ports where the electricity supply is arranged by the port authority.
- **Shortage of skilled workers.** Installation and maintenance of BE-CHE requires a workforce that is certified to operate on high-voltage equipment. There are already shortages of workers with that certification. If upskilling workers is not done quickly enough, this could become a bottleneck for a wider rollout of BE-CHE.



Call to action: How to reach a tipping point in BE-CHE?

Four key levers can be identified to reach a tipping point in BE-CHE.
Action is needed from all stakeholders in the port ecosystem to activate these levers.

Mapping of key levers and corresponding actions to reach a tipping point for BE-CHE, allocated to each key stakeholder.

Lever 1: Scale up demand and production of BE-CHE

Terminal Operators

1.1	Send strong demand signals to OEMs

Lever 2: Reduce cost through standardisation and modularisation

Terminal Operators & OEMs

2.1	Develop technology standards

Lever 3: Prepare terminal operations to be ready for rollout of BE-CHE

Terminal Operators

3.1	Re-invent operations to enable electrification
3.2	Develop terminal-level electrification roadmaps
3.3	Plan workforce training

Lever 4: Introduce incentives to develop the market for eCHE

Port authorities & affiliated government entities

4.1	Award extra credits to concession bids with zero-emission fleet
4.2	Require that bids for new concessions rely on zero-emission fleets
4.3	Offer to extend concession durations only to those terminal operators who agree to replace their diesel fleets with zero-emission CHE
4.4	Offer favorable financial lease tariffs or discounts to terminal operators who invest in a zero-emission CHE fleet
4.5	Assisting terminal operators with the infrastructure adjustments required for zero-emission CHE fleets to operate
4.6	Introduce, or extend existing, clean air mandates for CHE
4.7	Provide direct financial support to secure first investments case

Shipping line operators

4.8	Engage with customers to identify requirements for end-to-end zero-emission supply chains
4.9	Include zero-emission CHE in green shipping corridor requirements
4.10	Financially compensate terminal operators for value-add of zero-emission CHE

Suggested actions for industry stakeholders

Lever 1: Scale up demand and production of BE-CHE

Responsible stakeholders: terminal operators, OEMs

Terminal operators should work together and with OEMs, to create the conditions for a scale-up of the supply chain. This can decrease equipment prices, driven by battery technology learning curves and lower equipment premiums resulting from early-stage market growth. Scaling up would also allow the terminal industry to capture the cost reduction that is seen in the battery pack market, e.g. as in the automotive industry in recent years. To encourage OEM's investments in capacity expansion and dedicated production lines with increased scale, terminal operators should:

Action 1.1: Sending strong demand signals to OEMs to provide them with the confidence in future uptake needed to invest in capacity expansion: demand signals can take the form of purchase commitments or direct offtake agreements.

OEMs can ramp-up production capacity to reduce lead times and increase batch sizes, thereby making Battery-Electric Container Handling Equipment (BE-CHE) more accessible and affordable. To invest in capacity expansion, OEMs need confidence in future uptake, which can be provided by strong demand signals from terminal operators.

Lever 2: Reduce cost through standardisation and modularisation

Responsible stakeholders: terminal operators, OEMs

Terminal operators and OEMs should work together to create the conditions for a scale-up of the supply chain and driving down cost by:

Action 2.1: Developing technology standards across equipment categories. Standards reduce TCOs, help streamline production processes, and increase equipment interoperability. Specifically, standards should be developed for:

- Charging solutions, to ensure they can be used interchangeably for all equipment and suppliers.
- Battery designs and capacities, to 1) ensure battery swapping stations are compatible across OEMs, and 2) streamline operational adjustments.
- Battery management systems, to ensure that batteries, for which supply can be scarce, can be sourced from a wider pool of suppliers.

For OEMs, this would 1) build the confidence in customer requirements needed to ramp-up production capacity, 2) avoid duplicating R&D costs, and 3) enable production processes to be streamlined.

For terminal operators, this would increase equipment interoperability, which 1) avoids duplicating deployment costs, 2) unlocks access to a wider supply pool, and 3) enables deployment adjustments to be streamlined.

Inspiration from the mining industry

The **electrification** of **mining equipment** is under way, triggered by health & safety concerns and ventilation costs associated with diesel combustion fumes.

Mining companies representing **30% of the global metals market** (including BHP, Anglo American and Gold Fields) and **19 OEMs** have come together under the umbrella of the International Council on Mining and Metals (ICMM)'s **Innovation for Cleaner, Safer Vehicles** (ICSV) initiative to align on technology requirements and on what is needed to facilitate the transition to battery-electric equipment.

Lever 3: Prepare terminal operations to be ready for rollout of BE-CHE

Responsible stakeholders: terminal operators

Terminal operators should prepare now for a large-scale rollout of Battery-Electric Container Handling Equipment (BE-CHE), starting with optimising terminal design and operations for battery-electric operations to reduce downtime. Furthermore, technological solutions should be explored for reducing or eliminating charging downtime, in part with ultra-fast chargers and battery swapping, or in full with wireless power supply (WPS). To capitalise on future cost savings and secure a competitive advantage, terminal operators should prepare now for a large-scale rollout of BE-CHE by:

Action 3.1: Re-thinking the way terminals are operated to facilitate the adoption of BE-CHE:
Terminal operators can make adjustments to their operations that are conducive to fleet electrification, such as switching from a gang system to a pool system. They can also conduct terminal-level techno-economic studies to assess which charging solution enables a least-cost transition to BE-CHE.

Action 3.2: Developing terminal-level electrification roadmaps to identify in which terminals BE-CHE should be deployed first:
Terminal readiness for electrification can be assessed based on the extent to which downtime occurs naturally, a reliable and low-cost supply of renewable power is available, and existing diesel CHE is nearing the end of its lifetime.

Where readiness is deemed insufficient, action plans to make terminals electrification-ready should be drafted.

Action 3.3: Identifying workforce training requirements associated with switching to BE-CHE and start planning these: this includes training maintenance workforce on high-voltage equipment and CHE operators on battery management best practices. The adaptation of workforces to the progressive automation of CHE in the last decade shows that trainings and upskilling are within reach.

Lever 4: Introduce incentives to develop the market for eCHE

Responsible stakeholders: port authorities, government entities, shipping line operators

Terminal operators can gain a competitive advantage by transitioning to BE-CHE. As port authorities step up their decarbonisation efforts, electrified fleets with zero tailpipe emissions become a logical fit for new concession and concession extensions. Similarly, terminal operators with electrified fleets can gain an edge with shipping line operators looking to establish zero-emission shipping corridors.

Port authorities and affiliated government entities are well positioned to create better market conditions for zero-emission CHE fleets and simultaneously deliver social & environmental benefits to local communities. Port authorities could assist accelerating the adoption of zero-emission CHE by:

Action 4.1: Introducing a system for tendering that awards extra credits to bids relying on zero-emission fleets: This would level the playing field with bids relying on diesel fleets.

Action 4.2: Making the use of zero-emission CHE a requirement in requests for proposals (RFPs), to prevent bids relying on diesel fleets to be submitted.

For existing concessions, they can do so by:

Action 4.3: Offering to extend concession durations only to those terminal operators who agree to replace their diesel fleets with zero-emission CHE.

Action 4.4: Offering favorable financial lease tariffs or discounts to terminal operators who invest in a zero-emission CHE fleet.

Action 4.5: Assisting terminal operators with the infrastructure adjustments required for zero-emission CHE fleets to operate.

For example, depending on the jurisdiction, this can sometimes be done by:

1) enabling investing in grid connection enhancements where the power supply is not sufficiently reliable,
2) fast-tracking permitting for terminal adaptations, and
3) allowing for more flexibility in choice of power supplier to enable terminal operators secure renewable Power Purchase Agreements PPAs

Where new ports are developed, port authorities should be encouraged to take the actions mentioned above by international financial institutions (IFIs) when the latter provide the financing for the port construction. IFIs' financing of new infrastructure gives them leverage, which they can use to demand that new ports be zero-emission from the outset.

Affiliated government entities could facilitate the deployment of zero-emission Battery-Electric Container Handling Equipment (BE-CHE) by:

Action 4.6 – Introducing, or extending existing, clean air mandates for CHE.

Action 4.7 – Providing direct financial support (e.g. grants, subsidies or tax credits) to secure the investment case for the first batches of zero-emission CHE.

Shipping line operators should capture the value-added potential created by BE- CHE. Terminal operators can help shipping line operators establish green shipping corridors by transition to BE-CHE. Shipping line operators should therefore:

Action 4.8 – Engage with their customers to identify their requirements for end-to-end zero-emission supply chains.

Action 4.9 – Include zero-emission CHE in green shipping corridor requirements.

Action 4.10 – Financially compensate terminal operators for this value-add.

Lessons from California

In 2007, the **California Air Resources Board** (CARB) adopted the **At-Berth Regulation** to curb pollution from vessels at berth. The rule requires vessels at berth to **use either shore power or a CARB-approved control technology** to reduce emissions. Since 2014, the regulation has enabled an **80% reduction in harmful emissions,** proving that **mandates can decisively curb pollution.**

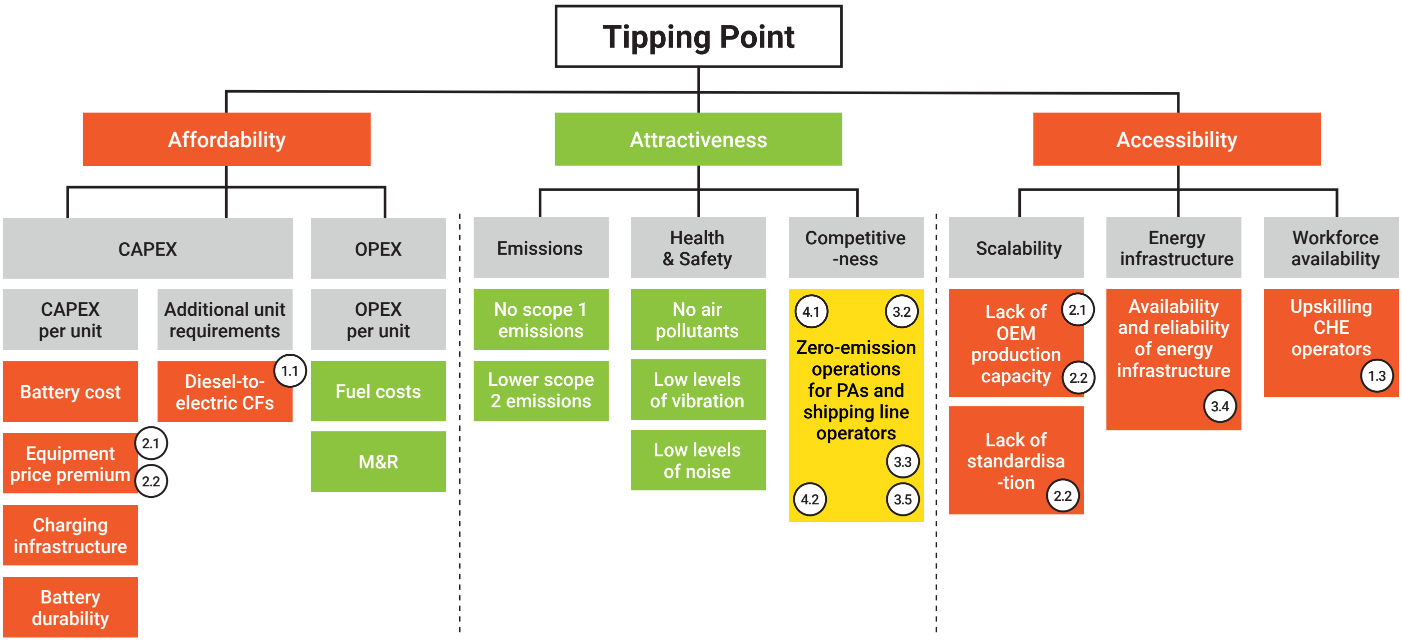
To fully eliminate air pollution in ports, these **mandates could now be extended to cover CHE.**

Appendix

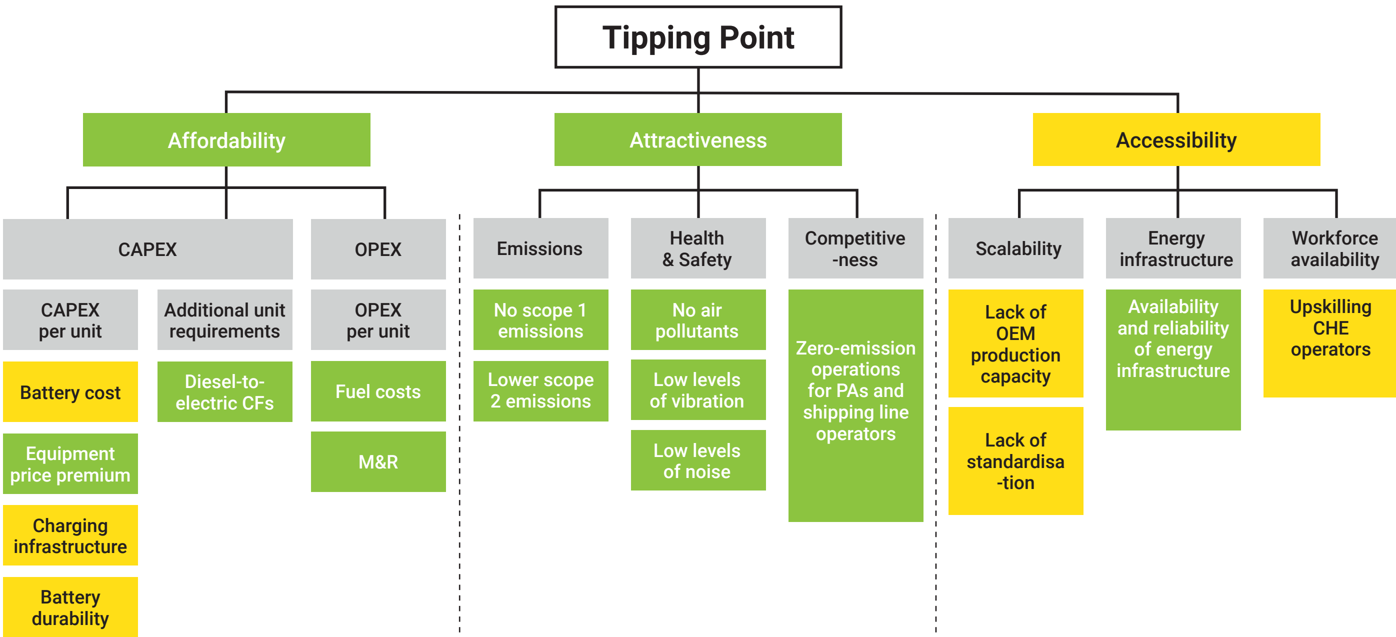
Appendix A. Mapping of challenge and levers to reach a tipping point for Battery-Electric CHE

Closing the gap — Widening the gap   (x) Action to address challenge

Challenges (today)



Forward-looking assessment



With thanks to our partners

This white paper was originally commissioned by APM Terminals. It was developed in April 2023 by Systemiq (report and analyses) and ZEnMo (analyses). The paper and its call to action has so far been endorsed by DP World, Eurogate, Smart Freight Centre and Port of Kalundborg. The Port of Rotterdam applauds the white paper's initiative to help further reduce greenhouse gas emissions within the logistics industry.

We are looking for your endorsement of the white paper's call to action for the entire port ecosystem and Container Handling Equipment (CHE) value chain to accelerate towards a tipping point for Battery-Electric CHE. The white paper presents the challenges faced in the market and identifies levers that can make Battery-Electric CHE competitive with diesel CHE. The white paper concludes that collective action by the entire ecosystem is required to bring the tipping point forward for Battery-Electric CHE and provides suggestions for concrete actions stakeholders can take to enable this. As such, your endorsement will signify a shared vision to initiate a fact-based debate on the decarbonisation of container terminals and ports. It's an opportunity to delve deeper into understanding, substantiating, and expanding upon the identified levers in the paper.

Please note that the information in the white paper is based on general market data. Further actions taken in the context of this call for action will also be carried out in compliance with competition law.