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Digital-Twin-Enabled Energy Management for Low-Carbon Port Cities: A Comparative Urban-Intelligence Framework for Genoa, Livorno and Naples

Irina Di Ruocco [1,*]

[1] Department of Economics, Mathematics and Statistics, University of Trieste, Trieste, Italy

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ABSTRACT

Ports are increasingly becoming urban cyber-physical systems in which maritime operations, terminal activities, buildings, electricity networks, renewable generation and environmental pressures interact. Energy Management Systems (EMS) can coordinate energy production and consumption, while Digital Twins (DTs) can connect real-time data, simulation and decision support. Yet port digitalisation and port decarbonisation are still frequently treated as separate domains. This paper develops a Digital-Twin-enabled energy-management framework for urban ports and applies it to three Italian port-city systems: Genoa, Livorno and Naples. The study combines official energy-environmental plans, port emission inventories, operational information and infrastructure data to examine three dimensions of urban intelligence: data integration, energy-system coordination and implementation capacity. The comparison reveals a strong dominance of maritime activities in port-related emissions, accounting for approximately 80.1% in the Western Ligurian Port System, 87.85% in Livorno and 97.0% in Naples. Shore-side electricity nevertheless produces markedly different estimated environmental returns: carbon-abatement intensity ranges from 0.330 tCO2eq/MWh in Naples to 0.400 tCO2eq/MWh in Genoa Pra' and 0.783 tCO2eq/MWh in Livorno. Planned intervention portfolios correspond to estimated emission reductions of approximately 9.0%, 14.3% and 10.2%, respectively. A sensitivity test for the Central Tyrrhenian case shows that implementation constraints can reduce the estimated portfolio effect from approximately 10.2% to 5.3%. Comparison with Rotterdam, Antwerp-Bruges, Valencia, Hamburg and Sines shows that international practice is moving from isolated smart assets toward integrated platforms linking sensing, simulation, energy optimisation and operational decisions. The paper therefore proposes a transferable architecture for Digital-Twin-enabled Port Energy Management and argues that urban intelligence emerges not from technology deployment alone, but from the capacity to connect information, prediction, physical intervention and verifiable environmental outcomes.

* *Corresponding author.*
E-mail address: irina.diruocco@deams.units.it
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1. Introduction

Ports concentrate a wide range of energy-intensive activities, including vessels at berth, cargo-handling equipment, terminal vehicles, warehouses, refrigerated units, buildings and lighting [1,2]. Their progressive electrification changes not only the amount of electricity required in port areas but also the way in which demand must be forecast, coordinated and supplied. Shore-side electricity, electric equipment, photovoltaic systems, storage and flexible loads increasingly interact with maritime schedules and with the wider urban energy network [1]. In port cities, this challenge is especially relevant because port activities coexist with dense urban areas, transport networks and local environmental objectives.

The regulatory context is accelerating this transition. The 2023 International Maritime Organization strategy [3] sets a net-zero ambition for greenhouse-gas emissions from international shipping by or around 2050. At European level, FuelEU Maritime [4] has applied fully since 1 January 2025, while Regulation (EU) 2023/1804 [5] on alternative fuels infrastructure requires qualifying TEN-T maritime ports to provide shore-side electricity capacity by the end of 2029. From 2030, covered container and passenger vessels are progressively required to use onshore power supply or equivalent zero-emission technologies at berth [4,5]. Port decarbonisation is therefore moving beyond isolated efficiency projects toward the coordination of transport operations, electricity infrastructure, renewable energy and governance.

This convergence is already visible in port practice. Genoa and Hamburg were early examples of port authorities taking an active energy-management role [6]. Rotterdam has since moved toward a Virtual Energy System in which physics-based Digital Twins model interacting energy flows; its 2025 Digital Report records more than 23 GWh of shore power delivered and three Virtual Energy System proof-of-concept applications [7]. Valenciaport plans an intelligent energy-management system based on Digital Twin technology for 2027; photovoltaic installations currently provide about 18% of the energy consumed across its port system, while planned wind generation is expected to raise internally supplied energy to approximately 51% [8]. In Italy, Livorno has tested a 5G-enabled Digital Twin fed by sensors, cameras and vehicle data to create a real-time virtual replica of terminal operations [9], while Trieste is developing a Digital Twin of the urban electricity grid to anticipate congestion and manage distributed resources and the growing electricity demand associated with port electrification; the project documentation identifies port-related loads in the order of 2-10 MW for vessels at berth and departure [10].

Recent research on Trieste further reinforces this system-oriented perspective. Di Ruocco and Mazzarino [11] propose a holistic port-system innovation model that combines territorial, technological, geographical and port-related dimensions and is designed to support replication across port environments. In a subsequent study, Di Ruocco and Mazzarino [12] apply a Digital Capability Twin to the Port of Trieste, comparing As-Is and To-Be configurations through stakeholder analysis and operational, environmental and economic KPIs; the approach links real-time monitoring and predictive analytics to strategic planning and risk mitigation. A forthcoming comparative study of Antwerp-Bruges and Trieste extends this trajectory to sustainable intermodal freight through digital automation [13]. Together, these contributions show that port digitalisation is increasingly being treated as a system-level transformation rather than as the adoption of isolated technologies. The present study builds on this trajectory by focusing specifically on the still underexplored coupling between Digital Twin functions, EMS decision support and decarbonisation performance.

These experiences also clarify the potential connection between Energy Management Systems and Digital Twins. The Digital Twin provides the data-integration, state-representation, simulation

and forecasting layer, whereas the EMS translates this information into operational decisions on load scheduling, shore-power coordination, storage dispatch, renewable integration and flexibility. Their integration can therefore be understood as a data-model-decision-feedback loop rather than as the simple coexistence of two technologies [14,15].

Energy management has long been identified as a strategic function for port authorities. Acciaro *et al.* [6] argued that ports can coordinate power generation, energy use and renewable-energy uptake rather than treating energy as a residual technical issue. Iris and Lam [1] subsequently systematised operational strategies, electrification, storage, renewable generation and EMS applications, while Sdoukopoulos *et al.* [2] showed that European ports still differ substantially in monitoring practices, energy-specific governance and technology uptake. More recent reviews confirm that no single measure is sufficient for port decarbonisation and that context-specific combinations of infrastructure, operational measures and governance arrangements are required [16,17].

A parallel literature has developed around Digital Twins. In port settings, DTs can synchronise physical assets and operations with virtual models, combine sensor and operational data, simulate alternative scenarios and support adaptive decision-making. Pang *et al.* [14] conceptualise the integrated port energy system as a multi-energy cyber-physical system in which the digital twin connects the physical equipment layer, data acquisition, intelligent decision-making and application services. Gao *et al.* [18] demonstrate how a DT can support energy-aware operational optimisation in an automated container terminal, while Zhang *et al.* [19] extend this logic to vessel operations and dynamic energy-efficiency assessment. These contributions show the technical potential of DT-based energy intelligence, but they remain only partially connected to the institutional and territorial conditions in which port authorities actually plan decarbonisation investments.

This separation creates an important research gap. Port decarbonisation studies often quantify technologies and planned savings without modelling the information architecture needed to coordinate them. Conversely, Digital Twin and EMS studies frequently assume that interoperable data, smart metering, controllable assets and institutional responsibilities are already available. The result is a gap between technical potential and implementable urban intelligence. This is particularly relevant for European port cities, where the port is simultaneously a logistics node, an energy consumer, a land-use system and a neighbour of dense urban communities.

The paper addresses this gap through a comparative assessment of Genoa, Livorno and Naples. The cases represent northern, central and southern Italian port-city systems under a common national and European regulatory framework, but with different traffic profiles, emission structures and implementation conditions. The empirical analysis does not claim that a full Digital Twin is already operational in all three ports. Instead, it uses their energy and decarbonisation plans to identify which data, infrastructure and governance functions would need to be integrated for Digital-Twin-enabled energy management. The specific innovation is to connect three analytical levels that are usually examined separately: normalised environmental and energy performance, the documented degree of digital-energy integration, and the robustness of planned decarbonisation outcomes to implementation constraints. These elements are then interpreted against international port experiences, allowing technical potential to be discussed together with data readiness, operational integration and governance capacity.

Accordingly, the paper addresses three research questions. RQ1 asks: How can Digital Twins and Energy Management Systems integrate operational, energy and environmental data to support decarbonisation decisions in urban ports? RQ2 asks: How do energy and emission structures, particularly maritime emissions and shore-side electricity performance, differ across Genoa, Livorno

and Naples? RQ3 asks: Which digital, infrastructural and governance conditions determine whether port decarbonisation potential can be translated into implementable smart-energy strategies? The contribution is both empirical and conceptual. Rather than proposing another technology-specific optimisation model, the paper develops a transferable diagnostic framework that links quantitative performance indicators, a Digital-Energy Integration Matrix, an implementation-sensitive robustness test and international functional benchmarking. In this way, it bridges the technical EMS/Digital Twin literature with the planning and governance conditions under which port decarbonisation measures are actually implemented.

2. Literature Review and Conceptual Framework

2.1. From Port Energy Efficiency to Integrated Energy Management

The relationship between ports and energy is historically close. Ports developed as gateways for passengers and freight but also as locations for coal, oil, refineries, pipelines and energy-intensive industries. With containerisation and terminal specialisation, energy management became increasingly distributed among port authorities, terminal operators, shipping companies, utilities and industrial actors [6]. The ecological transition is now reversing this fragmentation because electrification, renewable generation, alternative fuels and storage create direct interdependencies between maritime operations, terminal activities and regional power systems [1].

Acciaro *et al.* [6] marked an early shift by framing port authorities as active energy-management promoters. Their cases of Genoa and Hamburg already suggested that rationalising energy flows can generate efficiency gains and new strategic roles for port authorities. Iris and Lam [1] later organised the field around operational strategies, technologies and EMS, identifying peak shaving, electrification, cold ironing, storage, smart grids and energy monitoring as mutually reinforcing components. Sdoukopoulos *et al.* [2] found that the European state of practice remained heterogeneous and that energy-specific monitoring and management systems were still comparatively limited. Alamoush *et al.* [16] reached a similar conclusion from a broader review: individual measures have different abatement potentials, costs and operational constraints, so portfolios must be assessed for feasibility and effectiveness rather than considered in isolation.

The literature has since shifted toward system-level decarbonisation. Fadiga *et al.* [17], in a systematic review of 124 articles, identify the need to combine measures and develop context-specific strategies that account for stakeholder collaboration. This system perspective is essential because electrification can reduce local combustion emissions while simultaneously increasing electricity demand, creating new peaks and requiring coordination with renewable generation, storage and grid capacity. An EMS therefore becomes more than an energy-saving device: it is the operational layer that coordinates assets, forecasts and constraints.

2.2. Digital Twins as an Urban-Intelligence Layer

Digital Twins add a modelling and synchronisation layer to this energy-management problem. Pang *et al.* [14] argue that integrated port energy systems are characterised by multi-energy coupling and by the fusion of physical, information and value flows. Their proposed architecture links physical equipment, data acquisition, intelligent decisions and application services, emphasising that the main barrier is often no longer the availability of individual energy technologies but the integration of heterogeneous information across different time scales and data structures.

At the operational scale, Gao *et al.* [18] use a Digital Twin and Q-learning to optimise energy consumption in automated container-yard operations. Their work demonstrates the value of synchronising a virtual operational environment with physical processes so that alternative decisions can be tested before implementation. Zhang *et al.* [19] similarly propose a DT-driven energy-efficiency evaluation system for vessel operations, integrating sensor networks, high-fidelity virtual models and machine learning to capture dynamic interactions between vessel characteristics, terminal coordination and energy use. These studies move beyond static inventories toward continuous observation and adaptive optimisation.

Port-specific research also shows a gradual move from technology adoption to system-level digital capability. Di Ruocco and Mazzarino [11] analyse freight railway digital automation in Trieste through a holistic model that embeds technology within territorial, geographical and port-system conditions. Their European Transport study [12] operationalises this perspective through a Digital Capability Twin, As-Is/To-Be scenarios, stakeholder analysis and multidimensional KPIs. A forthcoming comparative contribution [13] broadens the perspective to sustainable intermodal freight across Antwerp-Bruges and Trieste. Together, these studies extend port digitalisation from individual technologies toward port-system, capability and cross-port intermodal perspectives. Their primary analytical focus, however, remains freight automation and intermodal processes rather than the explicit integration of port energy flows, EMS optimisation and decarbonisation governance.

This direction is also consistent with the wider smart-city literature, which increasingly distinguishes static auditing from dynamic intelligence. Fetalco *et al.* [20], for example, frame metering, structured reporting and data architecture as prerequisites for predictive urban energy analytics. Applied to ports, this implies a progression from digitised infrastructure to connected systems and, eventually, to intelligent decision loops. A port may possess smart meters, shore power, photovoltaic systems and digital platforms without yet having an integrated architecture that uses those assets to update forecasts and modify operational decisions.

2.3. Research Gap and Analytical Proposition

Three gaps emerge from the combined literature. First, empirical studies remain dominated by single-port or single-technology applications, which limits comparison across heterogeneous port-city contexts. Second, EMS optimisation studies commonly assume data availability and controllability, whereas planning documents often describe infrastructure without specifying interoperability, temporal resolution or decision rights. Third, the port-city dimension is only partially integrated into energy-management analysis even though grid constraints, urban air quality, mobility, land use and institutional coordination shape what can be implemented. Recent port-system and intermodal studies [11-13] partly address the fragmentation problem by treating digitalisation as a system-level transformation, but they do not explicitly connect Digital Twin functions with EMS decision support, energy-performance indicators and implementation-sensitive decarbonisation outcomes. This unresolved interface constitutes the specific gap addressed here.

The analytical proposition of this paper is therefore that port intelligence should be assessed as a chain rather than as an inventory of technologies. The chain connects: (i) physical assets and energy flows; (ii) sensing and data acquisition; (iii) a Digital Twin or equivalent modelling layer; (iv) EMS-based decision support and control; and (v) governance and feedback mechanisms that verify whether expected environmental benefits are realised. This proposition responds directly to the gaps identified above. Recent port digitalisation studies broaden the unit of analysis toward system and intermodal integration [11-13]. Digital Twin studies demonstrate the value of detailed operational

representation and simulation [14,18,19,21], while EMS applications show how forecasts, storage and energy-market information can be translated into operating decisions [15]. The missing step is a framework able to assess whether those functions can be connected under the heterogeneous data, infrastructure and governance conditions documented in real port plans. The contribution of the present study is therefore not a new optimisation algorithm, but a comparative and implementation-oriented framework that combines environmental performance, digital-energy integration and robustness to delivery constraints.

The proposed Digital-Twin-enabled Port Energy Management architecture is summarized in Fig. 1.

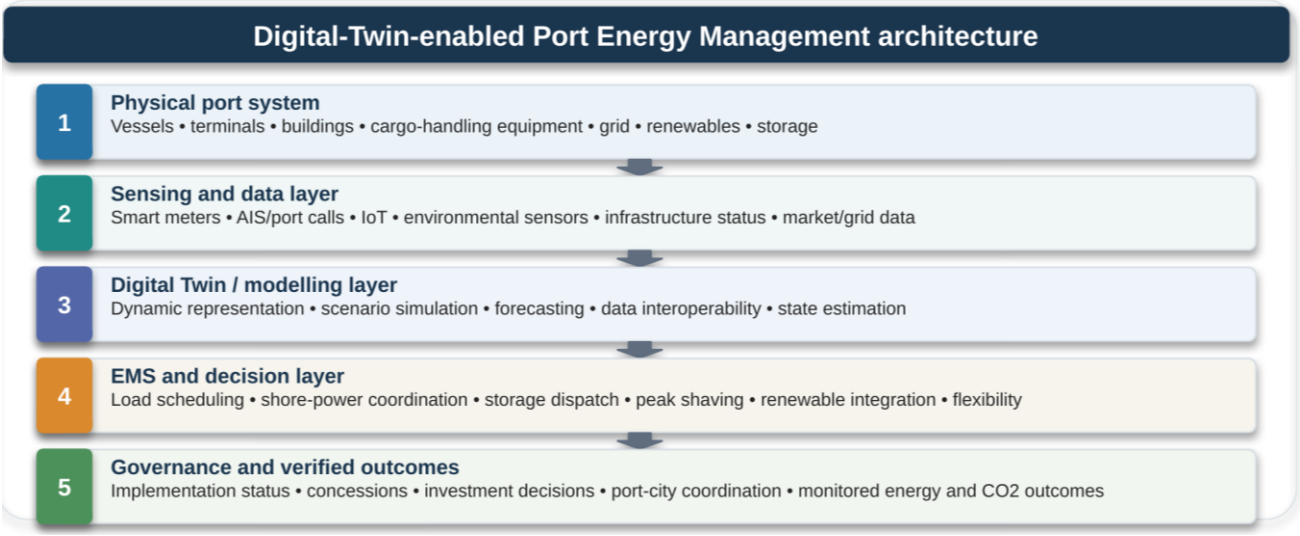


Fig. 1. Digital-Twin-enabled Port Energy Management architecture

3. Methodology

3.1. Research Design and Methodological Basis

The study adopts a structured comparative multiple-case design to examine how Energy Management Systems (EMS) and Digital Twin (DT) functions can support port decarbonisation. The methodological sequence is informed by two closely related strands of the literature. Eom *et al.* [21] develop a port Digital Twin through an explicit chain linking data architecture, operational modelling, simulation and comparison with observed port operations, while Rezende *et al.* [15] structure a seaport EMS around identified input variables, an optimisation/decision layer, baseline scenarios and sensitivity analysis. Building on this logic, the present study adapts the input-processing-output sequence to the type of evidence available for Italian port authorities: official emission inventories, energy-environmental plans, project data and documented digitalisation initiatives.

Genoa, Livorno and Naples are selected purposively as northern, central and southern Italian port-city systems operating within the same national and European regulatory framework but characterised by different traffic profiles, emission structures and implementation conditions. The study is therefore comparative rather than statistically representative. With only three cases and heterogeneous baseline years, an econometric model would not be appropriate. The chosen analytical model is a structured cross-case assessment combining normalised environmental indicators with a functional Digital-Energy Integration Matrix. The objective is not to rank ports, but

to identify how emission structure, mitigation potential, digital capabilities and implementation conditions interact.

3.2. Variables, Sources and Reference Years

The empirical database was assembled from the Environmental and Energy Planning Documents (DEASP), monitoring updates, sustainability and technical reports, traffic and infrastructure documents issued by the respective Port System Authorities [22-24]. For each variable, the publication year of the documentary source is distinguished from the reference year of the underlying observation. This distinction is essential because the official inventories do not share a common baseline year. Table 1 summarises the variables used in the analysis, their principal sources, temporal reference and treatment.

The variables, source documents, reference years and treatment rules used in the comparative assessment are summarized in Table 1.

Table 1
Variables, sources, reference years and data treatment

Dimension	Variable / code	Unit or categories	Main source (document year)	Data reference year	Treatment / analytical role
Environmental	Total GHG emissions (E_TOT)	tCO2eq/year	AdSP Mar Ligure Occidentale DEASP monitoring (2023) [22]; AdSP Mar Tirreno Settentrionale DEASP (2021) [23]; AdSP Mar Tirreno Centrale DEASP (2024) [24]	Genoa: 2016; Livorno: 2018; Naples: 2022	Converted to annual tCO2eq and retained at the original baseline year; no temporal interpolation.
Environmental	Maritime emissions and Maritime Emission Share (E_MAR; MES)	tCO2eq/year; %	Same official port/system emission inventories and DEASP documents [22-24]	Same year and boundary as E_TOT	MES calculated only when numerator and denominator refer to the same inventory boundary.
Energy	Shore-side electricity (EL_CI)	MWh/year	DEASP and shore-power technical/project documentation [22-24]	Project or operational scenario reported by each source	GWh converted to MWh; observed/operational values kept separate from planned values.
Mitigation	Avoided emissions from	tCO2eq/year	DEASP intervention sheets and	Project scenario	Standardised to annual avoided tCO2eq and used

	cold ironing (E_AV,CI)		technical assessments [22-24]		with EL_CI to derive CAI.
Mitigation	Portfolio avoided emissions (E_AV)	tCO2eq/year	DEASP mitigation portfolios and monitoring updates [22-24]	Port-specific baseline/scenario	Measures summed only where the institutional source treats effects as additive; overlapping effects are not double-counted.
Mitigation	Planned Emission Reduction (PER)	%	Authors' calculation from E_AV and E_TOT [22-24]	Same baseline/scenario pair	Normalised indicator used for cross-case interpretation; treated as ex-ante potential unless monitoring evidence shows realised savings.
Implementation	Intervention status (IMP)	Not documented / planned / pilot-partial / operational	DEASP updates, project and technical documents [22-24]	Latest available	Separates technological potential from implementation readiness; missing evidence is coded NA, not zero.
Digital	Monitoring and data integration (MON/RTD)	Qualitative functional categories	Port Authority digitalisation, technical and energy documents [22-24]	Latest available	Evidence classified by sensing, interoperability and real-time or near-real-time integration functions.
Digital-energy	Digital Twin / EMS capability (DT-EMS)	Qualitative functional categories	Port documents; methodological benchmark from Eom *et al.* [21] and Rezende *et al.* [15]	Latest available	Assessed across modelling/simulation, forecasting, optimisation/decision support, actuation and feedback.
Governance	Implementation and governance constraints (GOV)	Qualitative evidence	DEASP monitoring, authorisation and project documentation [22-24]	Latest available	Constraints such as authorisations, funding, connection availability and operational readiness are incorporated into the sensitivity interpretation.

The table records source year and data reference year separately. In particular, baseline emission inventories and intervention scenarios are not treated as observations from a common cross-section. International cases are excluded from the quantitative Italian dataset and are used only as methodological and interpretive benchmarks.

3.3. Data Treatment and Harmonisation

Data treatment followed four harmonisation rules. First, greenhouse-gas quantities were expressed in tCO2eq/year and electricity in MWh/year. Second, the original baseline year of each inventory was retained; no interpolation was performed to force Genoa, Livorno and Naples into a common year because this would require unsupported assumptions on traffic, fleet composition and activity levels. Third, ratios were calculated only when numerator and denominator referred to the same spatial and operational boundary. This is particularly relevant for Genoa, where the emissions denominator refers to the wider Western Ligurian Port System while the shore-power technology observation refers to Genoa Pra'. Fourth, observed or operational outcomes were separated from planned, simulated or estimated effects. Missing information was recorded as NA rather than interpreted as zero.

To obtain a common taxonomy across documents, mitigation measures were grouped into four functional classes: electrification and shore-side electricity; alternative fuels; renewable generation and energy efficiency; and digital/EMS measures. Values reported by different authorities were not combined unless their accounting boundaries and units were compatible. This procedure prioritises internal consistency over artificial numerical comparability.

3.4. Chosen Analytical Model and Indicator Construction

The chosen analytical model is a structured comparative multiple-case assessment. It combines three components: (i) emission structure, (ii) mitigation performance, and (iii) digital-energy integration. Quantitative indicators are calculated within each case and then compared descriptively; the Digital-Energy Integration Matrix is used to interpret whether the technological and informational conditions required for a DT-enabled EMS are documented. This design follows the input-model-output logic used in Eom *et al.* [21] and Rezende *et al.* [15], while avoiding the claim that the present study implements a real-time Digital Twin or an operational EMS optimisation algorithm.

$$MES_i = (E_MAR, i \,/\, E_TOT, i) \times 100 \quad (1)$$

$$PER_i = (E_AV, i \,/\, E_TOT, i) \times 100 \quad (2)$$

$$CAI_i = E_AV, CI, i \,/\, EL_CI, i \quad (3)$$

MES in Eq. (1) measures the share of maritime activities in the corresponding port/system greenhouse-gas inventory. PER in Eq. (2) expresses the expected annual avoided emissions of the intervention portfolio relative to the matching baseline. CAI in Eq. (3), expressed in tCO2eq/MWh, normalises the estimated environmental return of shore-side electricity and is calculated only where both electricity supplied and avoided emissions are available. These indicators are interpreted jointly rather than aggregated into a single performance score.

3.5. Digital-Energy Integration Matrix

The qualitative component assesses the extent to which each port system exhibits the functional elements required for Digital-Twin-enabled energy management. Five dimensions are considered: (1) physical decarbonisation infrastructure; (2) monitoring and data acquisition; (3) interoperability and digital representation; (4) simulation, forecasting or EMS decision support; and (5) implementation feedback and governance. Evidence is derived from official Port System Authority documents, energy and environmental plans, technical project documentation and, where relevant, documented digitalisation pilots [9,22-24]. For each dimension, the available evidence is classified into four categories: ND = not documented; P = planned or conceptual; PI = pilot or partially implemented; and OI = operational or integrated. The matrix is diagnostic rather than classificatory: categories are not aggregated into a synthetic maturity score because public documentation is uneven and the objective is to identify where the transition from individual digital or energy assets toward an integrated data-model-decision architecture remains incomplete.

3.6. Sensitivity and Robustness Analysis

A sensitivity analysis is applied where the expected emission-reduction potential of a port depends strongly on a single intervention. The purpose is to distinguish the technical potential reported in planning documents from the reduction that remains achievable under more restrictive implementation assumptions. For intervention k, a constrained implementation factor λ is introduced as shown in Eq. (4).

$$E_AV, sens \; = \; \Sigma_(j \neq k)\; E_AV, j \; + \; \lambda E_AV, k, \;\; 0 \leq \lambda \leq 1 \qquad (4)$$

The corresponding adjusted portfolio reduction is calculated using Eq. (5).

$$PER_sens \; = \; (E_AV, sens \; / \; E_TOT) \; \times \; 100 \qquad (5)$$

In the Naples case, the LNG-related contribution is excluded in the conservative scenario (λ = 0) because the 2024 DEASP identifies implementation and authorisation constraints affecting the original pathway [24]. The exercise should not be interpreted as an emissions forecast; it is a robustness test designed to evaluate how strongly the planned decarbonisation outcome depends on full implementation of the intervention.

3.7. International Benchmarking

Rotterdam [7], Antwerp-Bruges [25], Valencia [8], Hamburg [26] and Sines [15] are used as external benchmarks rather than additional observations in the Italian sample. The comparison focuses on functions demonstrated in the literature or official port documentation - real-time sensing, interoperable data, Digital Twin representation, energy-system simulation, storage or demand flexibility, EMS optimisation and feedback to operational decisions. This functional benchmark is used in the Discussion to interpret which elements of an integrated DT-enabled port EMS are already present, planned or still missing in the Italian cases.

The main analytical characteristics of the three Italian cases are summarized in Table 2.

Table 2
Comparative profile of the three Italian cases

Indicator	Genoa / Western Ligurian system	Livorno	Naples
Analytical role	North	Centre	South
Traffic profile	Large multipurpose freight and passenger gateway	Diversified freight port with significant passenger and rail activity	Multipurpose port with very high passenger/cruise activity
Reference GHG baseline	469,249 tCO2eq	217,158.5 tCO2eq	304,890 tCO2eq
Baseline year	2016	2018	2022
Maritime share of emissions	80.1%	87.85%	≈97.0%
Estimated portfolio reduction	≈9.0%	≈14.3%	≈10.2%
Comparability note	System-wide baseline; Pra' used for shore-power technology data	Port-specific baseline	Port-specific baseline

Source: authors' elaboration from official Port System Authority documents [22-24].

4. Results

4.1. Emission Structure: Maritime Activities Dominate the Port-City Carbon Footprint

The first result concerns the structure of port-related emissions. Although the inventories refer to different baseline years and accounting boundaries, they show a consistent pattern: maritime activities represent the dominant source of greenhouse-gas emissions. In the Western Ligurian Port System, ships at berth and manoeuvring account for approximately 80.1% of the total footprint. Livorno's 2018 inventory assigns 87.85% of emissions to maritime traffic. In Naples, the 2022 inventory indicates an even higher concentration, with the sea-side component close to 97% of the total. [22-24]

This pattern has an immediate implication for smart-energy strategy. An EMS limited to buildings, lighting or land-side equipment would optimise only a relatively small share of the relevant carbon footprint, especially in Naples. Vessel-related electricity demand must therefore enter the same data and decision architecture as terminal loads, renewable generation and storage. In Digital Twin terms, the port cannot be modelled only as a collection of stationary energy assets; berth occupancy, vessel type, time at berth and shore-power compatibility become state variables that materially influence the decarbonisation outcome.

4.2. Shore-Side Electricity: Identical Technology, Different Environmental Return

The cross-case shore-side electricity indicators are summarized in Table 3.

Table 3
Comparative shore-side electricity performance

Indicator	Genoa Pra'	Livorno	Naples
Shore electricity	7.0 GWh/year	17.15 GWh/year	36.0 GWh/year
Estimated avoided CO2eq	2,800 t/year	13,431 t/year	11,878 t/year
Carbon-abatement intensity	0.400 tCO2eq/MWh	0.783 tCO2eq/MWh	0.330 tCO2eq/MWh
Reduction vs port/system baseline	≈0.60%*	≈6.18%	≈3.90%
Implementation / evidence note	Pra' electrification completed; system denominator limits direct comparison	Planning estimate combining passenger and container facilities	Planned/estimated cold-ironing contribution in the 2024 DEASP

Source: authors' elaboration from [22-24].

** The Genoa percentage uses the wider Western Ligurian Port System footprint and is therefore not directly comparable with the port-specific percentages for Livorno and Naples.*

Shore-side electricity is the only major technology for which sufficiently comparable energy-supply and avoided-emissions estimates are available across the three cases. The normalised results are striking. Livorno records the highest estimated carbon-abatement intensity at 0.783 tCO2eq/MWh, more than twice the Naples value of 0.330 tCO2eq/MWh; Genoa Pra' lies between them at 0.400 tCO2eq/MWh. These values should not be interpreted as a ranking of the ports because they depend on different baseline years, fleet structures, electricity assumptions and utilisation profiles. They instead demonstrate that technology presence alone does not determine environmental performance.

For a Digital-Twin-enabled EMS, this heterogeneity is precisely the information that must be modelled dynamically. Vessel type, auxiliary-engine characteristics, connection duration, electricity carbon intensity, berth utilisation and renewable availability affect the marginal value of each MWh supplied at berth. A static infrastructure indicator such as 'shore power installed' therefore provides less decision value than a model that continuously estimates when, where and for which vessel the infrastructure produces the largest operational and environmental benefit.

4.3. Planned Decarbonisation Portfolios

The wider energy-environmental programmes also differ in their estimated aggregate effect. The Western Ligurian programme indicates an overall reduction of about 9% relative to its reference footprint. The Northern Tyrrhenian portfolio reaches approximately 14.3%, with cold ironing in Livorno contributing materially to the estimate. For the Central Tyrrhenian system, the measures considered correspond to approximately 31,436 tCO2eq/year, or about 10.2% of the reference baseline; cold ironing in Naples contributes an estimated 11,878 tCO2eq/year. [22-24]

4.4. Digital-Energy Integration Matrix

The documentary assessment confirms that the three cases are generally more advanced in physical decarbonisation measures than in the integration of sensing, modelling and energy-management functions. Table 4 reports the functional evidence using the four categories defined in

Section 3.5. The coding is deliberately conservative: a technology is classified as operational/integrated only where the available documentation demonstrates implementation beyond a conceptual or pilot stage.

The resulting documentary classification is reported in Table 4.

Table 4
Digital-Energy Integration Matrix for the three Italian port systems

Function	Genoa	Livorno	Naples
Physical decarbonisation infrastructure	OI [22]	PI [23]	PI [24]
Monitoring and data acquisition	PI [22]	PI [9,23]	PI [24]
Interoperability and digital representation	ND [22]	PI [9]	ND [24]
Simulation, forecasting or EMS decision support	PI [6,22]	PI [9,23]	P [24]
Implementation feedback and governance	PI [22]	PI [23]	PI [24]

Source: authors' assessment based on [6,9,22-24]. Codes: ND = not documented; P = planned/conceptual; PI = pilot or partially implemented; OI = operational/integrated.

The matrix shows a recurring gap between infrastructure deployment and system integration. Genoa provides the strongest evidence of operational physical infrastructure but the public documents reviewed do not demonstrate a port-wide Digital Twin or interoperable digital representation. Livorno is the clearest Italian case of Digital Twin experimentation: its 5G pilot integrates real-time sensor, camera and vehicle data with an operational control layer, although this does not yet constitute a fully integrated port-energy EMS [9]. Naples presents a substantial decarbonisation portfolio and formal monitoring framework, but evidence of integrated digital representation and energy decision support remains limited in the documents reviewed [24]. Across the three cases, the critical transition is therefore from individual assets and pilots to a continuous data-model-decision-feedback architecture.

4.5. Robustness of the Decarbonisation Portfolio: The Naples Sensitivity Test

The Naples case provides the clearest illustration of the distinction between technical potential and implementable potential. Approximately 15,232 tCO2eq/year, or 48.5% of the total expected reduction in the portfolio, are associated with the LNG-related measure, while Naples cold ironing contributes a further 37.8%. Together, the two measures account for approximately 86.2% of the expected reduction. The 2024 DEASP, however, records implementation and authorisation constraints affecting the original LNG pathway. If the 15,232 tCO2eq/year contribution is excluded as a sensitivity test, the estimated reduction falls from 31,436 to 16,204 tCO2eq/year, corresponding to a decrease from approximately 10.2% to 5.3% of the reference baseline [24].

This sensitivity result is important for the Digital Twin interpretation. A planning model that stores only technical capacities can overstate achievable decarbonisation if it does not incorporate project status, authorisations, connection availability, funding and operational readiness. In other words, the virtual representation should include governance and implementation states as well as physical energy flows.

5. Discussion

5.1. Italian Results in Relation to the International Literature

The first level of discussion relates the Italian findings to the international scientific literature. The dominance of maritime activities in the three inventories - approximately 80.1% in the Western Ligurian system, 87.85% in Livorno and 97.0% in Naples - is consistent with reviews showing that vessel operations and berth-related energy use remain central to port decarbonisation [16,17]. At the same time, the variation within a common national and European regulatory context demonstrates why port decarbonisation cannot be represented by a single technology coefficient or generic pathway. The results therefore reinforce the context-sensitive perspective advanced by Iris and Lam [1] and Alamoush *et al.* [16], but add a directly comparable North-Centre-South Italian evidence base.

The shore-power results deepen this point. Estimated abatement intensity ranges from 0.330 tCO2eq/MWh in Naples to 0.400 in Genoa Pra' and 0.783 in Livorno. The same nominal technology therefore produces different environmental returns because fleet composition, berth utilisation, electricity assumptions and operational schedules differ across ports. This finding is consistent with the literature on context-specific combinations of operational and technological measures [1,16,17] and with Digital Twin studies that treat the dynamic state of vessels, terminals and energy systems as a prerequisite for energy-aware optimisation [14,18,19,21]. The contribution here is to show that these differences remain visible even when the analysis is restricted to ports operating within the same national institutional framework.

The planned portfolio reductions - about 9.0% for the Western Ligurian system, 14.3% for Livorno and 10.2% for the Central Tyrrhenian system - also need to be read as implementation-dependent potentials rather than directly comparable forecasts. This complements optimisation-oriented EMS research such as the Sines application [15], where technical inputs, storage availability and dispatch conditions are sufficiently specified to generate operational recommendations. The Naples robustness test adds a different dimension: removing the constrained LNG-related contribution reduces the expected portfolio effect from about 10.2% to 5.3%. The result shows that implementation status, authorisations and delivery conditions can materially alter the environmental outcome and should therefore be represented within, rather than outside, the decision model.

Finally, the Digital-Energy Integration Matrix shows a recurrent asymmetry: physical decarbonisation assets and projects are generally more advanced than the data interoperability, simulation, EMS decision-support and verified-feedback functions needed to operate them as an integrated system. This finding is consistent with the uneven monitoring and governance maturity identified across European ports [2] and with systematic reviews that describe port decarbonisation as a fragmented combination of technical, organisational and institutional measures [17]. It also clarifies the practical relevance of the cyber-physical architectures proposed by Pang *et al.* [14] and Eom *et al.* [21]: the main gap in the Italian cases is not the absence of individual technologies, but the incomplete connection between sensing, modelling, decision-making and implementation feedback.

5.2. International Comparison: From Smart Assets to Integrated Port-Energy Intelligence

The international cases used as functional benchmarks are summarized in Table 5.

Table 5
International cases relevant to Digital-Twin-enabled port energy management

Case	Evidence type	Digital / energy approach	Reported or planned contribution	Relevance to Genoa–Livorno–Naples
Rotterdam, Netherlands	Port Authority Digital Report (2025) [7]	Virtual Energy System (VES): physics-based Digital Twin of interacting energy flows, including electricity, steam, prices and industrial interdependencies	Proof-of-value supports scenario analysis, operational insight and investment/design decisions for a future integrated energy system	Shows how a port-scale twin can move from asset monitoring to multi-carrier strategic and operational energy modelling
Antwerp-Bruges, Belgium	Port Authority smart-port programme [25]	APICA Digital Twin combines 3D visualisation with real-time information on ships, locks, infrastructure and wind-turbine energy production	Supports situational awareness, berth/incident management and monitoring of physical and energy conditions	Demonstrates integration of operational and environmental/energy data within one real-time port representation
Valencia, Spain	Port Authority Net Zero Plan / Strategic Plan 2035 [8]	Planned intelligent energy-management system based on Digital Twins, combined with OPS, renewables, storage and electrification	DT-based energy-management rollout planned for 2027 within a 2035 carbon-neutrality and energy-self-sufficiency roadmap	Closest policy analogue to the proposed architecture: decarbonisation assets are explicitly connected to an intelligent energy-management layer
Hamburg, Germany	Peer-reviewed smart-grid simulation [26]	Real-time demand/supply data, storage, peak shaving and virtual buffers linking Port of Hamburg and HafenCity	Simulation reduced renewable overproduction required for reliability from 95% to 65% and indicated up to 31% savings in new infrastructure costs	Shows the port-city scale value of coordinated demand flexibility and urban energy-grid integration
Sines, Portugal	Peer-reviewed EMS case study [15]	Centralised EMS using real port data, BESS scheduling, market participation and day-ahead carbon-intensity forecasts	At least ~17% annual emission reduction versus baseline in the reported EMS assessment, while providing actionable flexibility recommendations	Demonstrates the decision layer missing from static planning: forecasts are translated into hourly operational set-points and recommendations

Sources: [7,8,15,25,26].

The second level of discussion compares the Italian evidence with international port trajectories. This is a functional benchmark rather than a direct ranking of environmental performance, because system boundaries, operating conditions and technology maturity differ substantially. Rotterdam [7] emphasises energy-system scenario modelling across multiple carriers and industrial interdependencies. Antwerp-Bruges [25] uses a real-time twin primarily as an operational information and situational-awareness environment, while also incorporating energy-production information. Valencia [8] is particularly relevant because its roadmap explicitly links a future

intelligent energy-management system to Digital Twin technology, OPS, renewable generation, storage and electrification. Hamburg [26] demonstrates the port-city dimension by modelling the port together with urban loads and renewable supply, while Sines [15] shows how an EMS can turn forecasts and storage flexibility into day-ahead operational recommendations.

Taken together, these cases suggest an evolutionary pathway rather than a binary distinction between 'having' or 'not having' a Digital Twin. The first stage is digitisation: assets and energy flows are measured. The second is connectivity: operational, environmental and energy datasets are interoperable. The third is intelligence: models use these data to forecast system behaviour, test alternatives and support decisions. The final stage is verified adaptation: real outcomes are fed back into the model so that expected savings, constraints and future decisions are updated. This progression is more useful for the Italian cases than a simple technology checklist because their planning documents already contain many of the required physical interventions but provide less evidence of full cross-system integration.

The comparison also helps position the Italian evidence relative to the international literature without treating foreign cases as universal benchmarks. Rotterdam [7] and Antwerp-Bruges [25] operate within large north-European industrial and logistics clusters; Hamburg's study [26] is a simulation of a broader urban smart grid; Sines [15] focuses on a centralised EMS with specific storage and market assumptions; and Valencia's Digital-Twin-based EMS [8] is a planned deployment rather than a completed outcome. Their value lies in demonstrating functions that can be transferred selectively: multi-carrier modelling, real-time situational awareness, port-city demand flexibility, carbon-aware dispatch and implementation roadmaps.

5.3. Research Questions and Innovative Contribution

The results provide a direct answer to the three research questions. Regarding RQ1, Digital Twins and EMS perform complementary rather than interchangeable functions: the Digital Twin integrates and updates operational, environmental and energy states, while the EMS converts those states and forecasts into scheduling, dispatch and flexibility decisions. The comparison shows, however, that the full data-model-decision-feedback loop remains only partially documented in the three Italian cases. The practical integration challenge is therefore one of interoperability and institutional coordination as much as one of technology deployment.

Regarding RQ2, the three cases share a high dependence on maritime emissions but differ substantially in both emission structure and the estimated return of shore-side electricity. The maritime share rises from about 80.1% in the Western Ligurian system to 87.85% in Livorno and approximately 97.0% in Naples, while estimated shore-power abatement intensity varies from 0.330 to 0.783 tCO2eq/MWh. These differences confirm that common regulatory pressure does not generate uniform energy outcomes and that port-specific operational states must enter the assessment.

Regarding RQ3, the decisive conditions are the availability and interoperability of data, the maturity of electrification and monitoring infrastructure, the presence of modelling or EMS decision-support functions, and the governance capacity to translate planned measures into authorised, financed and operational projects. The Naples sensitivity test demonstrates the importance of the last dimension particularly clearly: technical potential can overstate implementable potential when project constraints are not represented.

The innovative contribution of the paper lies in combining these elements within a single comparative framework. Previous strands of literature have largely examined port energy efficiency,

EMS optimisation, Digital Twin applications or governance separately. The proposed approach connects four components - normalised environmental indicators, a qualitative Digital-Energy Integration Matrix, an implementation-sensitive robustness test and an external functional benchmark - without requiring the assumption that a fully operational Digital Twin already exists. This makes the framework usable as a diagnostic bridge between port planning documents and more advanced real-time EMS/Digital Twin architectures, and therefore potentially transferable to other port-city systems with heterogeneous data availability.

5.4. Implications for the Three Italian Port-City Systems

For Genoa, the presence of operational shore-power infrastructure [22] creates an opportunity to shift from infrastructure monitoring toward dynamic coordination. A Digital Twin could combine vessel arrivals, berth occupation, grid constraints and local generation to estimate the expected carbon benefit and power requirement of each connection. The system-wide emissions denominator used in the current comparison also illustrates why model boundaries must be explicit: a twin should allow users to switch between terminal, port and port-system views without mixing them in performance indicators.

For Livorno, the comparatively high estimated abatement intensity of shore-side electricity suggests that operational data could materially improve prioritisation and scheduling [23]. The documented 5G Digital Twin pilot further shows that real-time sensor, camera and vehicle integration is technically feasible at terminal scale [9]. The port's diversified freight, passenger and rail functions mean that different energy loads coexist and may create complementary flexibility opportunities. The international evidence from Hamburg and Sines is particularly relevant here: smart-grid coordination and forecast-based EMS decisions could help evaluate not only annual savings but also peak demand, storage value and the timing of shore-power use.

For Naples, the dominance of sea-side emissions makes vessel-related data central to any intelligent energy architecture. At the same time, the sensitivity test based on the 2024 DEASP [24] shows that the most sophisticated energy model would still be misleading if it ignored authorisation, financing and project-delivery status. The Digital Twin should therefore be interpreted broadly as a decision environment that represents both physical and institutional states. This is the main governance contribution of the paper: implementation readiness is not an external constraint added after optimisation; it is part of the system state that determines which decarbonisation scenarios are feasible.

5.5. Implications for Urban Intelligence and Port-City Governance

Reframing port energy management as urban intelligence also changes the role of the port authority. Rather than selecting technologies independently, the authority becomes an orchestrator of data standards, infrastructure interfaces, modelling assumptions and stakeholder decisions. This role is consistent with the energy-management function proposed by Acciaro *et al.* [6], but the availability of Digital Twins and advanced EMS makes the coordination problem more explicit and potentially more operational. Port authorities can define which datasets must be shared by concessionaires, how environmental performance is verified and how energy flexibility is valued across port and urban networks.

The port-city dimension is particularly important for electricity-intensive measures. OPS, charging and industrial electrification can produce local air-quality benefits while increasing peak electricity

demand. A port-only optimisation may therefore shift costs or congestion into the urban grid. The international comparison indicates that future systems should model the interaction between port loads, renewable generation, storage and surrounding urban demand. This perspective aligns closely with the scope of urban intelligence: the objective is not simply to make the port more digital, but to make infrastructure, energy and governance more adaptive within a shared territorial system. The Trieste electricity-grid Digital Twin provides a national example of this port-city scale: it is explicitly being developed to anticipate grid congestion and support the additional electricity demand generated by port electrification [10].

6. Conclusions

This paper reinterprets port decarbonisation through the joint lens of Digital Twins, Energy Management Systems and urban intelligence. The empirical comparison of Genoa, Livorno and Naples produces three main findings. First, maritime activities dominate the relevant carbon footprint, accounting for approximately 80.1%, 87.85% and 97.0% of the respective inventories. Second, identical decarbonisation technologies do not produce identical environmental returns: estimated shore-power abatement intensity ranges from 0.330 to 0.783 tCO2eq/MWh across the three cases. Third, technical potential and implementable potential can diverge substantially, as illustrated by the Naples sensitivity test in which the expected portfolio reduction falls from about 10.2% to 5.3% when one constrained measure is removed.

These findings support a broader conceptual conclusion. A smart port is not defined by the number of digital or low-carbon technologies deployed. Intelligence emerges from the capacity to connect sensing, modelling, decision-making and physical actuation, and to verify the environmental effect of those decisions. Within this architecture, the Digital Twin provides the dynamic representation and scenario environment, while the EMS provides the operational decision mechanism. Port-city governance connects both layers to investment, regulation, concession management and urban energy planning.

The international cases reinforce this interpretation. Rotterdam [7] illustrates multi-energy system modelling; Antwerp-Bruges [25] demonstrates real-time operational twinning; Valencia [8] is explicitly linking Digital Twins to intelligent energy management in its net-zero roadmap; Hamburg [26] shows the value of port-city smart-grid flexibility; and Sines [15] demonstrates carbon-aware operational EMS optimisation using real port data. These examples do not form a single maturity ranking, but they identify transferable functions that can inform the next stage of smart-energy development in Italian port cities.

Methodologically, the paper contributes a transferable diagnostic architecture for contexts in which operational Digital Twin data are not yet fully available. By combining performance normalisation, integration maturity, implementation robustness and international functional benchmarking, it links the technical promise of EMS and Digital Twins to the institutional conditions that determine whether decarbonisation measures can be delivered and verified.

The study has limitations. The Italian inventories use different baseline years and, in the Genoa case, a wider system boundary than the technology-specific Pra' analysis. Several reported reductions are planned or modelled rather than measured ex post. Public planning documents also do not provide the real-time data needed to validate a Digital Twin or optimise an EMS directly. Future research should therefore integrate live metering, vessel-call and grid data; validate the carbon-intensity assumptions used for shore power; and test whether a common Digital-Twin-

enabled EMS architecture can improve both operational performance and realised emissions across heterogeneous port-city systems.

The practical implication is clear: the next step for low-carbon ports is not simply to add more digital platforms or more electrified assets, but to connect them. Digital Twins can make system interactions visible; EMS can convert that representation into operational choices; and verified feedback can turn decarbonisation plans from static portfolios into adaptive urban infrastructure strategies.

Author Contributions

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Conflicts of Interest

The author declares that there are no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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