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D5 Mathematical Tool Kit

This document is the POTENT-X D5 deliverable. The deliverable constitutes a modelling tool kit that simulates the grid impacts of electrification in ports and proposes standardized evaluation methodologies.

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List of Abbreviations

ABM	Agent-Based Model
AFIR	Alternative Fuels Infrastructure Regulation
CETP	Clean Energy Transition Partnership
CTH	Chalmers University of Technology
DINS	Danube Inland Navigation System
DTU	Technical University of Denmark
EMS	Energy Management System
EMSA	European Maritime Safety Agency
GIS	Geographic Information System
GHG	Greenhouse Gas
IMO	International Maritime Organization
OPS	Onshore Power Supply
PtX	Power-to-X
USEV	University of Seville



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Executive Summary

The deliverable (D5) presents the mathematical toolkit that simulates the grid impacts of electrification in ports and proposes standardized methodologies for their evaluation. Electrification of ports includes developing power supplies for ships, port equipment, and vehicles, together with broader infrastructure and grid capacity to support the adoption of electric transport and the production of e-fuels in ports.

The deliverable supports the objectives of Task 2.3, advancing the reliable grid Impact assessment of Zero-Emission Refueling Infrastructure. The objectives include:

- Developing in-depth case studies to understand the real-world implications of grid impacts caused by electrified ports.
- Analyzing how infrastructure and fueling needs for zero-emission transport at European ports will affect the distribution grids.
- Formulating standardized methodologies to evaluate the grid impacts of electrified transport and e-fuel production at European ports.

The report demonstrates the following significant outcomes.

Despite the pivotal role of port electrification in decarbonizing maritime logistics, there is little consensus on what “port electrification” entails, which hinders port infrastructure planning. The deliverable develops a novel three-phase typology of port electrification, enabling consistent evaluation of decarbonization pathways in integrated port systems by providing clearer, more precise, and unambiguous formulations.

Selecting the right methodological foundation is crucial to developing the mathematical toolkit for port electrification assessment, as it defines the boundaries of its future potential. The deliverable provides a detailed assessment of existing approaches to modeling sustainable port infrastructure and shipping and demonstrates the significant potential of agent-based simulation models for real-world decision-making in the changing maritime sector. It also shows that agent-based models are trusted by maritime stakeholders.

The deliverable develops a framework to evaluate optimal charger locations for inland ports and the corresponding power supply demands, accounting for variables such as potential new charging stations. This approach aims to minimize investment costs while meeting the physical constraints of the transport and grid systems. The agent-based framework for assessing the inland electric ship charging infrastructure is applied to the in-depth case study of the Danube Inland Navigation System and demonstrates that infrastructure configuration is a primary determinant of the feasibility of shipping electrification. The framework provides significant



decision support for the multi-objective assessment of the performance of the battery-powered waterborne transport system, with a focus on infrastructure.

In addition to measuring total electricity demand, the deliverable presents a tool for grid-ready shore power planning using real-world port-call data. The tool is demonstrated for power load characterization at the Port of Valencia, where it constructs a high-resolution electrical load profile and characterizes operational shore power demand by vessel category, time, and berth zone, thereby identifying the main drivers of energy use, peak load, ramping stress, and future grid-planning requirements.



1. Introduction

Waterborne transport plays a major role in global freight transportation and, consequently, carries significant responsibility for reducing greenhouse gas (GHG) emissions. International organizations, including the International Maritime Organization and the World Association for Waterborne Transport Infrastructure, have emphasized the importance of shipping decarbonization and the transition toward more sustainable waterborne transport systems. Ports, as key nodes in waterborne transport systems, are also key hubs and primary enablers of shipping decarbonization. Electrification of ports is essential to successfully support decarbonization efforts in the maritime sector.

These developments create a demand for effective, standardized methodologies and decision-support tools for the design and assessment of electrification in ports, including the required infrastructure, operational strategies, and specific considerations for sustainable waterborne transport. One promising direction is the development of simulation models, ranging from high-level models for strategic planning and policymaking to detailed digital twins that represent complex operational behaviors. Another opportunity is to leverage real-world big data – a significant source of information on the practical implications of grid impacts caused by electrified ports.

The report presents deliverable 5 (D5) of the POTENT-X project – a modeling toolkit that simulates the grid impacts of electrification in ports and proposes corresponding standardized evaluation methodologies. It demonstrates the theoretical foundations, functionality, and benefits of various developed tools, integrated into a coherent decision-support framework. The sections of the report are organized to present different modeling tools of the kit in order, following the stages of their application.

Section 2 presents a conceptual approach to classifying port electrification into three phases based on the end use of electricity and the location of related activities within the port system. The proposed typology includes (i) electrification of vessels and shore-to-ship power connections, (ii) electrification of port-side operational equipment and vehicles, and (iii) supply of electricity-based fuels through Power-to-X processes. The analysis demonstrates that port electrification should be considered as a context-dependent system transformation shaped by regulatory requirements, infrastructure readiness, and operational characteristics of ports. The proposed approach provides a structured basis for port infrastructure planning and for a more consistent assessment of decarbonization pathways in integrated port systems.

Section 3 supports the selection of the methodology for developing the simulation-based mathematical toolkit. The section includes a detailed assessment of existing approaches to



modeling sustainable port infrastructure and shipping systems and identifies substantial potential for applying agent-based simulation models to decision-making in the evolving maritime sector. The analysis indicates that agent-based models are increasingly recognized as a relevant tool for assessing and improving complex waterborne transport systems operating under high uncertainty. The results also indicate considerable stakeholder trust in agent-based modeling approaches and a willingness to support their further development by allocating time and resources.

Section 4 demonstrates the developed agent-based approach for assessing optimal charger locations in inland ports and their associated power supply requirements. The approach accounts for factors such as the potential deployment of new charging infrastructure and aims to support cost-efficient infrastructure planning while respecting the physical and operational constraints of transport and charging systems. The developed methodology enables the evaluation of inland electric vessel charging infrastructure and its impact on the performance of the waterborne transport system from the perspectives of infrastructural feasibility and cost, transport efficiency, and energy efficiency. The applicability of the approach is demonstrated through an in-depth case study of the Danube Inland Navigation System (DINS), a strategically important European transport corridor connecting ten countries along the longest river in the European Union.

Section 5 presents a tool developed to support grid-ready shore power planning based on real-world port-call data. The tool enables the construction of high-resolution electrical load profiles for ports and supports the assessment of operational shore power demand under different traffic and infrastructure conditions. Its applicability is demonstrated through a case study of the Port of Valencia, where the approach is used to characterize shore power demand across vessel categories, temporal patterns, and berth zones within the port area. The results demonstrate the relevance of data-driven approaches for supporting port electrification planning and the integration of shore-side electricity supply into existing port and energy infrastructure.

2. The definition of Port Electrification

2.1. Background and motivation

Ports are increasingly becoming central actors in the energy transition of the maritime sector. Besides their traditional logistical role, ports are also major energy consumers and key interfaces among shipping, industrial activities, electricity systems, and fuel supply chains. Growing pressure to reduce greenhouse gas (GHG) emissions from shipping and port operations has accelerated the deployment of electrification technologies in ports worldwide.



International and regional policy initiatives, including the International Maritime Organization (IMO) greenhouse gas reduction strategy, FuelEU Maritime, and the Alternative Fuels Infrastructure Regulation (AFIR), have further strengthened the role of ports in supporting maritime decarbonization.

At the same time, the concept of “port electrification” is used inconsistently across academic, industrial, and policy literature. Different studies apply the term to substantially different technologies and system boundaries. In some cases, port electrification refers only to shore power systems for vessels at berth. Other studies also include individual and combined considerations of electrified terminal equipment, operational vehicles, renewable energy integration, battery storage systems, microgrids, and electricity-based fuel production, such as hydrogen and e-fuels.

This conceptual inconsistency creates practical challenges for infrastructure planning and policy analysis. Different electrification pathways result in fundamentally different electricity demand profiles, infrastructure requirements, and operational impacts. For example, the electrical load associated with shore power for cruise vessels differs significantly from the requirements of electrified container-terminal equipment or industrial-scale hydrogen production. These differences affect peak electricity demand, grid reinforcement needs, infrastructure costs, and investment timelines.

The present Section of the report is based on the paper published within the POTENT-X project by Li et al. (2026). It addressed the need for a clearer and more systematic understanding of port electrification from the perspective of infrastructure planning and integrated decarbonization strategies.

2.2. A unified typology of port electrification

The work developed a structured typology of port electrification based on electricity use and the location of electrified activities within port systems. Figure 1 illustrates how the proposed approach organizes port electrification into three interconnected phases:

1. Electrification of vessels and shore-to-ship connections;
2. Electrification of port-side operational equipment and vehicles;
3. Electricity-based fuel production through Power-to-X (PtX) processes.

The first phase focuses on electricity use at the berth through shore power systems and battery-charging infrastructure. Shore power, also referred to as cold ironing or onshore power supply (OPS), allows vessels to switch off onboard auxiliary engines during port stays and use shore-supplied electricity instead. Depending on vessel type and operational profile, this can

significantly reduce local emissions of carbon dioxide (CO₂), nitrogen oxides (NO_x), sulfur oxides (SO_x), and particulate matter in port cities.

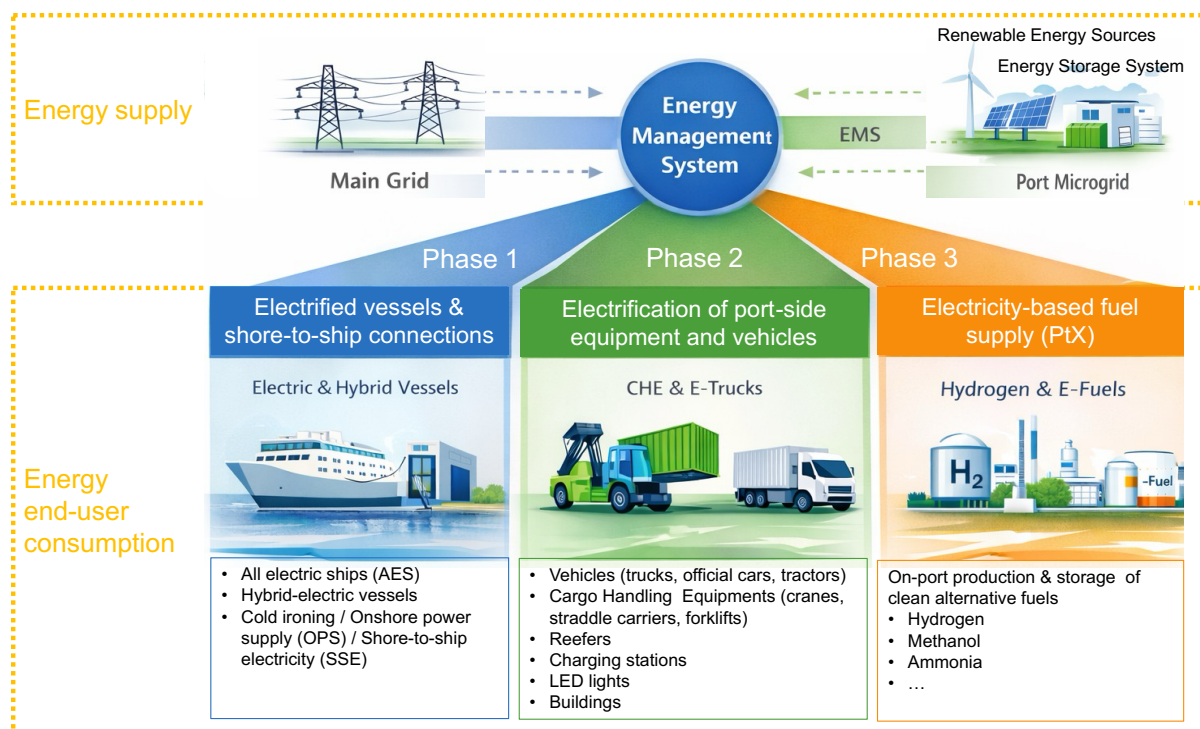


Fig. 1 – Three-phase typology of port electrification and associated technologies (Li et al., 2026).

The second phase includes the electrification of terminal operations and port-side equipment. This covers technologies such as electrified quay cranes, rubber-tired gantry cranes, forklifts, tractors, terminal trucks, automated guided vehicles, and refrigerated container systems. Compared to shore power systems, these applications are typically more closely linked to terminal operational processes and cargo-handling logistics.

The third phase extends electrification toward electricity-based fuel production within ports. In this case, ports evolve from electricity consumers to integrated energy-transition hubs that support the production, storage, and bunkering of hydrogen, ammonia, methanol, and other synthetic or low-carbon fuels. These applications are often associated with renewable energy integration, industrial decarbonization, and sector coupling.

The developed typology provides a more explicit and structured definition of port electrification compared to fragmented definitions found in the existing literature. It also enables a more consistent comparison of studies, technologies, and infrastructure implications across different maritime contexts.



2.3. Literature mapping and analysis

The study included a structured review and mapping of academic and policy literature related to port electrification. Figure 2 shows a hierarchical keyword-search strategy that was developed to distinguish between:

- general electrification literature;
- port-related electrification studies;
- and studies explicitly addressing electricity-grid implications.

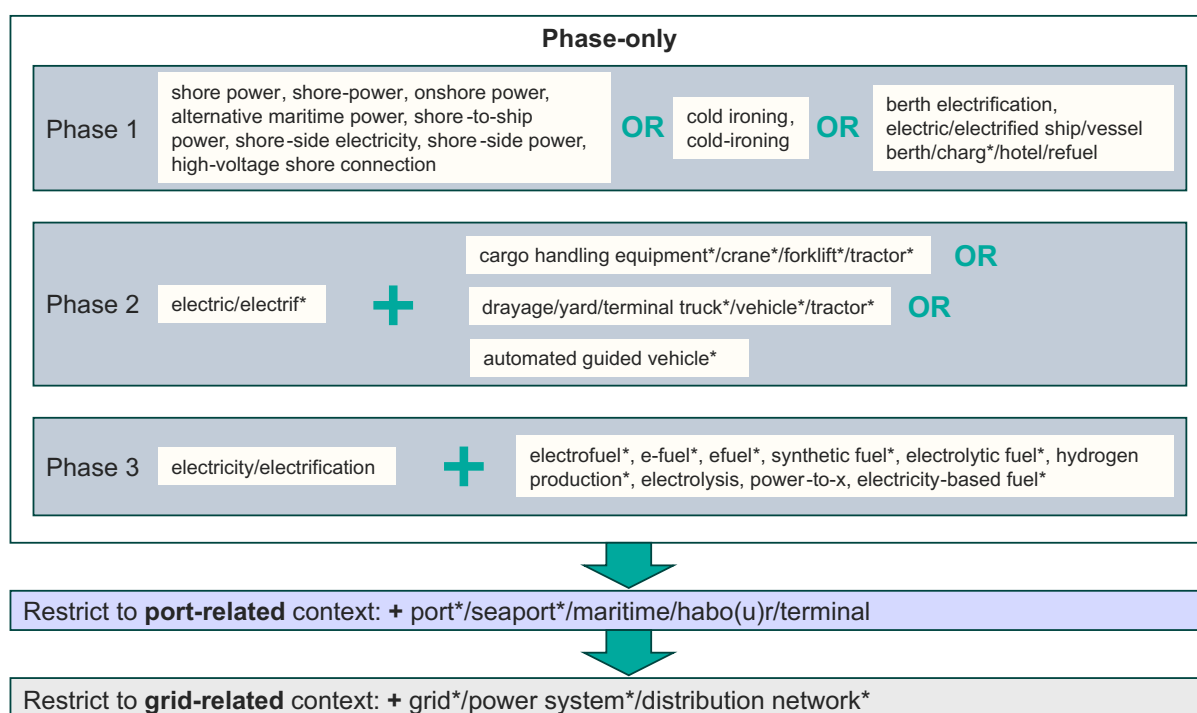


Fig. 2 – Hierarchical keyword-search strategy used for Scopus queries (Li et al., 2026).

The analysis revealed substantial differences in maturity and focus of research across the three electrification phases.

Phase 1, associated with shore power and vessel electrification, was identified as the most mature and port-specific research area. The literature in this field is relatively consolidated and strongly connected to environmental and grid-related topics. Common themes include berth electrification, shore power deployment, energy management, emissions reduction, and grid integration.

Phase 2, focused on electrified operational equipment and vehicles, was found to be more fragmented. Research is distributed across multiple operational domains, including cranes, terminal trucks, cargo-handling equipment, and logistics optimization. Container terminals dominate the literature, while other terminal types are substantially underrepresented.



Phase 3, associated with hydrogen and electricity-based fuel production, represents the fastest-growing but least port-specific research area. Most publications related to hydrogen, renewable energy, and e-fuels have emerged only in recent years. However, relatively few studies explicitly address how these technologies interact with port infrastructure and electricity systems.

The review demonstrated that electrification research grows substantially when broader transition technologies are considered, but only a limited share of studies explicitly addresses the operational and electricity-system realities of ports. Even fewer studies investigate infrastructure constraints such as:

- grid capacity limitations;
- simultaneity of electrical loads;
- power quality and harmonics;
- infrastructure reinforcement requirements;
- and temporal variability of electricity demand.

This imbalance indicates that port electrification research still remains only partially integrated with electricity-system analysis and infrastructure planning.

2.4. Context-specific nature of port electrification

One of the central findings of the study is that port electrification should not be treated as a uniform technological transition. Instead, electrification pathways are highly dependent on port characteristics, operational profiles, vessel traffic, and surrounding industrial systems.

The review demonstrated that different port functions are associated with substantially different electrification priorities and infrastructure requirements. Container terminals are strongly associated with electrified cargo-handling equipment, operational optimization, and large electricity demand from cranes, reefers, and terminal vehicles. Cruise and passenger terminals are more closely linked to shore power systems due to the large hoteling loads of passenger vessels during berthing. Electrified tractors and horizontal cargo-transport systems are more relevant to Ro-Ro terminals.

The study also identified that vessel type strongly influences the technical characteristics of shore power systems. Cruise vessels, ferries, container ships, tankers, and bulk carriers differ substantially in terms of:

- average electrical load;
- berth duration;
- voltage and frequency requirements;
- and traffic regularity.



Ports with highly regular traffic patterns, such as ferry and passenger terminals, may benefit from more predictable shore-power demand and improved infrastructure utilization. By contrast, ports serving heterogeneous cargo traffic may experience greater uncertainty related to the simultaneity of loads and infrastructure compatibility.

Phase 3 electrification pathways are particularly dependent on broader industrial and geographical conditions. Hydrogen and PtX systems require large storage and industrial infrastructure areas, strong electricity grid connections, and access to renewable energy resources. As a result, not all ports are equally suitable for developing energy-hub functions.

The study showed that port electrification can therefore both reflect and reshape port functions over time. Some ports are gradually evolving from traditional cargo-handling locations to integrated energy-transition hubs that combine renewable energy, storage systems, electricity management, low-carbon fuels, and industrial decarbonization activities.

2.5. Implications for infrastructure planning and electricity systems

The study highlighted that different electrification pathways generate fundamentally different electrical profiles and infrastructure challenges.

Shore power systems may produce highly variable peak loads depending on vessel arrivals and berth occupancy. Electrified operational equipment creates different demand patterns associated with terminal activities and logistics operations. PtX applications may introduce very large, relatively continuous industrial electricity demand for electrolysis and fuel production.

These differences have major implications for electricity-grid planning and infrastructure investment. Many ports currently operate with electrical infrastructure originally designed for conventional industrial loads such as lighting, cranes, and refrigerated containers. Large-scale electrification may therefore require substantial reinforcement of distribution and transmission systems.

The review further identified that grid-related aspects remain insufficiently represented in many electrification studies. Existing research often discusses grid implications only in simplified terms such as total electricity demand or peak load. However, practical deployment of electrification technologies requires a more detailed assessment of:

- temporal load variability;
- simultaneous charging demand;
- power quality;
- harmonic distortions from converters;



- voltage and frequency compatibility;
- and operational flexibility.

The findings therefore emphasize the importance of coordinated planning among ports, electricity grid operators, infrastructure developers, and policymakers.

2.6. Benefits and expected impact

The work contributes to a more systematic organization of the field of port electrification and provides a clearer conceptual basis for future research. The developed typology improves comparability between studies and supports more consistent modeling, scenario analysis, and infrastructure assessment.

The study supports port authorities, infrastructure developers, energy utilities, and maritime stakeholders in understanding how different electrification pathways affect infrastructure requirements and operational conditions.

The results can support:

- planning of shore power infrastructure;
- electrification of terminal operations;
- assessment of electricity demand;
- evaluation of future grid reinforcement needs;
- and strategic planning for hydrogen and PtX deployment.

The work also highlights the importance of adapting electrification strategies to the specific characteristics of individual ports rather than applying uniform technological solutions.

Port electrification contributes to the reduction of greenhouse gas emissions and the improvement of local air quality in coastal and port cities. The study supports more realistic and coordinated decarbonization planning by clarifying the infrastructure implications of different electrification pathways.

The findings are also relevant for policymakers and public authorities involved in:

- maritime decarbonization strategies;
- electricity-grid planning;
- renewable energy integration;
- industrial transition;
- and development of low-carbon transport systems.

Overall, the study demonstrates that port electrification should be approached as an integrated port–energy transition process rather than as a collection of isolated technologies.



3. Selecting the relevant methodology for the simulation-based mathematical toolkit

3.1. Approaches for simulation

This section supports the selection of the methodology for the simulation-based mathematical toolkit developed in the project. It is based on the detailed review of existing simulation approaches for sustainable shipping and port infrastructure published within the POTENT-X project by Kondratenko et al. (2026), which demonstrates that agent-based models (ABMs) provide significant capabilities for analyzing energy transitions in ports and complex maritime transport systems operating under uncertainty and evolving operational constraints.

According to Figure 3, the existing simulation methods for studying maritime and port sustainable transitions are classified into four major categories: dynamic systems, system dynamics models, discrete-event models, and agent-based models.

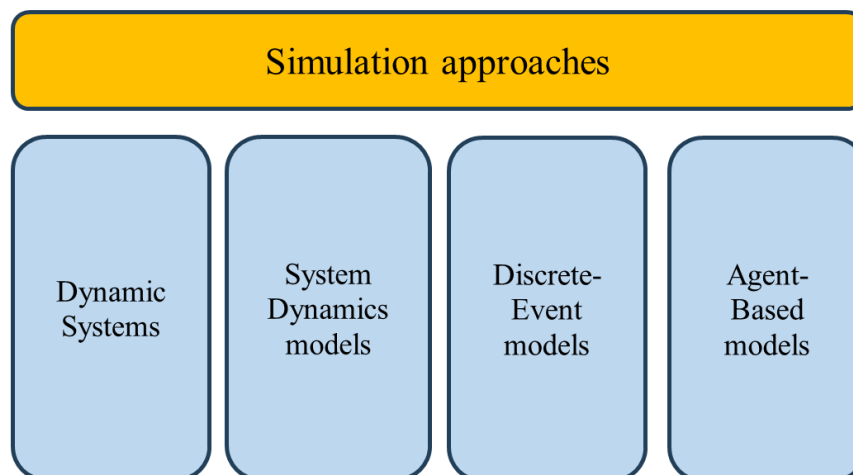


Fig. 3 – A Classification of simulation approaches (Kondratenko et al., 2026).

Dynamic-system models are widely used in ship engineering and hydrodynamics and are well-suited to highly detailed physical analysis of local technical processes, such as propulsion performance, hull resistance, and energy systems. Systems dynamics approaches are primarily used for strategic and policy-level studies, where aggregated system behavior and long-term feedback effects are analyzed. Discrete-event simulation is effective for conveyor-type logistics systems with repetitive operational sequences, such as manufacturing lines or regular cargo-handling processes.

However, the analysis indicates that these approaches have limitations when addressing highly interconnected maritime transport systems characterized by heterogeneous actors,

adaptive operational behavior, infrastructure constraints, dynamic routing decisions, uncertain environmental conditions, and evolving decarbonization pathways.

In contrast, for such applications, ABMs offer substantial advantages by explicitly representing independent actors and their interactions within a shared operational environment (see Figure 4). In ABM-based approaches, ships, ports, terminals, infrastructure assets, operators, regulators, and service providers can be represented as autonomous agents with individual objectives, operational logic, and decision-making behavior. System-level dynamics emerge from interactions between these agents and the surrounding environment. This enables a realistic representation of operational processes and supports detailed “what-if” scenario analysis under changing technological and regulatory conditions. ABMs are increasingly used across multiple levels of maritime system analysis, from strategic decision-making to operational planning.

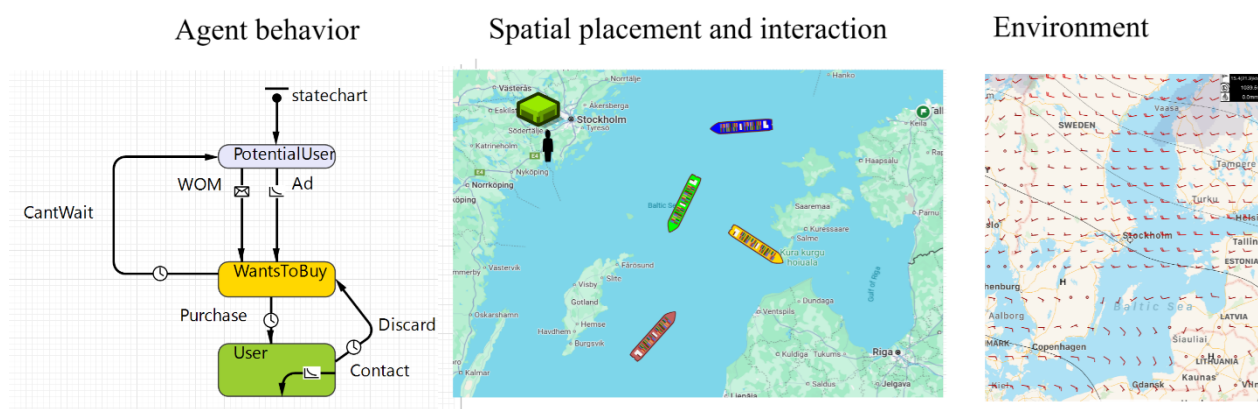


Fig. 4 – The basic components of an agent-based model (Kondratenko et al., 2025).

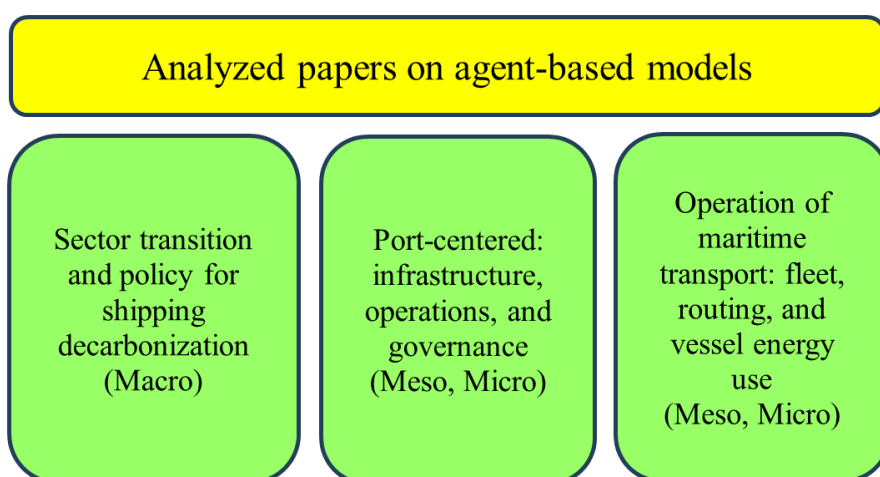


Fig. 5 – A Classification of agent-based simulation approaches by area of contribution (Kondratenko et al., 2026).



Figure 5 shows a classification of ABMs, dividing them into three categories: (i) sector-level transition and policy analysis for shipping decarbonization, (ii) port-centered infrastructure and decision-making, and (iii) operational modeling of maritime logistics and vessel energy use.

3.2. Agent-based simulation for studying energy transitions in shipping and port infrastructure

ABMs demonstrate significant capacity to analyze decarbonization pathways and policy instruments for shipping and ports. These models simulate technology adoption, fuel transitions, retrofitting decisions, and market interactions between shipping companies, shipbuilders, fuel suppliers, and regulators. The reviewed studies show that ABMs are particularly suitable for evaluating alternative-fuel adoption scenarios, carbon-pricing mechanisms, wind-assisted propulsion technologies, retrofitting strategies, and incentive schemes for low-emission shipping. The models can represent complex interactions among economic feasibility, infrastructure availability, operational requirements, and environmental regulations. This allows researchers and policymakers to evaluate how different policy measures may influence technology uptake and sector-wide emissions over long horizons.

The maritime sector can exhibit strong path dependency, in which a limited number of influential actors and early adopters may significantly shape the overall transition process. ABMs are therefore useful for evaluating coordinated policy packages and identifying practical barriers to deploying sustainable technologies.

Application of ABMs is well established for the analysis of port infrastructure, terminal operations, and maritime logistics. Existing applications include container terminals, Ro-Ro and Ro-Pax terminals, coal and liquid-bulk terminals, nautical services, and integrated port-management systems. This demonstrates that ABMs can effectively represent complex port operations involving multiple interacting resources, including berths, cranes, tugboats, terminal vehicles, pilotage services, and cargo flows. The models are used to evaluate infrastructure utilization, congestion, scheduling strategies, operational bottlenecks, and environmental performance. ABMs can support improvements in vessel turnaround time, terminal throughput, resource allocation, queue management, and overall energy efficiency. Particularly important for sustainable port planning is the ability of ABMs to analyze how operational optimization can reduce unnecessary waiting time, congestion, fuel consumption, and associated emissions.

The literature also demonstrates increasing integration of ABMs with Automatic Identification System (AIS) data, geographic information systems (GIS), real-world port-call datasets, and



operational statistics. This significantly improves model realism and enables direct application to practical infrastructure planning and operational decision-making.

ABMs demonstrate a strong capacity for operational studies of maritime transport systems, especially in sectors characterized by high uncertainty and difficult environmental conditions. The most prominent applications include polar shipping, offshore logistics, and electrified inland navigation systems. These applications often combine ABMs with detailed spatial and environmental models, enabling realistic representation of vessel routing, ice conditions, charging requirements, convoy operations, water-depth limitations, and weather impacts. The analysis shows that ABMs are especially valuable when operational constraints evolve dynamically, infrastructure availability changes over time, or vessel behavior depends on local environmental conditions.

Relevance is evident for electrified inland shipping systems, where operational feasibility depends strongly on charging infrastructure, route planning, and battery management strategies. In such applications, ABMs enable the simultaneous, detailed representation of ship energy consumption, charging behavior, cargo demand, and infrastructure utilization. ABMs are increasingly used as operational digital twins of maritime systems. These models support interactive scenario testing, operational optimization, and long-term infrastructure planning under realistic conditions.

One of the key findings is the considerable level of stakeholder engagement in ABM development within the maritime sector. Many of the ABM applications in the maritime sector were developed in direct collaboration with port authorities, shipping companies, infrastructure operators, terminal managers, and governmental organizations. Stakeholders contributed operational knowledge, real-world datasets, validation support, and financial resources for model development.

This indicates substantial trust among maritime stakeholders in ABM methodologies and their practical usefulness for decision-making. Compared to many other academic modeling approaches, ABMs demonstrate unusually strong potential for industrial implementation and real-world application. Reports show that stakeholder participation improves model realism, the quality of verification and validation, operational relevance, and acceptance of model-based recommendations (Kondratenko et al., 2026).

The findings, therefore, suggest that ABMs are not only academically relevant but also highly suitable for supporting evidence-based infrastructure and policy decisions in practice.

Existing application experience demonstrates that ABMs provide strong methodological capabilities for developing simulation-based mathematical toolkits for sustainable ports and shipping systems. Their flexibility, modularity, and ability to represent heterogeneous actors



and infrastructure interactions make them well-suited to modeling decarbonization pathways in complex maritime systems.

The analysis further shows that ABMs are especially effective in applications involving infrastructure planning, electrification, operational optimization, uncertain environmental conditions, and long-term energy transition scenarios.

Based on the reviewed evidence, the project adopts an agent-based simulation approach as the methodological foundation for the developed toolkit. The approach enables realistic representation of interactions between vessels, infrastructure, ports, energy systems, and operational stakeholders, while supporting scenario analysis and practical decision-making for sustainable maritime transport development.

4. Assessment of the Inland Electric Ship Charging Infrastructure

4.1. Motivation and Context

This section presents the developed agent-based methodology for assessing charging infrastructure requirements for inland electric shipping systems. The approach supports planning for charging-station deployment and associated electricity-supply requirements while accounting for operational, infrastructural, and geographical constraints in inland waterborne transport systems. The approach enables simultaneous evaluation of charging-infrastructure feasibility, transport-system performance, energy demand and charging behavior, operational reliability, and infrastructure-investment implications. The applicability of the methodology is demonstrated through a detailed case study of the DINS, one of the most strategically important inland transport corridors in Europe.

Electrification of inland waterborne transport is increasingly recognized as a promising pathway to reduce greenhouse gas emissions from the maritime sector. Compared with deep-sea shipping, inland shipping systems often operate on shorter, more predictable routes and remain in close proximity to shore-based infrastructure. These characteristics create favorable conditions for the deployment of battery-electric vessels and charging systems. At the same time, the electrification of inland navigation introduces significant operational and infrastructural challenges. The feasibility of electric shipping depends not only on vessel technology itself, but also on charging-station placement, power-grid accessibility, charging capacity, route geometry, cargo demand, navigational constraints, seasonal water conditions, and operational scheduling. As a result, infrastructure planning for electric inland shipping cannot be reliably addressed using simplified analytical approaches alone. The planning problem involves complex interactions between vessels, ports, cargo flows, charging behavior,



river conditions, and energy systems. The developed methodology addresses these challenges through an integrated agent-based simulation framework that represents the dynamic behavior of inland transport systems under realistic operational conditions.

4.2. Overview of the Developed Methodology

The developed framework models inland shipping operations as a dynamic system of interacting agents operating within a geographically detailed river environment. Figure 6 shows how real-life data on ports and charging points along the DINS is integrated into the GIS environment. Their locations are represented by GIS points. The core purpose of the methodology is to identify feasible charging-station locations, associated electricity-demand profiles, charging-utilization patterns, and infrastructure requirements to support electrified inland navigation. The methodology evaluates charging infrastructure not as an isolated energy system, but as an integrated component of the broader waterborne transport system. The detailed description of the framework and the in-depth case study of the DINS are being finalized and will be published as part of the POTENT-X project.

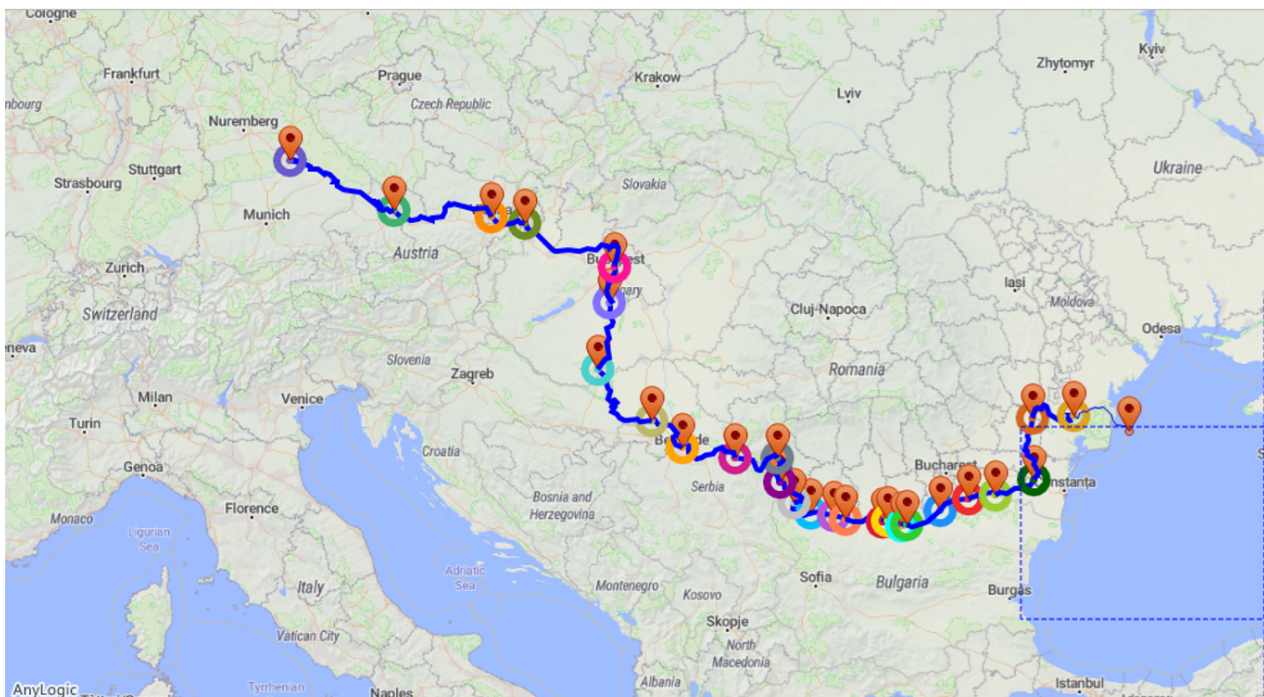


Fig. 6 – Location of GIS points, representing ports and charging points along the Danube Inland Navigation System, considered in the agent-based model.

The framework combines vessel-operation simulation, cargo-demand modeling, route planning, ship energy-consumption estimation, charging logic, and infrastructure interaction. This enables assessment of how charging infrastructure influences the overall performance and efficiency of inland shipping operations. The methodology specifically accounts for



operational scheduling constraints, convoy formation, port availability, vessel battery state, charging duration, river-depth limitations, lock operations, and route-dependent energy consumption. The developed approach, therefore, supports infrastructure planning under realistic operational conditions rather than idealized assumptions.

The framework applies an agent-based modeling approach in which individual system elements are represented as autonomous agents with their own operational logic and state variables. The main active agent categories include tug vessels, barges, and convoys. Ports and charging stations are modeled rather as resources, used by agents based on their demand. The vessel agents operate within a GIS-based representation of the Danube River system. Figure 7 shows a state chart for a pusher tug agent, including its variables and parameters. This represents the primary drivers of a simulation process.

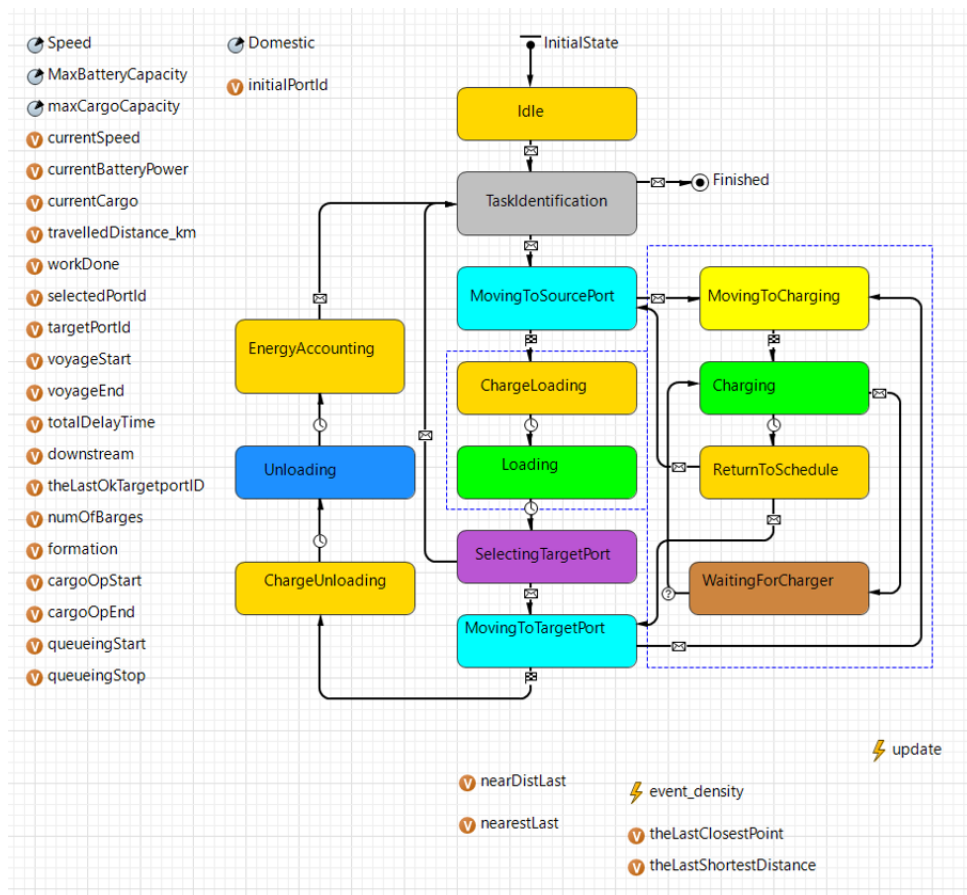


Fig. 7 – A state chart of a pusher tug agent with variables and parameters. The battery-powered pusher tug operates according to cargo demand – assembles cargo convoys, transports barges, consumes energy, and maintains the battery state of charge within an acceptable range.

The environment includes navigable river sections, ports, locks, charging locations, and regional navigational constraints. Cargo demand between ports is represented using real transport-demand data. Vessel agents dynamically form convoys and plan voyages according



to cargo availability, destination requirements, navigational restrictions, and charging feasibility. Figure 8 shows how convoys in the model operate by the DINS within the GIS environment.

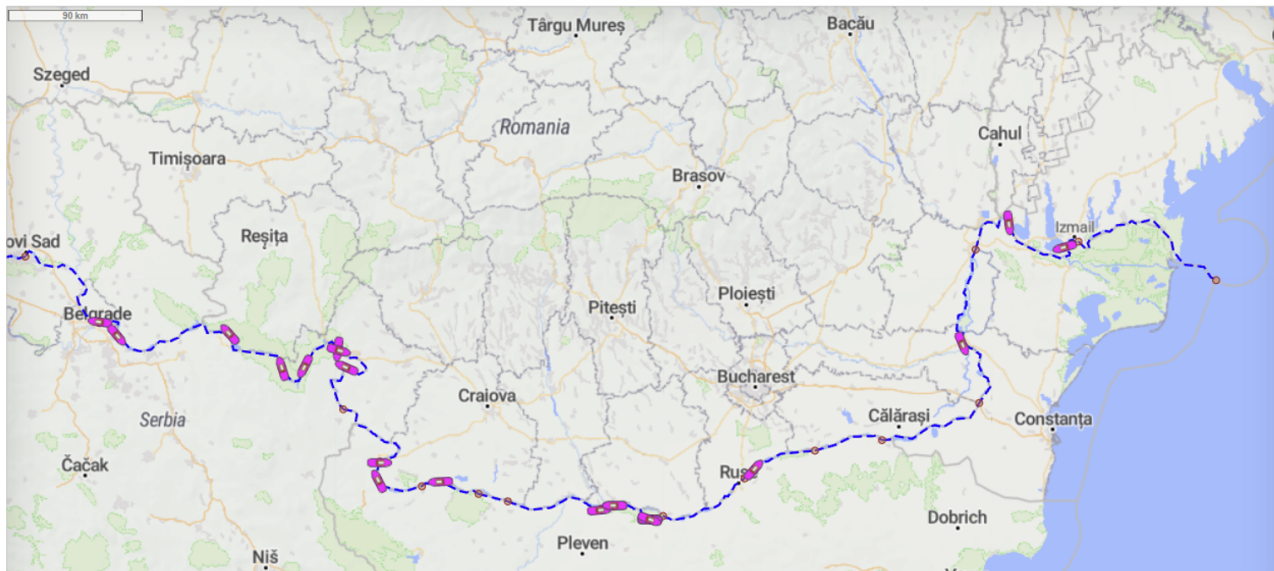


Fig. 8 – A snapshot of the simulation model showing how convoys, represented by pink ship symbols, operate by the Danube Inland Navigation System within the GIS environment.

The model continuously tracks the operational state of each vessel, including location, speed, convoy composition, cargo operations, and battery state of charge. Charging behavior is represented explicitly through charging-planning logic implemented at the vessel-agent level. Tug agents dynamically evaluate charging needs during operation and schedule charging stops based on remaining battery capacity, route distance, charging-station accessibility, operational timing, and transport-demand requirements. This allows the simulation to capture the interaction between transport operations and charging infrastructure in a realistic and operationally consistent manner.

The methodology is demonstrated through an extensive case study of the DINS. The Danube is the longest river in the European Union and forms a major inland transportation corridor connecting ten European countries. The river plays an important role in regional freight transportation and intermodal logistics, while also supporting European objectives for sustainable mobility and transport decarbonization. The developed simulation environment includes major Danube ports, navigational sections, locks, candidate charging stations, and regional waterway characteristics. The model incorporates detailed operational characteristics of inland shipping on the Danube, including variable water depths, shallow-water constraints, lock operations, and regional navigability limitations.

Water depth is particularly important for inland shipping because it directly affects vessel draft, convoy size, operational speed, and energy consumption. Seasonal changes in river

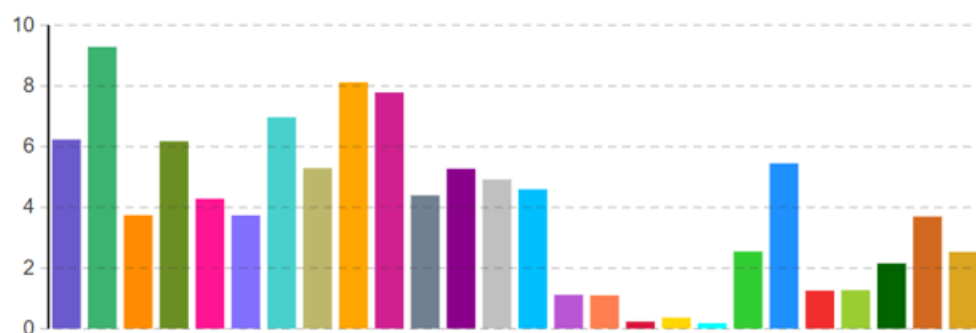


conditions, therefore, influence both transport performance and charging requirements. The model also considers realistic convoy configurations commonly used in Danube cargo transportation. Tug and barge technical parameters were adapted to represent battery-electric operation while maintaining operational feasibility under inland navigation conditions.

A key component of the methodology is the integrated vessel energy-consumption model, which is built by extending the approach by Marchal et al. (1996). The framework dynamically estimates vessel energy demand during operation based on convoy configuration, vessel speed, cargo load, route geometry, river current conditions, and water depth. The simulation continuously evaluates the battery state of charge and charging requirements throughout vessel operations. This enables estimation of charging frequency, charging duration, accumulated electricity demand, peak charging demand, and charging-station utilization. The methodology, therefore, provides a basis for assessing future power-supply requirements associated with the electrification of inland shipping.

Unlike simplified static approaches, the framework captures temporal variations in charging demand caused by operational traffic patterns and transport scheduling. This is particularly important for infrastructure planning because electrical-grid requirements are often determined by short-term peak loads rather than annual energy demand alone. The model also enables assessment of how charging-station deployment strategies influence operational performance and energy-system utilization.

The developed methodology supports the evaluation of alternative charging-infrastructure deployment strategies along the Danube corridor. The framework can assess centralized versus distributed charging concepts, alternative charging-station locations, charging-station spacing, charging-capacity requirements, and infrastructure expansion scenarios. The objective is not only to identify technically feasible charging locations, but also to support cost-efficient infrastructure planning while maintaining reliable transport operations. The model enables identification of infrastructure bottlenecks and operational limitations that may emerge under different electrification scenarios. For example, insufficient charging availability may result in increased vessel waiting times, reduced transport efficiency, route limitations, or operational infeasibility for specific cargo flows. Conversely, excessive deployment of charging infrastructure may significantly increase infrastructure investment costs without proportionate operational benefits. The methodology, therefore, supports balanced infrastructure planning through integrated evaluation of transport-system performance and charging demand. Figure 9 shows the outcomes of modeling traffic density and energy charged per charging station (in GWh) for a specific configuration of the charging infrastructure. Figure 10 shows the utilization of the Iron Gates I charging station over the total simulation period and the daily distribution of utilization across different seasons.



● Regensburg 6.24	● Linz 9.29	● Vienna 3.74	● Bratislava 6.18
● Budapest 4.28	● Dunaújváros 3.74	● Mohács 6.97	● NoviSad 5.29
● Belgrade 8.12	● Golubac 7.79	● IG1 4.39	● IG2 5.27
● Vidin 4.92	● Lom 4.59	● Dunim 1.12	● Oryahovo 1.1
● Somovit 0.24	● Nikopol 0.37	● Belene 0.19	● Svishtov 2.55
● Ruse 5.45	● Tutrakan 1.26	● Silistra 1.27	● Cernavodă 2.15
● Brăila 3.7	● Izmail 2.53		

Fig. 9 – The example of simulation outcomes for a specific configuration of the charging infrastructure: traffic density and energy charged per charging station, GWh.

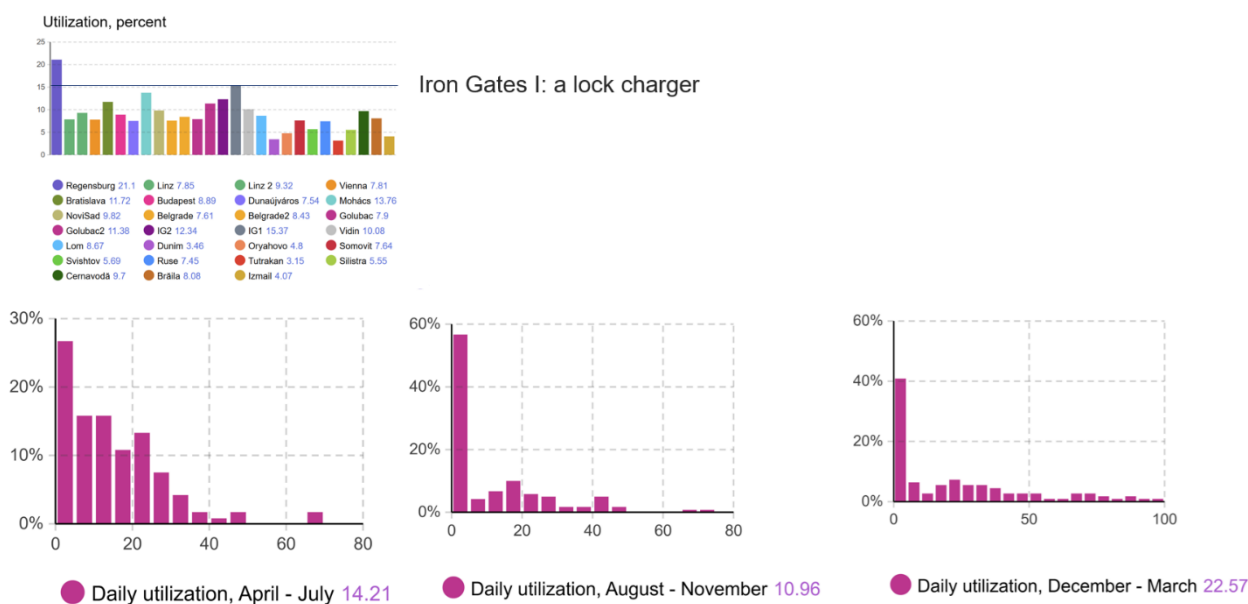


Fig. 10 – The example of simulation outcomes for a specific configuration of the charging infrastructure: the utilization of the Iron Gates I charging station for the total simulation period, and the daily distribution of the charging station utilization for different seasons.

4.3. Implications of the framework for the diverse stakeholders

The developed framework has strong practical relevance for inland navigation operators, infrastructure planners, port authorities, and energy system stakeholders. For industry stakeholders, the methodology supports evaluating electrification feasibility, planning infrastructure investments, developing fleet transition strategies, and optimizing operations. The framework can help identify economically and operationally viable charging strategies before large-scale infrastructure investments are implemented. For ports and infrastructure operators, the methodology provides decision-support capabilities for planning shore-side electrical infrastructure, evaluating charging demand, estimating future grid requirements, and prioritizing infrastructure deployment.

The approach also supports coordination between transport-system planning and electricity-network development. For policymakers and public authorities, the methodology enables the evaluation of inland shipping decarbonization pathways under realistic operational conditions. This is particularly relevant for long-term European objectives related to sustainable mobility, transport electrification, emissions reduction, and energy transition planning.

From a societal perspective, the methodology supports the transition toward lower-emission freight transportation systems. Inland waterborne transport is already an energy-efficient mode compared to road transport, and electrification may further reduce greenhouse gas emissions, local air pollution, and dependence on fossil fuels. The methodology, therefore,



contributes to broader European sustainability objectives while supporting resilient and efficient inland transport systems.

From a scientific perspective, the work demonstrates the applicability of advanced agent-based simulation methods for integrated maritime-energy-system analysis. The methodology contributes to the development of simulation-based decision-support tools that represent infrastructure interactions, operational uncertainty, energy-system dynamics, and geographically distributed transport systems. The framework also demonstrates how digital simulation approaches can support future development of intelligent and partially autonomous transport systems through explicit representation of operational decision-making logic.

5. Grid-ready shore power planning from port-call data: load characterization at the Port of Valencia

Beyond estimating aggregated electricity demand, the deliverable also introduces a more specialized methodology for grid-oriented shore power planning based on real operational port-call data. The approach is demonstrated through a case study of the Port of Valencia, where high-resolution temporal electrical load profiles are developed to evaluate shore power demand across different vessel categories, berth locations, and operational periods. The analysis identifies the principal contributors to electricity consumption, peak-demand events, load fluctuations, and ramping effects, thereby supporting assessment of future grid-capacity requirements and infrastructure planning needs associated with large-scale shore power deployment.

Specifically, the demonstration test case constructs a 15-minute-resolution electrical load profile for the Port of Valencia. Using 613 completed port calls recorded in March 2024, it characterizes operational shore power demand by vessel category, time, and berth zone, identifying the main drivers of energy use, peak load, ramping stress, and future grid-planning requirements.

5.1. Shore Power Demand Characterization by Vessel Type and Time

The study estimates shore power demand by assigning an electrical load to each vessel call. Four power-mapping versions were tested (see Table 1), moving from shore connection ratings reported in the European Maritime Safety Agency (EMSA) guidance, which are based on IEC 80005-1 (EMSA, 2022) to demand estimates based on auxiliary engine and boiler loads derived from the IMO GHG emissions study 2020 (IMO, 2020), with further refinement by ferry/cruise

separation and draft-based vessel-size bins. This progression substantially reduced the estimated March load: monthly energy demand fell from 53,454 MWh to 19,258 MWh, while peak simultaneous demand declined from 154.4 MW to 50.2 MW. The result shows that power-mapping assumptions strongly affect both energy-demand estimates and grid-capacity requirements.

Table 1 - Power model progression: total monthly energy and peak simultaneous demand.

Version	Logic	Energy (MWh)	Peak (MW)	Δ relative to v1
V1	EMSA reported (IEC-based ratings) connection ratings (EMSA, 2022)	53,454	154.4	0 %
V2	IEC-based EMSA ratings and ferry/cruise disaggregation	42,712	97.4	-20%
V3	IMO 4th GHG Study (auxiliary engine and boiler demand) (IMO, 2020)	20,492	60.0	-62%
V4	IMO and draft-based size bins	19,258	50.2	-64%

Using the final v4 model, March 2024 shore power demand was allocated across vessel categories. Table 2 compares call frequency, total energy demand, energy per call, and the relevance of the Alternative Fuels Infrastructure Regulation (AFIR), showing that grid-planning priorities depend not only on traffic volume but also on vessel-specific energy intensity.

Table 2 - Vessel category distribution and v4 energy demand (March 2024).

Category	Calls	Share of total calls (%)	Energy (MWh)	Energy per call (MWh/call)	AFIR Mandate
Container	256	41.8	9,833	38.4	Mandatory
Passenger	164	26.7	3,900	23.8	Mandatory
General Cargo	88	14.4	1,790	20.3	Mandatory
RO-RO	61	10.0	2,081	34.1	Partial
Tanker	28	4.6	1,200	42.9	Not mandated
Bulk	15	2.4	430	28.7	Not mandated



Figure 11 shows how shore power demand unfolds over time. The profile reveals that grid stress is driven by the timing and concurrence of high-load vessel calls, particularly passenger and cruise operations. In the passenger category, ferry services make up 88.4% of calls, while cruise ships represent a smaller share. However, cruise calls create large step changes in demand, with each arrival adding around 12 MW. As a result, passenger-vessel demand can drive short periods of high grid utilization even when the total number of cruise calls is limited.

Tanker demand in the final model exceeds the IEC-rated estimates by 63.5%, mainly because boiler loads are not captured by rated-power methods. The 50.2 MW peak on March 23 occurred with 31 vessels, below the monthly maximum of 32. Interestingly, weekend demand exceeds weekday demand by 21%, driven more by berth occupancy accumulation than by arrival rates. Peak arrival clustering between 17:00 and 19:00 on weekdays coincides with the Spanish grid's evening peak. This temporal overlap warrants further examination to assess whether Energy Management System (EMS) scheduling could reduce coincidence stress on the port and distribution grids.

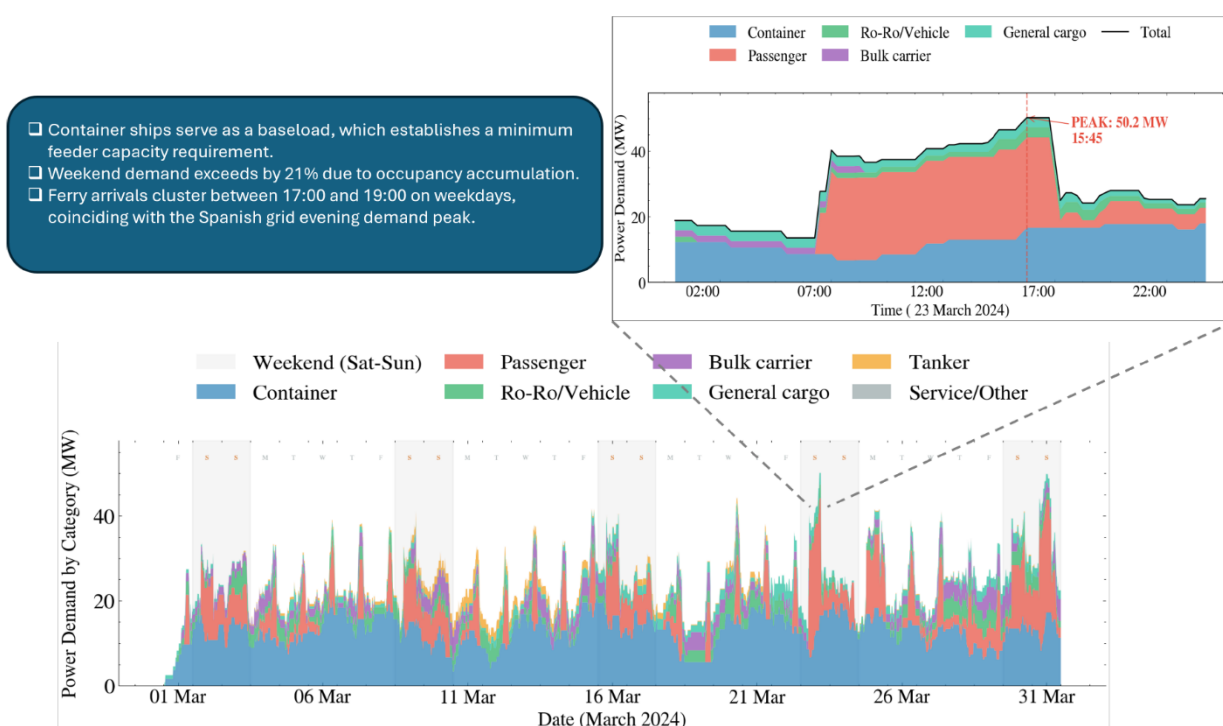


Fig. 11 – Estimated 15-minute shore power demand at the Port of Valencia (March 2024), with a maximum simultaneous load of 50.2 MW and substantial variation across the month. The call-out box shows the peak-load event over a 24-hour period and the surrounding short-duration variations in demand.



The call-out box in Figure 11 shows the peak-day demand profile, with a morning increase and a sharp 25 MW reduction at 16:00. This contrast characterizes the temporal variability of the overall demand profile.

5.2. Ramp Rate Analysis & Dynamic Grid Stress

The port-level ramp rate at a 15-minute resolution quantifies the rate of change in demand, bridging the static load model and dynamic power system simulation. Our analysis indicates that full AFIR compliance fundamentally alters the nature of grid stress rather than simply scaling it. Four scenarios are considered, differentiated by the probabilities of onshore power supply (OPS) adoption. The first scenario represents the current 2026 baseline conditions, derived from the DNV (2024) report. The second reflects a medium-adoption case projected to 2027. The third scenario is based on AFIR regulation, with adoption probabilities specified in the regulatory mandate (European Parliament and Council of the European Union, 2023). The fourth scenario assumes full electrification, representing an upper-bound case across all relevant operations.

The ramp-rate analysis identifies two main types of stress on the electrical grid during shore power operations. Vessel departures generally create more rapid power changes than arrivals, because ships disconnect from shore power much faster than they connect to it. Arrival procedures usually follow standardized, staged connection sequences, which allow power demand to increase gradually and can be managed through energy management systems. In contrast, vessel departures can create sudden drops in electrical load and therefore require more advanced operational coordination and grid flexibility measures. For example, the disconnection of a large cruise vessel with a shore power demand of 12.6 MW can cause a rapid 15-minute load change of approximately 1.67 MW per minute.

The analysis of real operational data from the Port of Valencia also shows that extreme load variations are primarily associated with large cruise and container vessels. These events generate significantly higher short-term grid stress than typical port operations, while average demand levels remain relatively stable. The results indicate that electrical infrastructure designed only for normal operating conditions may experience overload situations more frequently as shore power deployment expands. Consequently, future shore power planning should account not only for average electricity demand, but also for peak loads and rapid load variations caused by vessel connection and disconnection events.

6. Outcomes

This report provided in-depth case studies, which allowed for a better understanding of the real-world implications of grid impacts caused by electrified ports. Figure 12 shows that it



examined the effects of fueling/charging infrastructure and energy needs of electric transport operating in the port on distribution grids by

(1) formulating the scope of port electrification, which allowed for defining which energy must be included in the consumption estimates.

(2) developing an agent-based framework to evaluate optimal charger locations and energy consumption of electric transport based on realistic operation profiles. The framework minimizes capital costs of the charging infrastructure, meeting the physical constraints of the transport and energy systems.

(3) developing the methodology and recommendations for data-driven grid-oriented shore power planning based on real port calls.

The outcomes of the proposed process can be further complemented by in-depth power flow analysis using electric power distribution system simulators like OpenDSS (EPRI, 2026) to connect and assess the charging points within the grid based on anticipated demand from charging profiles and energy consumption. The proposed framework can also be integrated into digital twins of larger scale and coupled with software for designing and analyzing energy systems with multiple energy carriers, like Calliope (The Calliope team, 2025), making it applicable across diverse transport modes for evaluating the grid of electrified transport and e-fuel production.

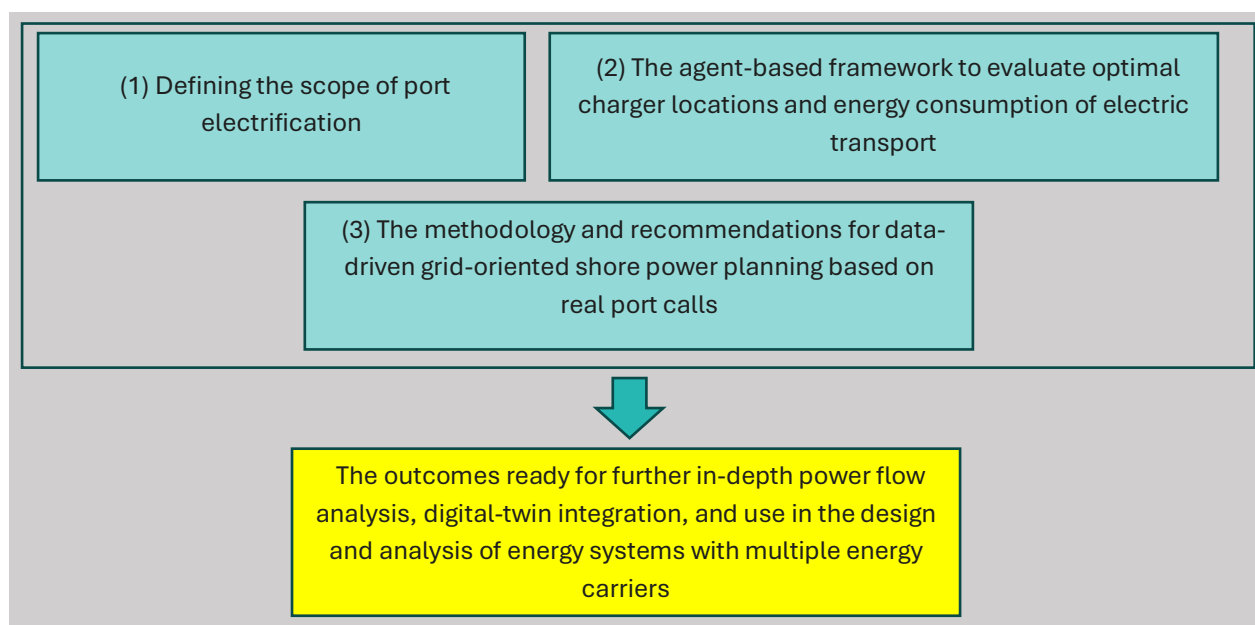


Fig. 12 – The delivery outcomes and their positioning in the wider context.



7. Conclusions

The study demonstrated that port electrification is not a single technological category but rather a set of interconnected, context-dependent transition pathways with substantially different infrastructure and operational implications. The developed three-phase typology provides a structured basis for understanding and comparing electrification strategies across ports and maritime systems. By distinguishing between shore power systems, electrified terminal operations, and electricity-based fuel production, the work supports more realistic infrastructure planning and integrated decarbonization analysis.

The report indicates the growing importance of coordinated planning between ports and electricity systems. Future development of port electrification will increasingly depend not only on individual technologies but also on grid readiness, renewable energy integration, operational flexibility, and cross-sector coordination.

Inland navigation is complicated by significant irregularity and uncertainty in waterway transport capacity, which varies with the season and corresponding water levels. Significant dynamics in energy consumption for individual vessels and the entire fleet result in irregular load on the charging infrastructure, which must be planned for the worst-case scenario. This may result in lower utilization of charging stations compared to road transport. High energy demand per battery-powered ship, pronounced operational asymmetry, and continuous operation make infrastructure configuration a primary determinant of both the feasibility of electrification and the performance of the waterborne transport system across KPIs.

The report shows significant potential for the electrification of inland shipping on the Danube. The developed methodology demonstrates strong potential for supporting electrification planning in inland navigation systems. The case study shows that a realistic assessment of electric inland shipping requires an integrated analysis of transport operations, charging infrastructure, electricity demand, navigational conditions, and vessel behavior.

The results indicate that charging infrastructure significantly influences the operational feasibility and efficiency of electric inland navigation systems. Consequently, infrastructure planning should be considered as a system-level problem rather than an isolated engineering task. The framework demonstrates strong applicability for scenario analysis, infrastructure planning, transport-system optimization, and policy-support studies related to inland shipping decarbonization. Although demonstrated for the Danube corridor, the methodology is transferable to other inland navigation systems and can be adapted for future studies of sustainable waterborne transport infrastructure.

The presented methodology demonstrates that shore power planning requires not only estimation of total electricity demand, but also detailed assessment of temporal load



dynamics and operational variability within ports. The Port of Valencia case study shows that high-resolution port-call data can support more reliable evaluation of peak demand, load fluctuations, and grid stress associated with vessel connection and disconnection events. The results highlight the importance of integrating energy-management strategies and flexible grid-planning approaches into future port electrification projects. The developed approach, therefore, contributes to the design of more resilient and operationally efficient shore power systems, supporting the large-scale implementation of port electrification and maritime decarbonization policies in Europe.



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