TIC4.0 NOVEMBER, 2025

White Paper Summary:

Smart eCHE Operations for Container Terminal

Contents

This paper is based on a full publication that provides more detailed insights into the topic. To access the complete material, please refer to this **LINK**.

1. Introduction

The digital and sustainable transformation of container terminals is increasingly shaped by the rapid expansion of Electric Cargo Handling Equipment (eCHE). These battery-electric and plug-in hybrid machines offer clear benefits—lower emissions, reduced noise, and higher energy efficiency—yet their successful deployment requires more than simply replacing diesel engines with electric powertrains. Electrification introduces new operational dependencies: charging cycles must be synchronised with logistics, energy availability must be continuously monitored, and multiple systems must communicate reliably in real time.

In this evolving landscape, interoperability becomes essential. Today, terminals operate fleets composed of heterogeneous equipment, manufacturers, charging technologies, and management systems, all generating and consuming operational, energy, and maintenance data. Without a shared semantic foundation, this diversity leads to fragmented data flows, bespoke integrations, limited visibility, and rising complexity—ultimately constraining the scalability and efficiency of eCHE operations.

TIC4.0 addresses this gap by providing a unified semantic and data-model framework for port-terminal digitalisation. By defining standardised concepts, observed properties, and communication structures, TIC4.0 establishes the foundations for seamless data exchange across electric vehicles, charging systems, terminal control platforms, and energy-management functions. This common vocabulary enables real-time coordination, predictive analytics, and the orchestration of charging and operations at fleet and terminal scale.

Purpose and Scope

The purpose of this document is to define a structured, information-centric framework for the efficient, safe, and scalable operation of battery-electric Cargo Handling Equipment (BE-CHE) in container terminals. It specifies the key data, semantic elements, and system interactions needed for real-time coordination across equipment, operational platforms, charging management, and terminal energy systems. By clarifying which information must flow and for what purpose, it enables full interoperability and provides the foundation for a unified TIC4.0 semantic model that supports energy-aware decision-making and optimised electrified operations.

Scope:

- **Focus on** container terminals.
- Address challenges such as **aligning charging with logistics and ensuring effective communication** and coordination.
- Support **fleet optimization**, **minimize operational disruptions**, and reduce environmental impact.
- Define **key information needs:** battery status, vehicle location, operator availability, job orders, charging station status, and grid capacity.

This section sets the stage for understanding how TIC4.0 standards can help ports integrate eCHE efficiently, safely, and sustainably, leading naturally into the historical and technological context that underpins these advancements.

2. Context

The electrification of terminal equipment is reshaping port operations, replacing predictable diesel machinery with battery-electric fleets that depend on coordinated charging, real-time routing, and tighter integration between vehicles, chargers, and operational systems. As Portwise observes, effective electrification requires a structured approach: clearly defining objectives and constraints, modelling battery performance and charging behaviour, and evaluating the resulting effects on energy demand peaks, fleet sizing, and overall CAPEX/OPEX. This makes electrification not just a technological shift but a redesign of operational processes and infrastructure.

At the same time, the growing variety of OEMs, charging technologies, and management platforms raises the risk of fragmentation. Portwise notes that decisions on propulsion, charging regimes, battery characteristics, and infrastructure capacity are interdependent and must be evaluated together. Simulation is essential to understand these trade-offs, but it relies on consistent, interoperable data—something TIC4.0 enables through standardized models and harmonised semantics.

Background: Electrification of Container Terminals

From Manual to Smart: The Evolution of Terminal Equipment

The growing adoption of eCHE—such as electric terminal trucks and AGVs—is reshaping terminal operations. Moving from diesel to electric fleets is not only about reducing emissions: it requires rethinking how activities are planned, coordinated, and monitored. Charging management, dynamic routing, and synchronisation with charging points demand adapted workflows and real-time information integration, while energy and grid management become central for maintaining operational continuity.

The main challenge is fragmentation: multiple OEMs, charging solutions, and management systems risk creating technological silos that undermine efficiency and scalability. Without shared data structures and communication rules, each new system adds complexity and integration cost. This is where TIC4.0 plays a critical role, providing a common semantic framework, standardised data models, and unified communication protocols that enable interoperability across vehicles, chargers, and operational platforms—supporting more coordinated, sustainable, and resilient electric terminal operations.

Types of Electric Terminal Equipment

The electrification of container terminals involves a wide range of Battery-Electric Container Handling Equipment (BE-CHE), including vehicles for transport, stacking, and lifting. Insights from ZEPA (2024), PEMA, and port-sustainability literature highlight the main categories of equipment and their role in reducing scope 1 and 2 emissions while improving efficiency. Their successful integration depends on standardized data frameworks such as TIC4.0 to ensure interoperability across diverse systems.

Electric Terminal Tractors (eTTs)

Electric terminal tractors handle most intra-terminal container movements and are well suited to electrification due to their short, repetitive cycles. Powered by high-capacity lithium-ion batteries, they deliver zero emissions and lower operating costs through regenerative braking.

Key points (ZEPA, 2024):

- **Energy use**: 2.6–3 kWh per move; ~2,600 MWh/year per unit . Compatible with plug-in, fast charging, or battery-swap systems.
- **Operational benefits:** Lower noise and vibration, plus real-time telemetry for optimization.
- **Market outlook:** ZEPA projects 3,500–5,400 units for its members (2025–2035), and 23,000–36,000 globally.

Charging-schedule alignment remains a challenge, mitigated through TIC4.0 standard messages for battery, job, and grid data.

Electric Straddle Carriers

BE-straddle carriers replace diesel engines with battery systems for lifting and stacking in dense yards.

Key points (ZEPA, 2024):

- **Energy use:** ~6.2 kWh per move; ~6,200 MWh/year per unit.
- **Sustainability:** Eliminating diesel can avoid 30–36 Mt CO_2 globally by 2035.
- **Market outlook:** 400–700 units for ZEPA operators; 2,700–4,700 globally.

With higher upfront costs but TCO parity expected by 2025, their integration requires coordinated data exchange—supported by TIC4.0 standards.

Electric Lift Trucks and Cranes

This category includes top loaders, reach stackers, empty-container handlers, and automated stacking cranes.

Key points (ZEPA, 2024):

- Energy use: ~4.4 kWh per move; ~4,400 MWh/year per unit. Supports hybrid charging (e.g., pantographs or depot systems).
- Environmental gains: Reduced noise and emissions; sensor data enables predictive maintenance.
- Market outlook: ZEPA forecasts 400–800 units by 2035, or 2,700–5,300 globally.

Despite strong sustainability benefits, fragmented OEM systems risk creating data silos, which TIC4.0 addresses through unified semantic and interoperability standards.

Broader Ecosystem: Charging Infrastructure and Interdependencies

BE-CHE requires substantial infrastructure, with ZEPA operators expecting 1,300–2,100 chargers by 2035—mainly 350–500 kW units plus some fast chargers. Globally, this may total 8,700–14,000 chargers, creating interdependencies that require real-time data to avoid bottlenecks (ZEPA, 2024).

The diversity of electric terminal equipment underscores the complexity of port electrification, with ZEPA fleets alone projected to require 800–1,200 GWh annually by 2035. Overcoming interoperability challenges is essential, and TIC4.0 provides the shared standards needed to synchronize equipment, optimize charging, and support a more sustainable, autonomous port ecosystem.

3. Key Challenges and Constraints

Introducing BE-CHE brings benefits but also challenges in infrastructure, charging, logistics, and maintenance. Battery integration in RTGs, straddle carriers, and AGVs requires careful planning of charging and grid interaction. TIC4.0 supports this through real-time data on infrastructure, energy demand, and fleet coordination, helping reduce downtime and improve efficiency.

Infrastructure, Charging & Logistics

Charging and Logistics Integration

Terminal charging must align with fast logistics. PEMA notes that capturing regenerative energy can cut consumption by 73%. While stationary and inductive methods minimize interruptions, the challenge lies in synchronizing charging with handling cycles. TIC4.0 standards enable predictive coordination using SOC and weather data. Crucially, poor charging regimes strain the grid, and maintaining unnecessarily high SOC levels reduces equipment turnover and productivity.

Infrastructure and Fleet Usage

Terminal infrastructure must support battery energy and cooling needs, with capacity choices balancing genset size and operating patterns. Modular batteries enable retrofitting straddle carriers and AGVs, while shallow depth of discharge extends lifespan for intensive workflows. Conductor rails and cable-reeling systems supply grid power to E-RTGs, boosting efficiency. TIC4.0 provides standardized data for monitoring usage, regeneration, and infrastructure health.

Availability for Charging

Charging availability depends on infrastructure like conductor rails, cable reels, and inductive loops. While BMS and TIC4.0 standards optimize scheduling using real-time data to navigate grid constraints, trade-offs remain. Specifically, maintaining consistently high SOC levels reduces flexibility during peak windows, leading to cumulative throughput losses.

Regulations

Regulations are accelerating electrification: UL1642 covers lithium-ion safety, the EU Battery Regulation 2023/1542 mandates life-cycle management and standardization, and UN 38.3 guides transport and installation. Surplus renewable energy lowers charging costs, and batteries reduce operating expenses despite higher upfront investment. TIC4.0 supports compliance by standardizing data for emissions reporting and grid interaction.

Operations, Planning & Maintenance

Electrification changes terminal planning and maintenance, replacing diesel models with battery systems that enable efficiency and predictive management. PEMA notes that batteries in RTGs and AGVs reduce maintenance thanks to fewer mechanical parts and regenerative energy. TIC4.0 supports this shift with a unified data framework for planning, repairs, and workforce adaptation.

Maintenance & Repair (Changes at the level of tools and infrastructures)

Maintenance shifts to electrical and thermal management for largely maintenance-free Li-ion batteries (PEMA). Diagnostics require specialized tools, such as thermal imaging, while infrastructure needs cooling and modular designs for quick swaps. The BMS isolates failures (e.g., overvoltage). Furthermore, TIC4.0 integrates standardized fault data with the Terminal Operating System (TOS), enabling automated alerts and significantly reducing repair times.

Impacts on Planning (Operations and Maintenance)

Battery adoption adds SOC, cycle life, and regenerative energy variables to terminal planning. Hybrids optimize genset use, while fully electric equipment requires scheduling during non-peak hours. Maintenance shifts to condition-based models using DOD/temperature data. Batteries enable energy buffering for operational flexibility, supported by TIC4.0 for real-time data and grid forecasting. Strategic choices in sizing, charger distribution, and charging policies directly impact CAPEX, weight, and peak electrical consumption.

Impact on the Workforce

The shift to batteries requires upskilling in high-voltage safety, BMS operation, and thermal management. Staff must understand chemistries like NCM and standards such as UL1642, with training focused on diagnostics and safe handling. Roles become more data-oriented, and TIC4.0 helps by providing standardized, user-friendly data interfaces that support reskilling.

Battery Health, Reliability & Monitoring

Battery health is critical for reliable port operations, with monitoring systems needed to manage degradation and maintain continuity..PEMA highlights how factors like environment and usage affect lithium-ion longevity in RTGs and AGVs. TIC4.0's data protocols strengthen monitoring and prediction, improving overall battery management.

Reliability (Depending on weather conditions)

Battery reliability in ports is challenged by humidity, salt, and temperature extremes, with heat accelerating degradation and cold reducing discharge performance. Cooling systems, sealed enclosures, and BMS help maintain stability, while weather also affects regenerative energy and cycle life. TIC4.0 improves reliability by standardizing sensor data for real-time adjustments to environmental conditions.

Health Degradation and Health Status

Degradation appears as capacity fade driven by DOD, SOC, temperature, and C-rate. PEMA notes that deep DOD sharply reduces cycle life, while high SOC and heat accelerate aging. SOH remains difficult to measure, relying on indirect signals like voltage and impedance, and is worsened by overcharging or high C-rates. TIC4.0 improves SOH estimation by standardizing multi-factor data models for more accurate, proactive health management.

Difficulty in Estimating Battery Health

Estimating SOH is difficult due to nonlinear aging, limited sensors, and the effects of calendar aging—worsened by high SOC. Telematics on cycles, temperature, and usage can improve accuracy by 20–30%, but data silos hinder this. By unifying these sources, TIC4.0 enables interoperable, multi-modal data models that turn rough estimates into more reliable insights for maintenance and optimization.

4. Standardization landscape

Review of Standardisation Initiatives

International standardisation efforts led by ISO and IEC are shaping the regulatory framework for EV charging, automated coupling, and industrial battery safety in eCHE and port-side energy systems.

IEC SyC SET coordinates IEC–ISO work on electrified transport, covering interoperability, safety, charging infrastructure, and system architecture.

IEC Initiatives

- **IEC TC 69** develops core standards for conductive and inductive EV charging, including energy transfer, operation, and safety.
- **IEC TC 69** WG14 focuses on automated charging via robotic connectors and docking interfaces.
- **IEC SC 23H** defines safe, interoperable plugs and couplers for industrial and EV applications.

ISO Initiatives

- **ISO TC 22 WG31** standardises vehicle telematics, diagnostics, and V2I communication for smart charging.
- **ISO TC 22 WG37** defines EV performance, interoperability, and safety requirements.
- **ISO TC 204 WG14** addresses ITS, V2X, and cooperative systems relevant to autonomous port equipment.
- **ISO TC 299** establishes safety and performance norms for robotics, including robotic charging.

Key Published and Upcoming Standards

- **ISO TS 5474-5 (2024)** — Requirements for automated conductive charging without human intervention.
- **ISO 12768-1 (2025)** — Architecture and testing for automated docking systems.
- **IEC TS 61851-27 / -26 / -28 (2025)** — Technical and communication requirements for automatic EV couplers and docking.
- **IEC 62196 / IEC 63379** — Core AC/DC connector standards and next-generation high-power interfaces.

Battery & Energy Storage Standards

- **IEC 62619** — Safety requirements for industrial lithium batteries (venting, thermal protection, abuse tests, BMS).
- **IEC 62620** — Performance testing for traction batteries (capacity, cycle life, thermal stress).
- **IEC 62933** Series — Standards for stationary energy-storage systems used in port charging hubs (safety, performance, environmental impact, grid and renewable integration, cybersecurity).

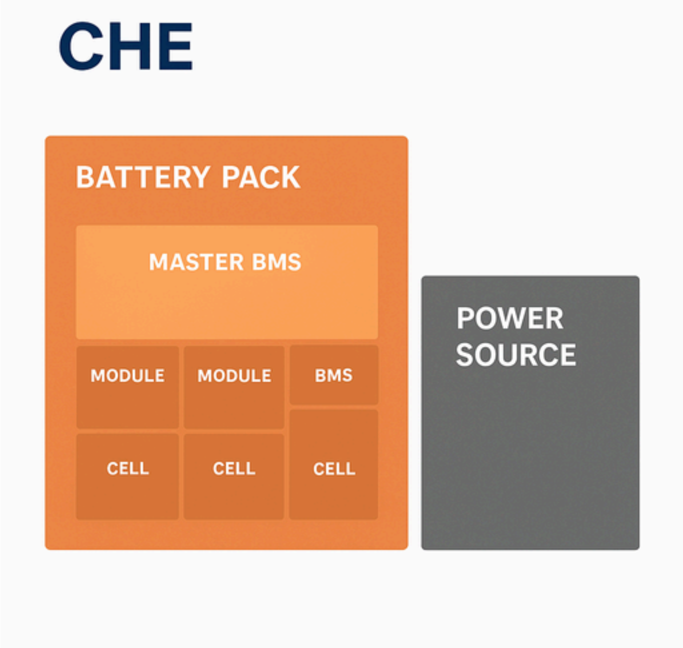
These initiatives collectively provide the foundation for safe, interoperable, and scalable electrification of container-terminal equipment and charging infrastructure.

5. Information Requirements

Effective BE-CHE operation depends on timely, accurate and standardized data. This section outlines the key information for smart EV operations—supporting efficient fleet use, reduced downtime and interoperability—grouped into four themes: Telemetry (real-time data), the CHE Management System (planning), the Charging Management System (CMS) and the Terminal Energy Management System (TEMS) for energy flows and grid interaction under TIC4.0 semantics.

The subsections describe the essential data for each theme based on core use cases such as battery health, charging opportunities, task coordination and energy forecasting.

Figure 1. Hierarchical Structure of the CHE Battery System



CHE Telemetry (IoT) Execution

Telemetry captures real-time data from IoT sensors in eCHE and infrastructure, providing raw, time-sensitive information for monitoring, fault detection, and performance tracking.

As noted in PEMA, it also records regenerative energy from lifting, lowering, and deceleration, enabling battery recovery and reducing overall energy use.

CHE data

Identification data (ID, type, brand, model) ensures asset traceability, while operational parameters—location (logical or GPS/RTLS), power state, and working modes—support availability checks, task allocation and charging-opportunity planning.

Energy data covers consumption, recovery and efficiency to enable predictive charging and coordination with CMS and TEMS. Maintenance data includes health events, warnings and faults for predictive maintenance.

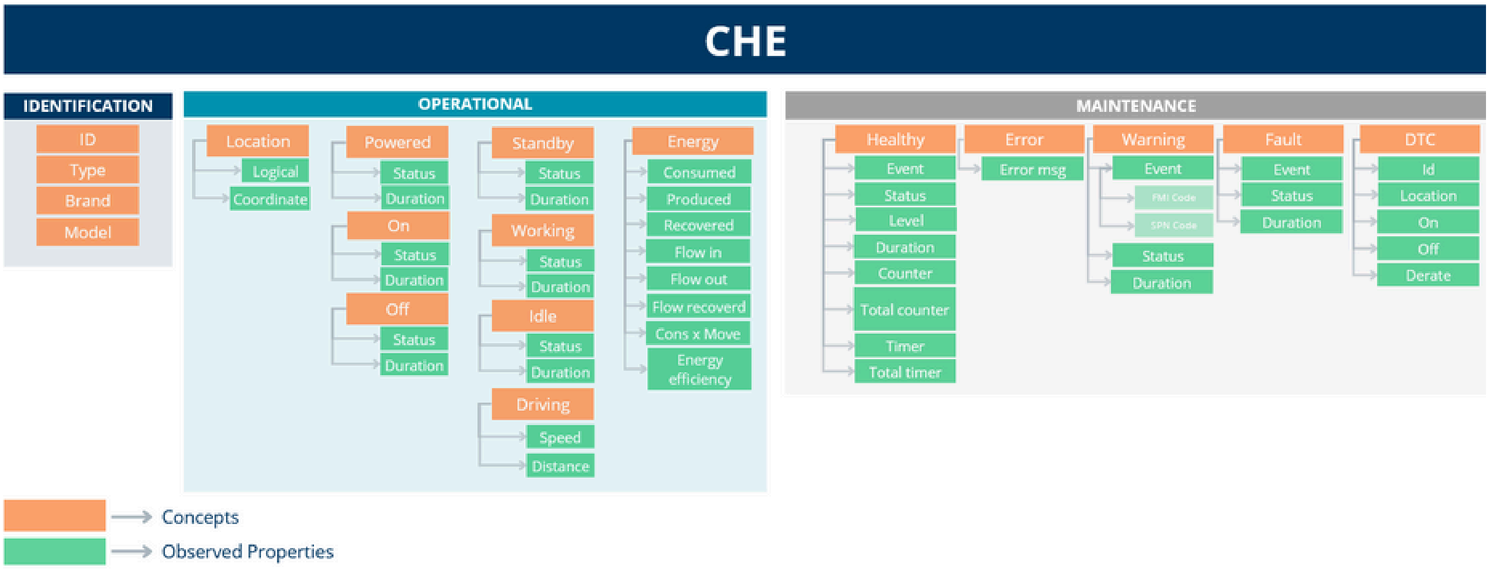
Together, these elements give a unified view of the CHE, combining identification, operations, energy and maintenance within the terminal context.

Power source

In the CHE semantic model, the Power Source focuses solely on the unit supplying energy. It captures targeted data for fleet-level monitoring and optimization.

Identification (ID, type, brand, model) distinguishes each unit in mixed fleets. Operational data includes power states, working/idle conditions, and energy flows—consumed, recovered, and efficiency—supporting performance tracking and charging/refueling planning. Maintenance information (health events, errors, warnings, faults) enables predictive management and lifecycle planning.

Figure 2. Semantic Structure of the CHE Entity



Battery-related data

In this paper, we focus exclusively on lithium-ion battery systems, the dominant technology in industrial and EV applications due to their energy density and lifecycle performance. The architecture assumed is hierarchical: a Master BMS (MBMS) supervises the Battery Pack, aggregates data from modules and cells, and communicates pack-level information. Although multiple BMS units may exist at different levels, a master supervisor always coordinates the pack and can report module- or cell-specific data through unique IDs.

Identification parameters (ID, type, brand, model) ensure traceability, while operational data—power states, working/idle modes, and battery metrics (SOC, SOH, voltage, current, discharge limits)—support monitoring, planning and safe operation. Maintenance information, including health events, warnings, faults and diagnostic codes, enables predictive maintenance and troubleshooting.

This chapter focuses on the Battery Pack level (TIC4.0 “Energy Tank”), as terminal operations rely on aggregated MBMS outputs rather than module-level detail. The Battery Pack provides the most relevant operational and maintenance data for fleet and energy management.

Figure 3. Semantic Structure of the Power Source Entity

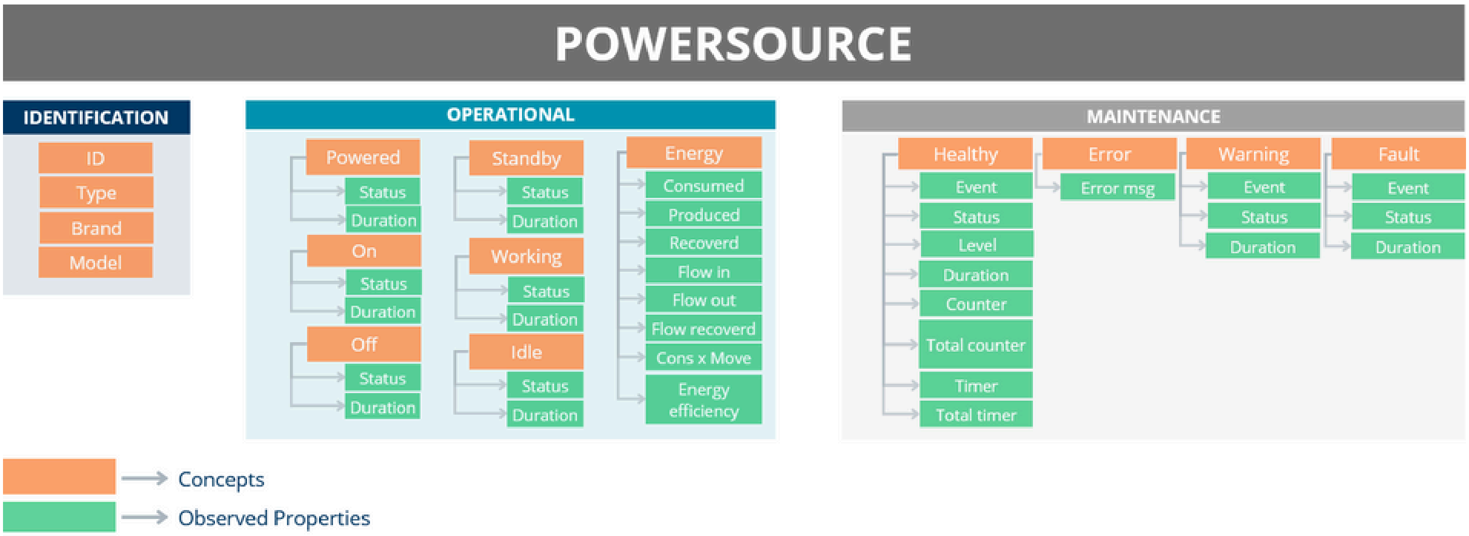
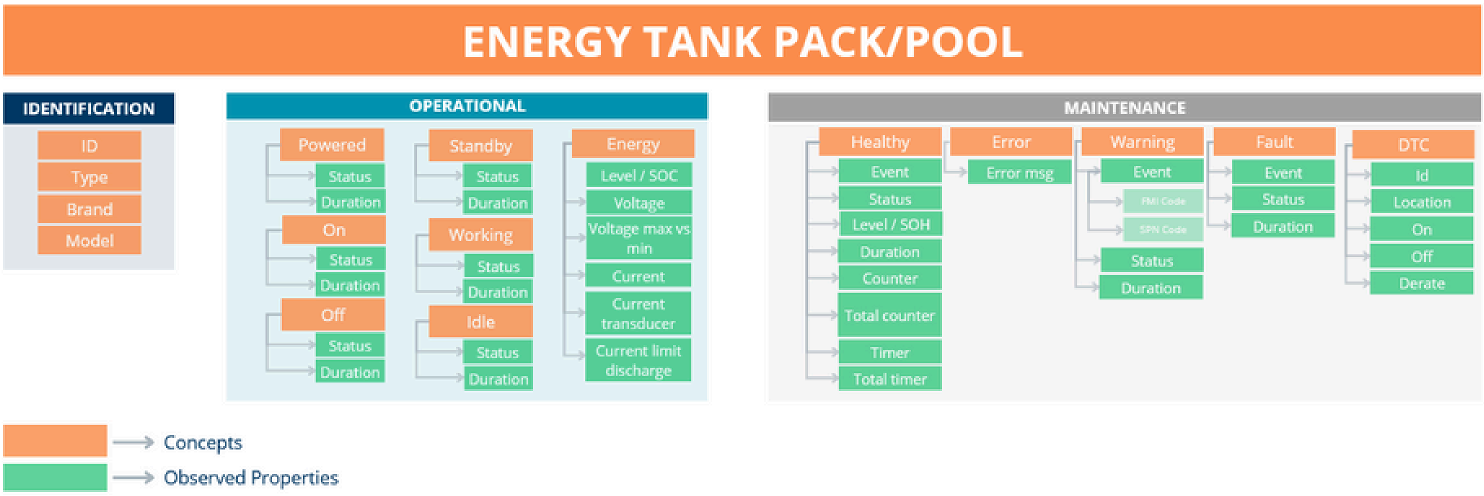


Figure 5. Semantic Structure of the Energy Tank Entity



Clear standardization of BE-CHE data, distinguishing between subjects (CHE) and sub-subjects (Power Source, Battery Pack), is essential for consistency and operational value. A common data language ensures interoperability, while appropriate detail levels keep information actionable for operations and structured for long-term optimization.

Terminal Control System: Energy Consumption

Standardizing BE-CHE data while distinguishing between subjects (e.g., the CHE) and sub-subjects (e.g., Power Source or Battery Pack) is essential for clarity and operational value. Standardization ensures a common language across systems, while differentiation allows each layer to be represented at the right level of detail. This balance enables effective fleet and energy management, supports interoperability, and keeps data both actionable and structured for long-term optimization.

Energy Consumption Profiles

Energy consumption profiles convert sensor data into metrics like kWh per move, shift consumption, and recovered energy. This helps planners quickly see whether a machine has enough energy for its next task, expressing energy as remaining operational capacity—how many moves or jobs can be completed before charging is needed.

Job-Related Coordination

Job orders from the TOS are matched with each CHE's real-time energy status to ensure the machine can complete the assigned task. For example, before dispatching a straddle carrier for a stacking cycle, the system checks predicted energy consumption to avoid mid-operation interruptions. This embeds energy availability into task assignment, keeping operations running smoothly.

Battery and Vehicle Integration

The system considers more than SOC, incorporating battery and vehicle condition into planning. A tractor with high SOH and stable temperatures is preferred for intensive moves, while regenerative-braking data helps assign vehicles to stop-heavy routes. This links operational efficiency to energy intelligence, enabling smarter fleet use.

Fleet-Level Aggregation

Beyond individual vehicles, the Terminal Control System aggregates fleet-wide energy status, showing total demand, expected peaks, and load-balancing needs.

This helps supervisors decide when to rotate equipment, prioritize charging, and prevent bottlenecks, allowing the fleet to operate as a coordinated system rather than isolated units.

Predictive Analytics and Alerts

Operational continuity relies on anticipating issues before they disrupt workflows. The CHE Management System flags anomalies—like unexpected energy use or insufficient charging—so maintenance can act early, preventing interruptions.

Charging Management System (CMS)

The CMS coordinates charging according to operational needs and vehicle availability. Using telemetry and CHE data, it manages and prioritizes charging orders and handles dependencies like battery swaps or fast charging. Its goal is to minimize downtime by aligning charging with dynamic workflows.

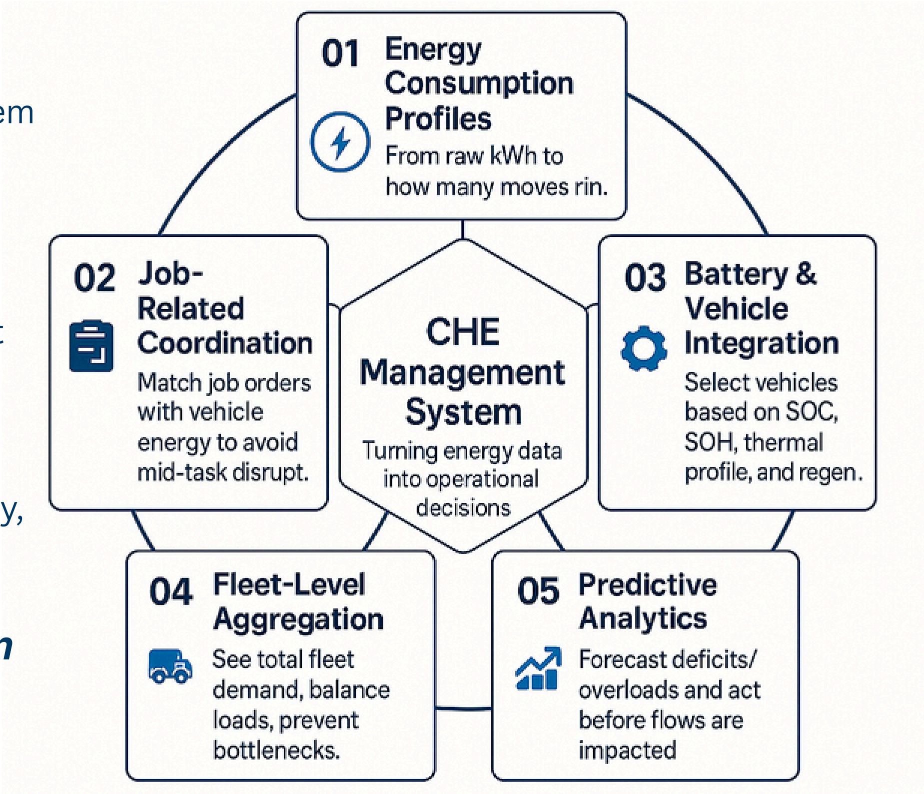
BE-CHE Data

BE-CHE data covers vehicle ID and type, while battery metrics (SOC, SOH, temperature, voltage, current) define the charging profile. Requirements set target energy, connector, power and time window, and location shows charger proximity to avoid extra movements.

Charge Point Data

Charge point data includes ID, type and specs for assignment. Availability states indicate usability, while capacity shows rated and available power. Operational status reports alarms, faults and logs for safe, analysable operation.

Figure 6. Operational Functions Enabled by the CHE Management System



Electrical Grid Data

Grid data defines local capacity and contracted power, setting limits for simultaneous charging. Real-time terminal and sector consumption shows demand patterns, while constraints such as peak limits and regulations shape flexibility. Tariff signals and cost variations help shift charging to lower-cost periods.

TOS Data

TOS data provides work windows, shifts and mission assignments, indicating when each CHE can be paused. Gaps between tasks define real charging opportunities, while prioritization rules determine which vehicle should charge first to keep operations flowing.

Security and Maintenance Data

This includes charging history and anomalies to track performance. Safety alarms flag issues like overheating or disconnections, while predictive maintenance uses sensor data to anticipate failures and plan timely interventions.

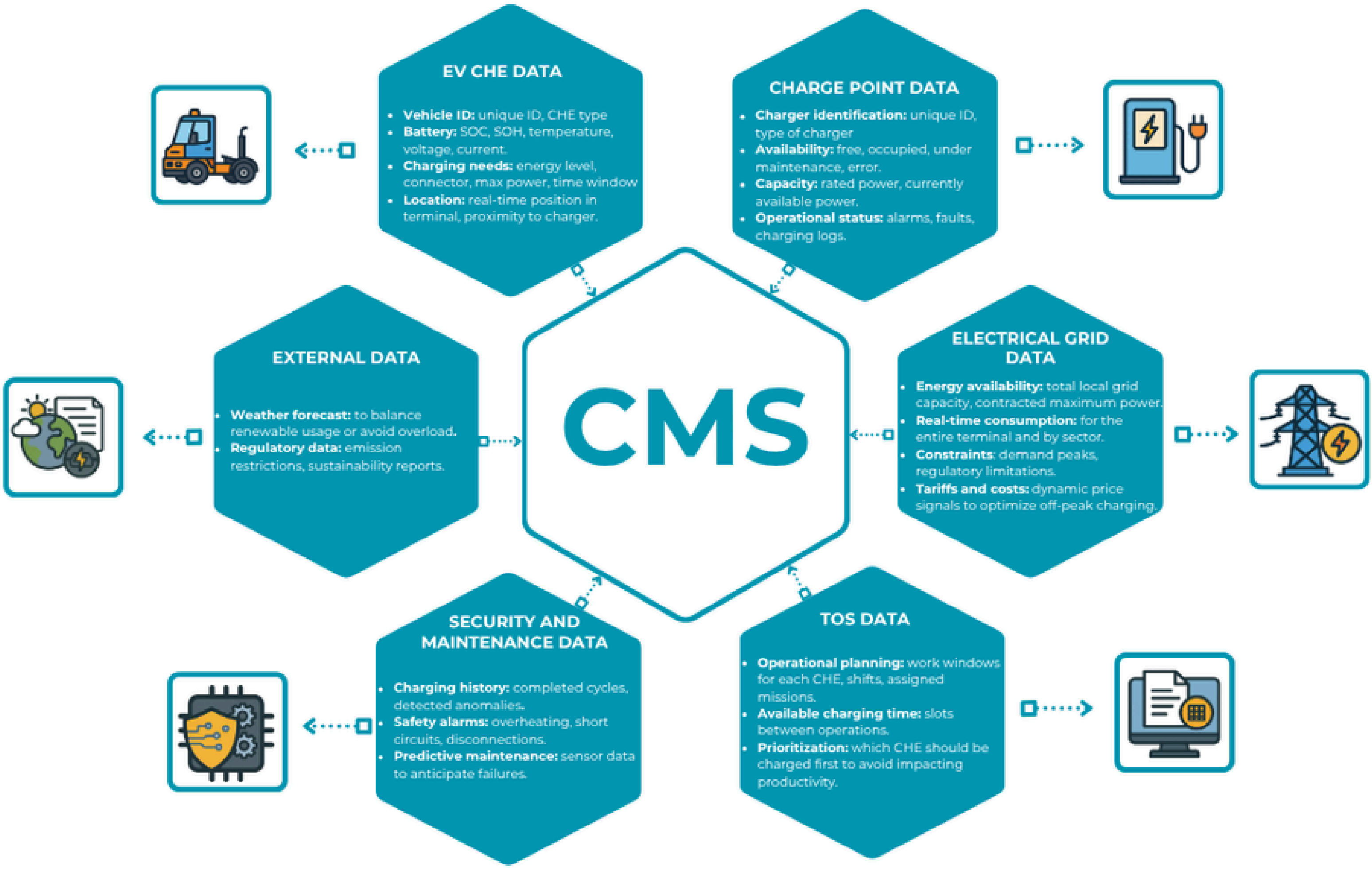
External Data

External inputs include weather forecasts to support renewable integration and avoid overloads. Regulatory data adds constraints like emission limits and reporting needs. Links to EMS or Smart Grid platforms enable coordination with wider port or city energy systems.

Operational Demand

Operational demand captures the terminal’s energy needs based on equipment use, task schedules and throughput plans. Forecasting and monitoring help align supply with operations, avoid peaks and coordinate predictions between operational planning and the energy management system.

Figure 7. CMS Data Ecosystem



EV CHE DATA

- **Vehicle ID:** unique ID, CHE type
- **Battery:** SOC, SOH, temperature, voltage, current.
- **Charging needs:** energy level, connector, max power, time window
- **Location:** real-time position in terminal, proximity to charger.

CHARGE POINT DATA

- **Charger identification:** unique ID, type of charger
- **Availability:** free, occupied, under maintenance, error.
- **Capacity:** rated power, currently available power.
- **Operational status:** alarms, faults, charging logs.

EXTERNAL DATA

- **Weather forecast:** to balance renewable usage or avoid overload.
- **Regulatory data:** emission restrictions, sustainability reports.

ELECTRICAL GRID DATA

- **Energy availability:** total local grid capacity, contracted maximum power.
- **Real-time consumption:** for the entire terminal and by sector.
- **Constraints**: demand peaks, regulatory limitations.
- **Tariffs and costs:** dynamic price signals to optimize off-peak charging.

SECURITY AND MAINTENANCE DATA

- **Charging history:** completed cycles, detected anomalies.
- **Safety alarms:** overheating, short circuits, disconnections.
- **Predictive maintenance:** sensor data to anticipate failures.

TOS DATA

- **Operational planning:** work windows for each CHE, shifts, assigned missions.
- **Available charging time:** slots between operations.
- **Prioritization:** which CHE should be charged first to avoid impacting productivity.

Terminal Energy Management System (TEMS)

Electrified terminals rely on advanced energy management to balance power supply and demand in real time. Their systems span the external grid, internal controls and major electrical loads. Reliable, efficient operation requires information exchange across several domains, outlined below.

Electrical Grid Capacity and Power Monitoring

This covers the external grid’s capacity, import limits, current draw and power quality. The TEMS must stay within these constraints, preventing overloads and reacting to grid events or maintenance alerts.

Availability of Internal Energy Resources (Renewables & Storage)

Covers on-site renewables and storage.

By managing solar, wind and batteries, the TEMS balances self-supply and grid use, charging during surplus and discharging during peaks.

Electricity Market Conditions

Covers price signals and tariffs that guide energy use. The TEMS adjusts operations to market prices and demand-response programs to cut costs or generate revenue.

Critical Events and Alarms

Covers fault and safety alerts in power systems. The TEMS must detect issues and respond quickly to maintain continuity and safety.

Grid Operator Signals

External utility signals guide terminal behavior. The TEMS responds to load-reduction requests, curtailments and compliance requirements.

Environmental and Weather Conditions

Environmental data shows how conditions affect energy supply and demand. Weather impacts renewables and cooling/heating needs, while extreme events require preventive action.

A terminal energy management system integrates diverse data to control and optimize energy flows. By managing demand, grid capacity, local generation, market signals, charging, alarms and weather, it keeps operations reliable, economical and sustainable —enabling smarter, cleaner terminals.

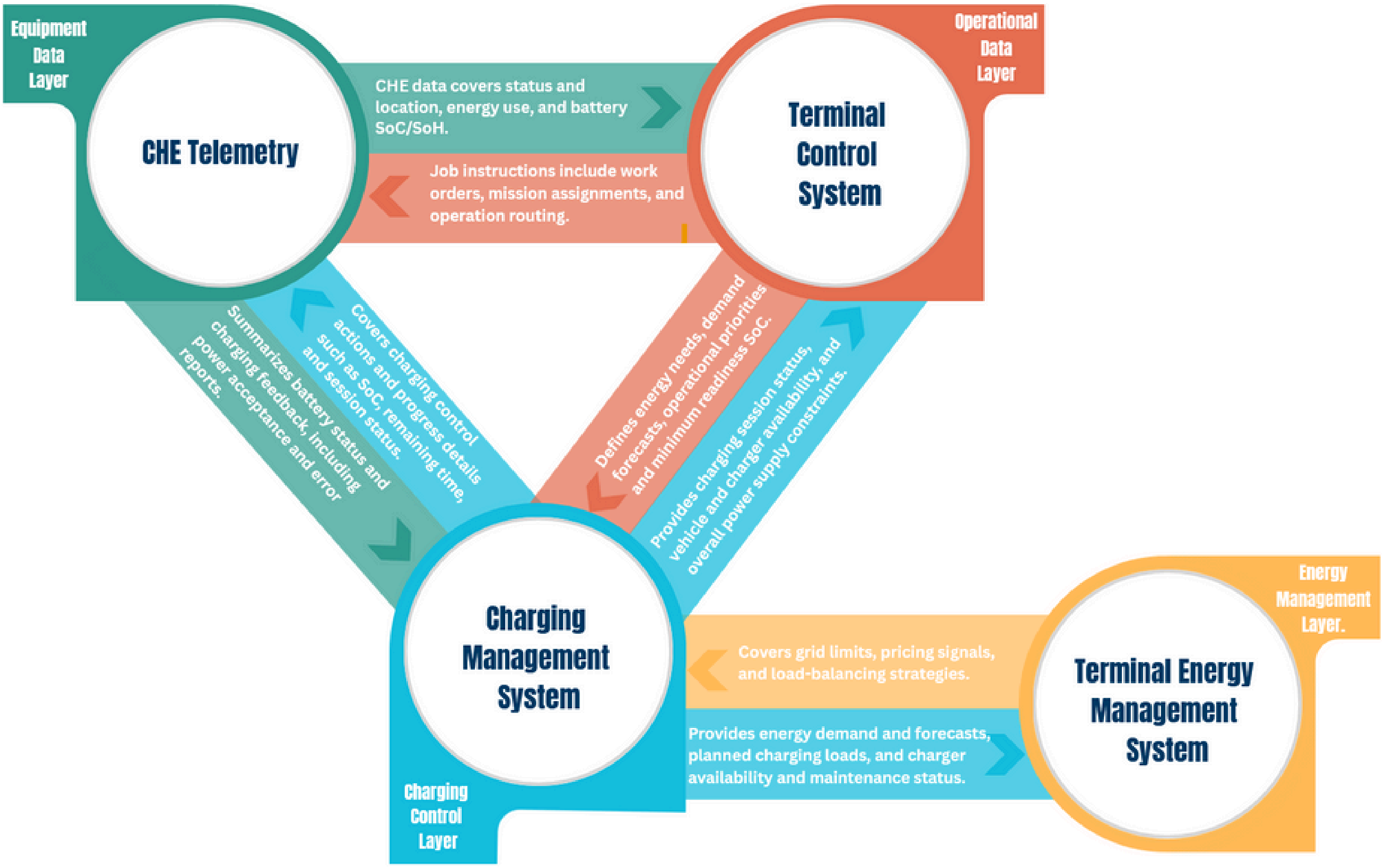
6. System Integration and Communication

This section defines how information flows across the functional layers that enable BE-CHE operations in a terminal: Equipment Data, Operational Data, Charging Control, and Energy Management. The focus is deliberately information-centric: we describe what information moves where and for what purpose, rather than prescribing which software product or module must perform each task. Each terminal may allocate decision-making and execution responsibilities to different systems according to its own constraints, maturity, and integration strategy.

The layers used here represent functions that must be performed—capturing field data from BE-CHEs, orchestrating operations, executing and supervising charging, and balancing energy supply and demand—without implying a rigid system architecture. By clarifying the types of information exchanged between layers and the role each layer plays in using that information (e.g., monitoring fleet condition, scheduling missions, coordinating charging, and enforcing grid or cost constraints), terminals can design interoperable solutions that remain technology-agnostic and future-proof.

The diagram that follows summarises these bidirectional exchanges and anchors the subsequent interface descriptions.

Figure 8. System Interfaces



CHE data covers status and location, energy use, and battery SoC/SoH.

Job instructions include work orders, mission assignments, and operation routing.

Covers charging control actions and progress details such as SoC, remaining time, and session status.

Summarizes battery status and charging feedback, including power acceptance and error reports.

Defines energy needs, demand forecasts, operational priorities and minimum readiness SoC.

Provides charging session status, vehicle and charger availability, and overall power supply constraints.

Covers grid limits, pricing signals, and load-balancing strategies.

Provides energy demand and forecasts, planned charging loads, and charger availability and maintenance status.

CHE ↔ Terminal Control System

The Equipment Data Layer and the Operational Data Layer interact to ensure that planning and execution reflect the real-time condition of the electric fleet. Telemetry provides the Terminal Control System with performance, location, and energy information, enabling forecasts of availability and charging or maintenance needs.

Conversely, the operational layer sends task-level instructions to the CHE—routing, priorities, and timing—ensuring coordinated control while the equipment layer provides the real operational constraints.

Information from CHE to Terminal Control System

- Operational Status: active, idle, maintenance.
- Energy Condition: SOC, SOH, consumption.
- Performance Data: utilisation, cycle times, efficiency.
- Location & Movement: position and routing.
- Diagnostic Data: faults or anomalies.

This information allows dynamic assessment of fleet readiness and supports schedule adjustments based on equipment condition.

Information from Terminal Control System to CHE

- Tasks & Instructions: routes, mission type, start/end points.
- Scheduling: start/stop orders, idle times, charging windows.
- Operational Constraints: operating mode and safety or speed limits.
-

These exchanges ensure that each CHE performs tasks according to operational priorities and its current energy and condition limits.

Terminal Control System ↔ CMS

Telemetry enables operational awareness, allowing the Operational Data Layer and the Charging Control Layer to align charging with fleet status and mission plans. Once vehicle availability is known, this information is passed to the charging function to ensure energy supply supports operations.

Whether standalone or integrated, the charging function converts operational demand into charging actions. The Terminal Control System signals which vehicles need energy and when, and the CMS fulfils this within infrastructure limits to keep operations aligned.

Information from Terminal Control System to CMS

- Charging Demand: vehicles requiring energy, estimated needs, urgency.
- Operational Priority: criticality based on upcoming missions.
- Availability Windows: idle periods suitable for charging.
- Location & Resources: vehicle position and nearby chargers.

This allows efficient charging schedules that prioritise vehicles by operational impact.

Information from CMS to Terminal Control System

- Charging Status: session progress, SOC evolution, ETA for completion.
- Vehicle Readiness: expected availability for operations.
- Infrastructure Status: charger availability and condition.
- Energy Supply Condition: grid or capacity constraints.

This feedback maintains visibility and enables adjustments to prevent energy limits from affecting performance.

CMS ⇔ CHE

Once the vehicle connects to a charger, a direct link between the Charging Control Layer and the Equipment Data Layer enables real-time control of the charging session. The CMS handles authorisation, power allocation, and termination, while the CHE reports battery and system status throughout the process.

In terminals without a dedicated CMS, these functions may be integrated into other systems or handled by smart chargers. Regardless of implementation, a charging control function must coordinate and monitor the physical charging process once the vehicle is connected.

Information from CMS to CHE

- Session Control: start, stop, or modulate charging.
- Power & Profile: power settings, rate, phase transitions.
- Progress & Authorisation: session confirmation and safety checks.
- Safety Signals: shutdown or stop commands if irregularities appear.

This ensures charging proceeds safely and according to defined parameters.

Information from CHE to CMS

- Battery Condition: SOC, SOH, voltage, current, temperature.
- Connection Data: charger link confirmation, vehicle ID.
- Charging Feedback: power acceptance and deviations.
- Fault Data: alerts, warnings, safety triggers.

This feedback enables continuous adjustment of charging parameters and full process visibility. Once charging ends, the CMS updates the operational layer to confirm readiness and free the charging point.

CMS ⇔ TEMS

The interaction between the Charging Control Layer and the Energy Management Layer links real-time charging operations with the terminal’s wider energy context. While the CMS manages each vehicle’s charging session, the TEMS oversees supply availability, capacity, and cost, ensuring charging aligns with grid limits and energy-efficiency goals.

In some terminals, a standalone TEMS may not exist; its functions may be integrated into the CMS, an EMS, or another supervisory system. In all cases, energy management must keep charging activities aligned with real-time supply conditions and strategic objectives.

Information from CMS to TEMS

- Energy Demand: aggregated and forecasted load, expected peaks.
- Charging Schedule: planned sessions and consumption periods.
- Infrastructure Status: charger availability or faults.
- Events & Alerts: deviations between planned and actual demand.

This helps the TEMS anticipate power needs and ensure the infrastructure can support charging operations.

Information from TEMS to CMS

- Energy Supply: available capacity, renewable input, constraints.
- Tariff Signals: dynamic pricing and optimal charging periods.
- Load Management: instructions to shift or balance charging.
- Grid Notifications: reduced capacity or demand-response events.

This feedback allows the CMS to adapt charging schedules and profiles to maintain operational continuity while optimising energy use and costs.

7. Next Steps

The next stage of this work focuses on operationalizing the conceptual framework presented in this paper by identifying and defining the data elements required to support Smart EV operations. The goal is to create a coherent semantic layer that enables the generation of the information previously described. A preliminary list of candidate data elements is available in the full working document at the provided **link**; it is not included here to avoid exceeding the length of this publication.

Our approach will progress through four layers—CHE, TCS, CMS, and TEMS—ensuring that each phase builds on validated requirements before advancing. The data defined in each phase will be incorporated directly into the TIC4.0 data model upon completion, allowing iterative consolidation and early industry alignment.

Phase 1: CHE Data Definition

We will identify the essential data needed to represent equipment operation, energy behaviour, and condition, and integrate the resulting definitions into the data model at the end of the phase.

Phase 2: TCS Data Definition

This phase will specify the information required for mission coordination, equipment allocation, and energy-aware planning. Once completed, these definitions will form the second module in the data model.

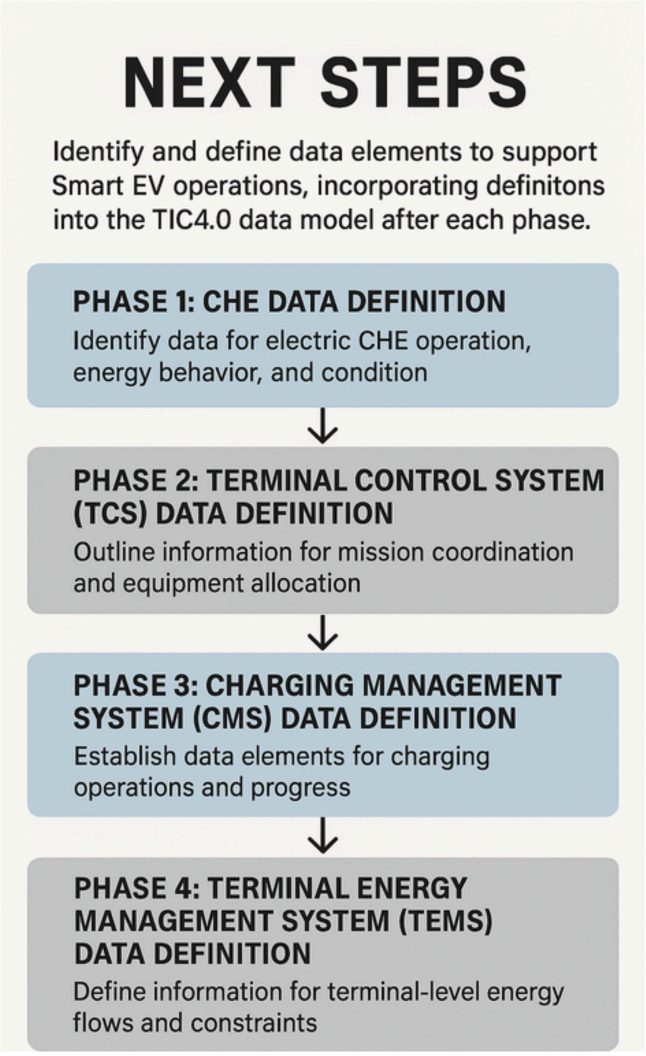
Phase 3: CMS Data Definition

We will define the data needed to manage charging sessions, charger availability, charging profiles, and power allocation. The CMS layer will be integrated into the data model immediately after validation.

Phase 4: TEMS Data Definition

Finally, we will define the data necessary to represent terminal-level energy flows, capacity constraints, and load-balancing strategies. This phase will complete the integration of the Smart EV semantics into the data model.

This phased and iterative methodology ensures semantic consistency across layers and enables the specification to evolve in a controlled and transparent manner, supporting validation and future deployment across the industry.



NEXT STEPS

Identify and define data elements to support Smart EV operations, incorporating definitons into the TIC4.0 data model after each phase.

PHASE 1: CHE DATA DEFINITION
Identify data for electric CHE operation, energy behavior, and condition

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PHASE 2: TERMINAL CONTROL SYSTEM (TCS) DATA DEFINITION
Outline information for mission coordination and equipment allocation

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PHASE 3: CHARGING MANAGEMENT SYSTEM (CMS) DATA DEFINITION
Establish data elements for charging operations and progress

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PHASE 4: TERMINAL ENERGY MANAGEMENT SYSTEM (TEMS) DATA DEFINITION
Define information for terminal-level energy flows and constraints

7. Conclusions

The transition toward eCHE operations represents a defining step in the digital and sustainable evolution of container terminals. As this paper has shown, electrifying CHE not only reduces emissions but also reshapes operational dynamics, energy flows, and decision-making processes across the terminal ecosystem. Understanding these interactions—between equipment, control systems, charging infrastructures, and energy management layers—is essential for enabling efficient, safe, and economically viable EV deployment at scale.

The analysis presented highlights the need for a unified semantic architecture capable of supporting real-time telemetry, energy-aware dispatching, coordinated charging, and terminal-wide energy optimisation. Existing industry systems are not yet fully equipped to handle this level of integration, particularly in terms of data structures, interoperability, and cross-layer information flows. By mapping the relationships between CHE, the Terminal Control System, the Charging Management System, and the Terminal Energy Management System, this paper provides a conceptual baseline that clarifies the functional and informational requirements for future EV-ready operations.

Moving forward, the definition of a structured, standards-aligned data model will be essential to operationalizing Smart EV concepts. The phased methodology proposed—starting with CHE semantics and progressing through TCS, CMS, and TEMS—will create an interoperable foundation capable of supporting both current needs and future innovations such as AI-driven optimisation, predictive maintenance, and energy flexibility services. As these definitions are incorporated into the TIC4.0 data model, the industry will gain a shared, future-proof framework to accelerate EV adoption and ensure that the next generation of port operations is both digitally advanced and environmentally responsible.

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