DeCoInter – Decarbonisation of Maritime Sector and its Impact on Green Energy Transition

WP2 – Maritime ports and their regions as moderators of transition towards blue renewable energy

A2.3 Development of theoretical assumptions for a dedicated tool for mapping and prioritizing energy transition of seaport related activities.

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Introduction

The seaport sector occupies a pivotal position in the European Union's decarbonisation agenda. Ports work as complex nodes where maritime transport, shore logistics, energy systems, various institutions and urban environments intersect. As such, they represent concentrated points of greenhouse gas (GHG) emissions but also high potential for coordinated mitigation through electrification, alternative fuels, and systemic optimisation.

From a theoretical standpoint, transitions in ports can be viewed through the lens of socio-technical system transformation (Geels, 2011). Ports are multi-actor systems embedded within broader institutional and economic landscapes; therefore, change processes cannot be reduced merely to technological innovation. Instead, they depend on co-evolutionary dynamics among technology, regulation, market structures, user practices, and social expectations. This multi-level interaction is what drives large-scale sustainability transitions across sectors. The European Green Deal objectives, emerging amendments to maritime regulation and regional strategies have increased the demand for quantitative, harmonised monitoring systems that can support planning and policy compliance across ports (Geels, 2011).

Empirical studies in maritime and port-city contexts reinforce this understanding. According to Panagakos et al. (2019), European ports increasingly function as living laboratories for energy and digital transition, where decarbonisation pathways must integrate governance, spatial planning, and data-driven monitoring systems. Their findings highlight the urgent need for harmonised quantitative tools that allow ports to evaluate, benchmark, and coordinate transition actions across institutional and regional boundaries.

Within this framework, the DeCoInter Project WP 2 Activity 2.3 directly responds to the policy and analytical gap identified by Geels (2011) and Panagakos et al. (2019). It aims to develop a scientifically robust theoretical foundation describing what data, indicators, and structures are necessary to create a digital decision-support tool for mapping and prioritising activities related to the green energy transition of ports.

The envisaged DeCoInter digital tool will therefore be:
- Universal and scalable, enabling interoperability among ports of varying sizes and capacities;
- Data-driven and harmonised, capable of integrating multiple energy, environmental, and operational datasets;
and
- Participatory and multi-actor-oriented, reflecting the socio-technical nature of ports as identified in sustainability transition theory.

This approach builds on the body of research led by Henesey et al. (2003, 2005, 2009), who emphasise that sustainable port management requires the coupling of digital modelling with stakeholder interaction and system-wide intelligence. Their agent-based simulation and decision-support methodologies illustrate how data, organisational dynamics, and governance mechanisms co-determine port performance and adaptability during transition processes.

DeCoInter A2.3 seeks to combine the multi-level transition logic with the multi-agent governance and simulation frameworks by bridging conceptual theory with practical implementation for digital port ecosystems.
The digital tool conceptual assumptions were agreed upon during expert workshops involving project partners and during previous activities within the project.
The tool shall support ports in:

- Mapping greenhouse gas (GHG) emissions
- Identifying emission hotspots
- Simulating energy transition scenarios
- Supporting ESG and CSRD-compliant reporting
- Prioritising decarbonisation investments

The tool is not intended to function as a real-time digital twin. Due to budget and data constraints, it should operate primarily on structured manual data input and predefined templates. The structure of this A2.3 is organised as follows:

a) Introduction;
b) Analysis of the theory about existing socio-technical systems;
c) Analysis of the multi-level perspective (MLP);
d) Analysis of multi-stakeholder governance principles;
e) Analysis of the geographic information systems (GIS) and spatial analysis;
f) Analysis of the sustainability assessment frameworks;
g) Analysis of the digital twin concept;
h) Discussions;
i) Conclusions.

All these components will collectively provide the theoretical and methodological foundation for the creation of the DeCoInter Digital Twin Tool under Activity 2.4, supporting the long-term decarbonisation and digitalisation of the South Baltic port ecosystem.
This document defines the technical and functional requirements for the development of a digital tool for mapping and prioritising the energy transition of seaport-related activities.

The document is intended for the IT company responsible for the design, development, testing, and implementation of the tool.

Socio-Technical Systems

Ports represent dynamic socio-technical ecosystems shaped by the interactions of technology, institutions, organisations and people. Understanding these interdependencies is essential for developing a digital tool that can meaningfully support the energy transition process.

Ports are a multi-layered structure co-depending on each layer for its successful co-working. To put it in an easy-to-understand sequence:
- **Technology** provides the means.
- **Institution** provides the rules.
- **Organizations** provide the coordination.
- **People** provide the adaptation and meaning.

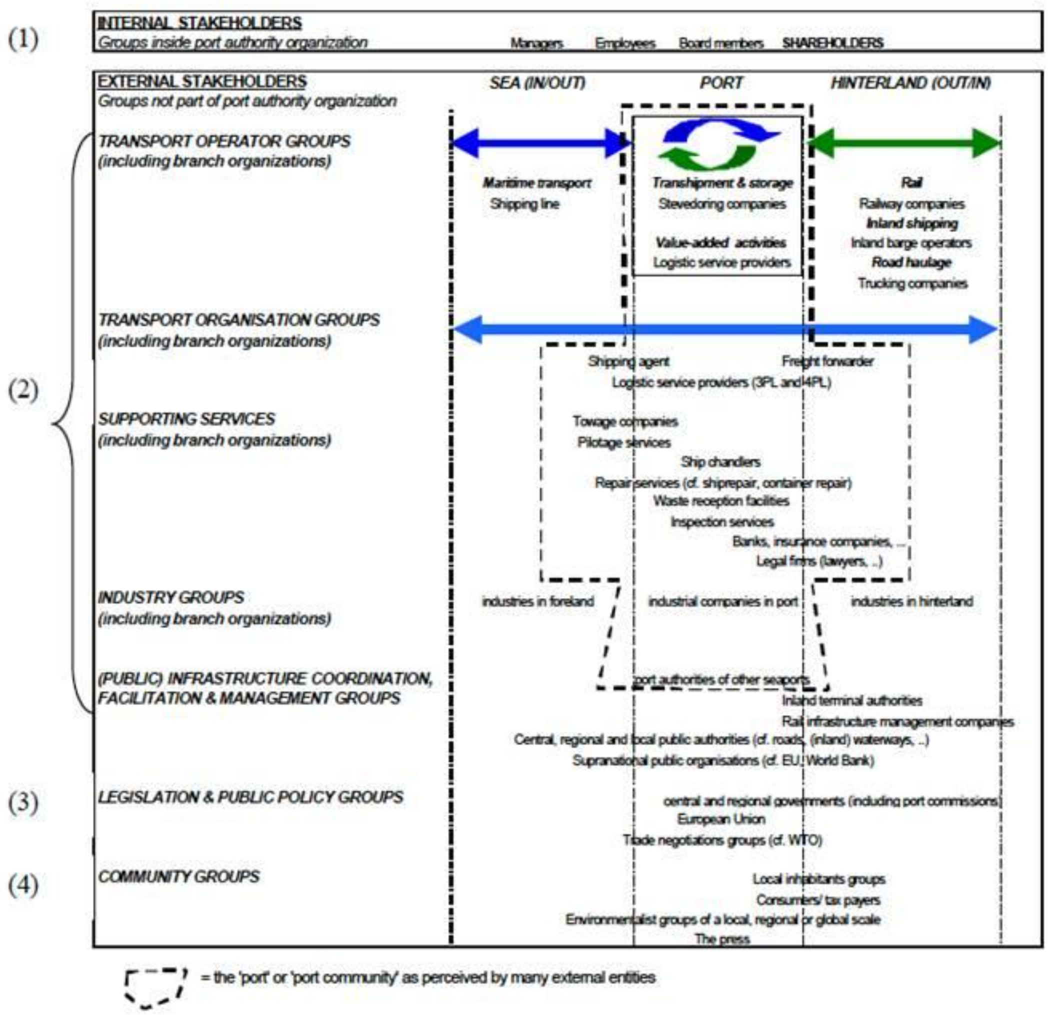
Following (Markard et al., 2012) ports can be conceptualised as multi-layered systems where technology provides the means; institutions provide the rules; organisations provide the coordination; and people provide adaptation and meaning. In particular, existing socio-technical systems are aggravated by path-dependence and lock-ins (Klikou et al., 2015). These layers do not operate independently. Mature port technologies are interwoven with user practises, complementary technologies, value chains, business models, institutions and political structures: together these elements constitute a meso-level ‘socio-technical regime’ (Markard et al., 2012; Rip & Kemp, 1998). Due to this complexity, technological change tends to be incremental, and the emergence of radical innovations requires structural change (Damman and Steen, 2021). So far, the focus has been on individual technologies and systems, but now there is a growing interest in linkages and interactions across multiple systems (McMeeking et al., 2019). Loorbach and Geerlings (2017) see the situation of ports as a lock-in: enormous infrastructure investments have been made, and practices and institutions have been developed to facilitate the current regime. However, given the external pressures linked to climate change and the development of niche innovations, it is likely that over time tensions in the current regimes will lead to systemic change. Achieving sustainability transitions therefore requires structural reconfiguration rather than isolated technological fixes.

Daniel, Makokha, Ren and Olatunji (2025) scoping review of digital transition of critical infrastructure in maritime ports illustrated that when port fails or under-performs in critical energy infrastructure transition (CEI) or even digital transition, it often is because of a misalignment of the socio-technical layers rather than just a tech bug. The study found that the key challenges to digital transition in CEI in maritime include skill shortages, resistance to collaboration, unclear ROI, and wide disparities in digital maturity. Their transformative potential is constrained by insufficient integration, underutilised data, and misalignment between stakeholders and governance structures.

Henesey et al. (2003) contribute to this understanding by analysing the port community as a set of stakeholder relations that can be simulated using multi-agent modelling, thereby exposing the socio-technical layers and their mutual dependencies. Their work emphasises that effective port governance and transition cannot rely solely on technical innovations but must also address institutional and organisational dynamics.

1. **Picture**
   The port community stakeholders according to the L.Henesey et al. 2003

Figure 1. The Port Community Stakeholders according to the Authors



Each port is a living ecosystem and if one layer fails, the system's integrity collapses – which is why socio-technical analysis is very valuable for the DecoInter project. Based on analysed resources these questions should be answered when reviewing the organisations adaptability to change:

1. What are the major actors (organisations) and what roles do they play?
2. What are the key technologies and infrastructures, and how do they integrate?
3. What are the formal rules/institutions governing the system, and what informal practices shape what really happens?
4. How do people (workers, managers, operators) experience and shape the system?

5. What are the dependencies and feedback loops (e.g., data informs decisions; decisions change processes; processes create data)?
6. Where are the vulnerabilities and how does the system recover from disruptions?

Multi-Level Perspective (MLP)

Multi-Level perspective (MLP) and Socio-Technical systems (STS) are related but distinct frameworks are used to analyse how technology, society, and institutions interact, especially in processes of innovation and sustainability transitions. While STS focuses on how social and technical elements are interdependent within a system and how they co-evolve, and shape each other, MLP focuses on how transitions (major system changes) occur over time, describing how innovations move from small niches to replace dominant socio-technical regimes under broader landscape pressures. For example, sustainability transition from fossil fuels to renewables.

F. W. Geels (2002) in his "Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study" research policy proposed that multi-level perspective uses three analytical levels:

1. Niche (micro): protected spaces where radical innovations emerge.

2. Regime (meso): dominant, stable configurations of practices, rules and technologies.

3. Landscape (macro): broad external environment (culture, politics, economy, climate change, etc.).

In the research about small and medium-sized ports (SMSPs) sustainability transition researchers L. Gerlitz, C. Meyer and L. Henesey (2024) explain MLP analytical levels in clearer words. Micro level as a firm level, as firms operating in ports. Meso level as a port ecosystem. And macro level as an intervention with regional, national, or global socio-technical systems. They add that one requires not only systemic, but holistic understanding of ports and involvement actors from Quadruple helix – academia, business, policymakers and society at large. A holistic approach is also needed in the design of command-and-control regulations in shipping. I. Stalmokaitė and J. Yliskylä-Peuralahti (2019) highlights that even though regulations play a role in motivating shipping companies to advance their sustainability practices, a partial solution, focused on one emission source only, might increase emission levels of another when solving a particular environmental problem with newly introduced environmental technology. It is concluded that there is a need to understand the role of other policy instruments like market-based measures, private standards and policy mixes in polycentric maritime environmental governance.

When planning the practical MLP use in the DecoInter projects activity 2.3, the tool should help identify where the port stands in the energy transition and support decision-making for sustainable transformation. For example, analyse the niche innovations, current regimes, policy instruments, external pressures, market-based measures etc., to help make a knowledge-based decision towards greener energy transition. One should ask and answer questions based on the analysed research and use three MLP analytical levels:

1) Niche (micro) level:

- What radical innovations or practices exist? (technical prototypes, demos, pilot projects).
- Who are the niche actors? (startups, research groups, lead users, NGO projects, pilot ports, firms working in ports).
- What resources and protection do niches have? (funding, regulation exemptions, testbeds, living labs).
- How are expectations and narratives formed and stabilized? (promotional material, consortium visions, roadmaps).
- What learning and articulation processes are happening? (R&D learning curves, standards development, demonstration results);
- Evidence of scaling momentum? (growing deployments, investor interest, supply-chain emergence).

2) Socio-technical regime (meso) level:

- What elements compose the current regime? (Main technologies, infrastructures, business models, regulations, standards, professional practices).
- Which organizations and networks coordinate and reproduce the regime? (incumbent firms, port authorities, utilities, trade associations).
- Which formal and informal rules and routines maintain stability? (regulations, procurement rules, training, insurance practices).
- Where is the regime experiencing tensions or performance problems? (congestion, emissions limits, cost pressures, reputational risks);
- What incumbent responses to niches exist? (adoption, co-optation, lobbying, minor adaptations).

3) Socio-technical landscape (macro):

- Which slow/large trends and shocks are relevant? (policy shifts, climate targets, fuel price shocks, geopolitics, social norms).
- Are there sudden landscape events (shocks) creating windows of opportunity? (crises, new international rules, major subsidies);
- How stable or volatile are landscape pressures? (gradual vs abrupt — affects pathway type).

Analysed literature suggests that we should also include a cross-level dynamics level, which would act as key diagnostic questions:

- Do landscape pressures create windows of opportunity for niches? If so, when and why? (F. W. Geels, 2001);
- Are niches sufficiently matured and aligned to exploit regime weaknesses? (tech readiness, business models, actor coalitions) (F. W. Geels, 2001);

- Is the regime being adjusted (transformation/reconfiguration) or replaced (substitution/de-alignment)? (Geels & Schot 2007).
- What transition pathway best fits the observed interactions? (transformation, reconfiguration, technological substitution, de-alignment & re-alignment) (Geels & Schot 2007).

Multi-Stakeholder Governance Principles

Ports are socio-technical ecosystems involving multiple independent yet interdependent actors. Governance depends on transparent information exchange, trust-building and structured participation. Henesey et al. (2003) introduced a stakeholder-mapping framework identifying four principal groups: Internal Stakeholders, External Economic Stakeholders, Legislation & Public Policy Stakeholders, and Community Stakeholders. Their modelling emphasizes simulation of “what if” stakeholder-relation scenarios to support decision-makers.

In order to create “what if” scenarios, creators of the digital tool must ensure that there exists a shared vision or strategic alignment that ensures every stakeholder to a common long-term vision for decarbonization and resilience of the port eco-system. There should be a joint strategic roadmap, co-developed energy transition plan, in alignment with national climate goals and municipal plans.

There is also a need for transparent and standardised information exchange between stakeholders and, in order to reach that, DecoInter digital tool could work as a functional shared digital platform or data hub that has a specific data governance framework for data sharing. For example, every stakeholder has to accept and use certain formats, information sharing frequency, confidentiality rules, etc. As mentioned before it also could ensure operational transparency, where stakeholders could reach information about ports‘ energy demand or supply statistics, show shared forecast for vessel traffic, grid loads, renewable integration, etc. In order to be trusted the digital tool also could use verification and audacity indicators like third-party verification of emissions data or agreed carbon accounting methodology (e.g. GHG Protocol for ports). The table below could be used as an inspiration for what measurements could be monitored and what indicators to measure their activity used.

1. Table

Suggested measurements and corresponding activity indicators

Principle	Core criteria	Example indicator (measure)
Shared Vision & Strategic Alignment	Co-created roadmap; scenario planning	Published roadmap; # of joint milestones achieved
Transparent Information Exchange	Data governance; shared platform	Existence of data hub; % of actors uploading validated data
Participatory Decision-Making	Formal council; inclusivity	Council meeting frequency; stakeholder diversity index
Roles & Accountability	RACI; KPI ownership	RACI published; % KPIs with named owners
Fair Cost & Risk Sharing	PPPs; tariff transparency	% of project capex shared; cost allocation formula in contracts
Regulatory Alignment	Regulator participation; permitting sync	Time to permit (days); alignment score to national policy
Environmental & Social	Air/water monitoring; workforce transition	Local NOx/PM trends; # retraining slots offered
Innovation & Learning	Pilots; R&D partnerships	# pilots active; lessons learned published
Monitoring & Continuous Improvement	Dashboards; audits	Dashboard availability; # audits per year

An important part of multi-stakeholder governance principles and monitoring, reporting and continuous improvement where progress toward energy transition goals is tracked, independently evaluated, and adjusted based on evidence. This could be done by implementing a KPIs dashboard where digital tool could show real-time or quarterly dashboard showing energy use, emissions, project status. Every transition element should have defined KPIs. Forward thinking to the digital twin concept, this dashboard could be duplicated where it would adapt to the changes made during the energy transition simulations and maybe even indicate the effect done by showing distinct colors in the dashboards' dimension fields.

To put theory into a practice, there are real life examples, where ports implement Multi-stakeholder governance principles into their management. The very well-documented case is a Port of Rotterdam (Netherlands) where port authority is acting as a convener for multi-stakeholder collaboration (terminals, shipping lines, logistics providers, municipal/regional government, knowledge centers, and utilities). Initiatives include Portbase (data-sharing / single window), joint decarbonisation consortia, Just-In-Time arrival coordination, and EU-funded alliances for zero-emission logistics — all set up to coordinate investments, operations and digital/energy infrastructure across actors. These arrangements combine operational data sharing, joint projects, and formal governance roles (Chandra and Hillegersberg, 2017). Another example could be Alamoush et al. (2024) research on stakeholder management for port energy projects and comparative reviews of sustainability drivers in ports where authors proposed a 5-step life-cycle stakeholder management approach for Port Energy Transition Projects (PETPs). They identified 22 stakeholder groups potentially involved in PETPs and proposed the five steps on when to include each stakeholder group: Identify → Prioritise → Visualise → Engage → Monitor. They argue this lifecycle helps port managers design engagement strategies, build trust and allocate resources.

Geographic Information Systems (GIS) and Spatial Analysis

Every port is uniquely designed to its geographical location and infrastructure. Location, proximity, and physical capacity matters when considering energy infrastructure in ports which is strongly spatial. Digital tool creators should not only include in-land infrastructure, but the one in the water as well. For all the mentioned purposes, DecoInter digital tool should include Geographical Information system (GIS) for current and planned infrastructure (cabtos, berth lengths, different storage zones and terminal types of cargo, etc.), as well as their impact on port areas and logistics to help improve port environmental score.

GIS is a technology with a general purpose – adaptable technology for managing ports space. Also, GIS has capabilities in the fields of design, analysis and simulation, which improves management of port space and increase decision-making capacity (Rodellas et al. 1998).

In their work Rodellas et al. described how GIS was implemented for the berth management in the port of Barcelona. This technology allowed not only daily monitoring of the vessels in the port but also made it possible to view the occupancy of the wharves on a particular day or during a specific period of time. Authors shared that at the time (year 1998) current management was based on a combination of the log of wharf occupancy by vessels and an icon representation to scale of port wharves and vessels. The status of the vessel in the information system (request, authorised, in port, about to depart) was represented by distinct colors. If a temporal representation of the past or scheduled occupancy of the wharf was required, the wharf-time diagram had been generated.

Since GIS stores information about different port elements and characteristics (occupancy of the berthing line, use of cranes, rails and road network, mooring posts, ramps, water depths, etc.), it could also be implemented for traffic simulation when looking for the environmentally friendliest solutions. Author Stadnikov, V. (2025) reviews GIS implementation examples in major global ports of Rotterdam, Hamburg, Antwerp and Barcelona. This review states that the experience of these ports demonstrates that GIS enables logistics optimization, land-use control, monitoring the technical condition of engineering networks and real-estate objects, environmental monitoring as well as safety and emergency-risk forecasting. Although this passage does not explicitly list specific datasets, it defines the themes and object classes that GIS must handle in order to achieve these results. Because GIS is used for controlling land use, it must work with this spatial data:

1. parcel boundaries.
2. land-use zoning layers.
3. functional areas of the port (industrial zones, logistics areas, hazardous zones, etc.).

GIS supports monitoring the technical condition of engineering communications. This means GIS uses engineering network and infrastructure data such as:

1. underground and above-ground utilities.
2. pipelines (fuel, oil, water, sewage).
3. electricity, communication, drainage systems.
4. structural elements of port facilities.

Monitoring the technical state of real-estate objects requires GIS data such as:

1. building footprints (vector).
2. construction parameters.
3. technical passports.
4. operational status.

GIS is used for logistics optimisation and it requires:

1. road networks (internal port roads, rail lines).
2. cargo flow paths.
3. terminal layouts.
4. berth locations.
5. storage yard geometry.

To enable GIS environmental monitoring, there is a need for the use of:

1. environmental condition datasets.
2. contamination/pollution monitoring layers.
3. air/water quality measurements.
4. ecological protection zone boundaries.

The system supports analysis and forecasting of emergency situations, meaning GIS uses:

1. hazard zones.
2. risk models.
3. accident history and incident locations.
4. spatial topology for predicting vulnerable areas.

Sustainability Assessment Frameworks

The energy transition in seaports requires a multidimensional sustainability assessment capable of integrating environmental, technical, social, and governance factors. Recent research emphasizes that ports must move beyond traditional environmental reporting and adopt holistic, metrics-based frameworks that monitor progress toward decarbonisation, operational transformation, community wellbeing, and transparent governance (IAPH, 2023; Puig et al., 2017). The framework presented here synthesizes findings from port decarbonisation literature, GHG accounting research, and sustainability management standards such as EcoPorts PERS, GRI, and the World Ports Sustainability Program.

Energy consumption, renewable energy share, and greenhouse gas emissions (Scopes 1–3) form the core of the assessment. Studies agree that GHG reduction is the most critical element of port transition pathways (Shen et al., 2025; Acciaro et al., 2014). Measuring absolute emissions alongside intensity metrics (e.g., kg CO_2e/ton cargo) enables cross-port comparability and avoids biases related to port size. Shore power adoption and tCO_2 avoided are included because shore-side electricity consistently ranks as one of the most impactful measures for reducing local air pollutants and berth-related CO_2 emissions (Holder, 2024; van Duin et al., 2022). Tracking the share of renewable energy is essential for determining how quickly a port is decarbonising its own operations (Cholidis, 2025).

Also, technical readiness - electrification of cargo-handling equipment, provision of alternative fuel bunkering (hydrogen, ammonia, methanol), renewable generation capacity, and grid adequacy - directly influences a port's ability to enable low-carbon operations (Lindstad & Eskeland, 2022). Research stresses that electrification feasibility and grid interconnection capacity are often the primary bottlenecks for port decarbonisation (Gkonis & Psaraftis, 2020). Digitalisation indicators (energy management systems, smart charging) are included because smart control can reduce peak loads and improve overall system efficiency (Taneja et al., 2021).

Beyond climate mitigation, ports must protect air quality, water resources, and local ecosystems. NOx, SOx, and particulate matter monitoring is scientifically justified by their strong correlation with health outcomes in port-adjacent communities (Johansson et al., 2020). Biodiversity and habitat restoration metrics reflect best practices in coastal ecosystem management (Puig & Darbra, 2019). Climate-resilience indicators (adaptation planning, flood-risk mitigation) follow the growing body of literature demonstrating that sea-level rise and extreme weather pose substantial risks to port infrastructure (Hallegatte et al., 2013).

Yet another important sustainability measurement is social responsibility. Social responsibility - such as safety performance (LTIFR), local employment, and workforce transition programs - is increasingly recognized as integral to a just transition in port environments (Merk, 2022). Governance indicators measure transparency and alignment with international reporting standards; research shows these factors improve stakeholder trust and accelerate decarbonisation investment (Puig et al., 2017). Including green-investment share reflects findings that energy transition progress depends heavily on capex allocation and access to sustainable finance (OECD, 2021).

2 Table

Sustainability assessment framework for port's energy transition

SUSTAINABILITY ASSESSMENT FRAMEWORK FOR PORTS' ENERGY TRANSITION

PILLAR	INDICATORS	UNIT	DATA SOURCES
PILLAR A Energy & Emissions	Total GHG emissions (Scopes 1, 2 & 3)	tCO_2e/year	GHG inventories
	GHG intensity	kg CO_2e/TEU	GHG inventories
	Share of renewable energy	%	Energy meters
	Electricity consumption	MWh/year	Energy meters
PILLAR B Operational & Technical Transition	% of cargo handling equipment electri-	%	Equipment inventories
	Alternative fuel bunkering capacity	H_2 MW	Infrastructure records
	Installed port renewable generation ca-	MW	Infrastructure records
	Energy storage capacity	MWh	Infrastructure records
	Grid interconnection capacity adequacy	%	Grid operator data
PILLAR C Environment & Resilience	NOx, SOx, PM emissions	tons/year	Air quality monitors
	Water pollution incidents	number/year	Incident reports
	Area of natural habitat preserved or rest-	hectares	Environmental reports
PILLAR D Social, Governance & Finance	Lost Time Injury Frequency Rate	LTIFR	Adaptation plan
	Workforce transition programs	✓ %	HR records
	Local procurement & employment hare	%	Procurement records

This framework above is grounded in contemporary scientific research and port-sector sustainability standards. It integrates emissions reduction, technological transformation, ecological stewardship, and social wellbeing - dimensions consistently identified in the literature as essential to assessing the true sustainability of port-energy transition pathways. By combining target-based scoring, transparent reporting, and scientifically justified indicators, the framework supports robust monitoring and comparable performance assessment across global ports.

Digital Twin Concept

European ports are striving for technological solutions to cope with their environmental footprint dictated by strict EU regulations towards green ports. There is an emerging digital twin technology that has the potential to increase the energy transition and efficiency of the multifaceted and interconnected port processes. The downside is - there is still a lack of cross-domain understanding of what constitutes a digital twin.

First, there is a need to understand how Digital Twin (DT) concept is understood in literature. Sepasgozar, S. M. E. (2021) explains DT as a technology facilitating the connectivity required between the physical environments and digital ecosystems, for example, advanced automation, the implementation of robotics, improvements in machine-to-machine (M2M) communication, and human-to-machine or human–computer–machine communications. The only consensus in reviewed literature is that a DT is a digital representation of a physical object. It is useful for monitoring, controlling, or inspecting physical objects such as a vehicle.

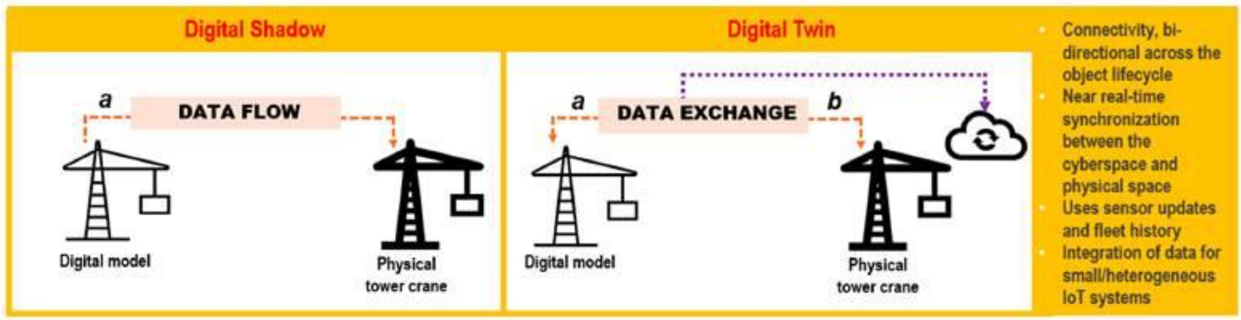
Drawing on the work of Jiang et al., some of the core aspects of the digital twin are summarised here:

1. Components: a digital twin and its physical counterpart consist of Physical Entities, Virtual Models, Physical-Digital Connections, Data, and Services, both in the real world, which need to be modelled, and those in the cyber world.
2. Temporal span: a digital twin is designed to mirror its physical counterpart throughout its life cycle (design, prototyping, manufacturing, deployment, maintenance, and disposal). Creator of the digital tool must note that each of these phases, comprising different functionalities, may require different timescales at which components will have to operate.
3. Functional scope:
    - Modelling: a digital twin is a grouping of models and algorithmic components that jointly describe a complex system and allow to estimate the impact of likely outcomes, e.g., to test what-if scenarios and enable predictive maintenance.
    - Visualization: a digital twin enables a digital replica of all static and dynamic processes as well as the components of its physical counterpart.
    - Interaction: a digital twin is characterized by its bidirectional character, enabling it to directly influence the actual system based on its actions, changes, and predictions.
    - Synchronization: the digital twin is continuously updated in a timely manner by various components and processes of the actual system whenever needed.
    - Self-Improving: a digital twin is a (self-)improving system that can be progressively improved and extended through the increasing accumulation of data and knowledge over time.

There is a similar concept to a Digital Twin – a Digital Shadow (DS). The difference between DT and DS is that while DS is the one-way data flow, DT data is exchanged between both the virtual and physical entities (Figure below) (Sepasgozar, S. M. E. (2021)). Comparing different definitions, it is evident that the more recent definitions of DT focus on dynamics, learning, and evolution, rather than just being digital shadows of static objects in the real world (Klar et al.).

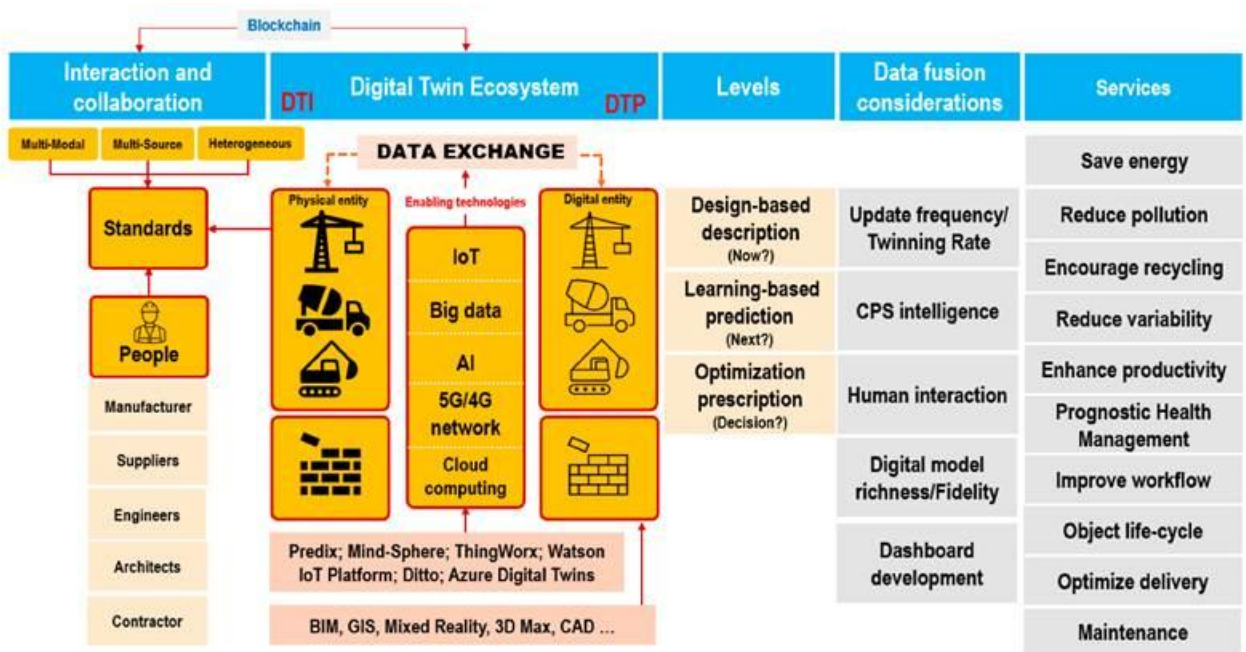
2 Picture

Difference between Digital Shadow and Digital Twin



Cholidis et al. apply digitals twin as a framework incorporating digital shadow technologies enabling real-time system monitoring, simulation, and long-term optimization. However, DS does not allow the bi-directional data exchange which allows self-optimisation based on the returning data which is available via DT. Klar et al. identify digital twins as providing situational awareness and comprehensive data analytics capabilities for intelligent decision-making, comparable to complex systems in smart cities and supply chains. The Liu et al. study proposes a Digital Twin + Blockchain model for enhanced transparency and traceability. Although definitions and characteristics differ, analysed literature demonstrates that digital twins among various domains have common objectives, including fault detection, product/process optimization, evaluation of potential operation scenarios, monitoring, and the ambition to save costs while enhancing safety and sustainability (Klar et al.). Sepasgozar, S. M. E. (2021) suggests that DT can have more services that are shown in the following figure.

3 Picture
Digital Twin services



Authors Klar et al. mention that ports serve not only as industrial clusters, but as well as an information hubs. As ports handle a multitude of processes performed by a variety of actors in parallel, it is increasingly important to improve the overall view of port processes and identify potential bottlenecks to increase efficiency, safety, and sustainability throughout the port ecosystem. Consequently, the implementation of the port's digital twin should provide an elevated level of connectivity and visibility to provide situational awareness that best benefits the many transportation chains that pass through the port. Beyond situational awareness, ports also benefit from higher levels of automation, as terminal automation can directly improve performance indicators such as cost, efficiency, safety, and reliability. (Notteboom et al.).

Increased terminal automation is also needed to cope with the increasing size of cargo ships and growing freight volumes. According to Vis et al., on paper, operations take place at five different areas, namely at the berth, quay, transportation, yard, and gate, leading to a large magnitude of interlinked processes that can be classified into strategic and operational problems. A second requirement for the port's digital twin is therefore to provide data-driven analytics to aid holistic decision-making. Furthermore, the port is a hub of numerous processes involving multiple actors and dimensions. Ports not only align the interests of employees, management and shareholders, but also serve with a wide range of stakeholders, including terminal operators, vessel operators, railways, shippers, industry associations, municipalities, and government agencies. A third requirement for the port's digital twin suggested by Vis et al. is therefore to foster cooperation between the various port stakeholders.

WP2.1 data adaptation for WP2.3 Theoretical foundation for digital tool

WP2.1 report analysis on the development status of the blue renewable energy potential in the South Baltic Region (Germany: Mecklenburg Western Pomerania, Poland, Lithuania, Latvia, Estonia, Sweden, Danmark), where the key task was to estimate the supply potential and do an availability schedule analysis showed that current developments across the region demonstrate varying degrees of maturity in blue renewable energy deployment, from Sweden's ambitious offshore wind expansion plans targeting 90 TWh of additional capacity, to Poland's ORLEN offshore wind projects in the Ławica Odrzańska area, and Denmark's established position as a global leader in offshore wind technology. Major ports including Rostock, Gdynia, Klaipėda, Liepāja, Tallinn, Malmö, and Copenhagen are increasingly recognizing their potential to integrate marine renewable energy sources—including offshore wind, solar, tidal, wave, and marine biomass - into their operational frameworks while simultaneously supporting broader regional decarbonization goals.

However, significant challenges persist across technical, regulatory, financial, and collaborative dimensions. These include complex spatial planning requirements, marine biodiversity protection concerns, grid connectivity limitations, regulatory constraints, funding gaps, and coordination challenges among diverse stakeholders ranging from port authorities and energy utilities to private operators and municipal governments. The integration of emerging digital technologies and AI tools for energy forecasting and transition planning adds another layer of complexity while offering unprecedented opportunities for optimization.

After analysing all the given concrete examples from South Baltic region ports the following table was created in order to group energy transition barriers into types, mitigation measures mentioned in the report, real life examples and good practices on how the limiting factor could be lifted. The "Limiting Factor - Good practice examples" table below could be used as an example when programming the digital tool for ports that are planning their energy transition by covering part of the possible real life example limitations.

3 Table

Limiting Factor - Good practice examples

Barrier / Limiting factor	Type	Mitigation measure mentioned in report	Concrete port example from report	Good practice / reference activity
Lack of long-term planning certainty	Governance / Policy	National and regional port energy transition strategies	German ports long-term hydrogen and electrification roadmaps	Integrated port energy masterplanning
Fragmented governance & many stakeholders	Governance	Creation of coordination platforms and port-led steering groups	Baltic pilot ports cooperation structures	Port authority as energy transition orchestrator
Insufficient grid capacity	Technical / Infrastructure	Grid reinforcement & staged infrastructure planning	Lithuanian port grid bottleneck case	Early grid planning with TSO/DSO

High investment costs	Financial	Blended finance, EU funding, public co-investment	Interreg / CEF-funded pilot infrastructures	Phased investment & public-private co-financing
Uncertain demand for alternative fuels	Market	Pilot projects, anchor customers	Hydrogen and shore power pilots in German and Danish ports	Demand aggregation & lead user strategy
Lack of standardisation (fuels, plugs, interfaces)	Technical / Market	Alignment with EU standards and TEN-T framework	OPS standardisation examples	Standards-first infrastructure deployment
Limited space in ports	Spatial / Planning	Multi-use infrastructure & spatial integration	Compact energy hubs in Baltic ports	Energy hub concept in ports
Risk-averse private investors	Financial / Market	Public risk-sharing & guarantees	Public-backed pilot investments	De-risking through public anchor projects
Lack of skills and institutional capacity	Social / Organisational	Capacity building and knowledge transfer projects	DeCoInter knowledge exchange activities	Port staff energy transition training programs
Unclear business cases	Financial / Market	Stepwise scaling & temporary subsidies	Early OPS business case examples	Start with captive fleets / regular lines
Slow permitting procedures	Regulatory	Early authority involvement & strategic planning	Infrastructure permitting examples	Parallel permitting & planning processes

Also, data from WP2.1 can be categorised differently by showing digital tool users existing projects from the South Baltic Sea region. The users could be offered to use other ports' good practices and generate a good ports' example driven energy transition. In this way, data from WP2.1 needs to be categorised in a different way shown in a 'South Baltic Region ports good practices' table below.

4 Table

South Baltic Region ports good practices

Concrete action / project	Port / Region	Purpose	Status
Large-scale shore power for cruise ships (20 → 48 MVA)	Copenhagen Malmö Port	Eliminate ship emissions at berth	Operational / expanding
Shore power for ferries	Copenhagen Malmö Port	Reduce emissions	Operational since 2021
Shore power in Aarhus	Port of Aarhus	Emission reduction	Operational, expanding
Shore power in Fredericia (CEF-funded)	ADP Fredericia	Decarbonize container vessels	Under construction
Green hydrogen plant (2.25 MW PEM)	Klaipėda	Fuel port equipment & vehicles	Under construction, 2026
OPS for Ro-Ro & cruise vessels	Klaipėda	Electrify ships at berth	Under construction
Quay electrification	Klaipėda	Enable OPS	Completed / ongoing
Port Electrification Study	Klaipėda	Grid & demand planning	Ongoing 2025–2026
SAF production plant (Arcadia eFuels)	Vordingborg	E-fuels for aviation	Permitted
Biomethane plant (Green2X)	Vordingborg	Renewable gas	Planned
100 MW hydrogen electrolyzer	Rostock	Green hydrogen production	Under construction
LNG bunkering vessel	Klaipėda	Transitional fuel	Operational since 2017
Rooftop PV at port tenants	Klaipėda	On-site RES	Operational
Microgrids + battery pilots	Rostock, Sassnitz	Grid stability	Pilot
Digital twins & AI energy systems	MV ports	Energy optimization	Pilots

However, WP2.1 analysis showed that there are more just not yet implemented green energy project opportunities that have to be tested first. These opportunities are shown in the 'Green Energy Opportunities in the South Baltic Region' table below. The green energy opportunities table represents three columns starting with the limiting factor, then what are the opportunities to solve it and how it removes the limitation. However, each of these examples given in the table needs to be explored and researched first in order for the port to use it, so it stands only as an idea on what could be implemented to help ports in Green energy transition.

5 Table

Green Energy Opportunities in the South Baltic Region

Limiting factor	Additional good practice	What it solves
Space constraints in ports	Floating solar in basins	Uses unused water surface
Grid congestion	Port island-mode microgrids	Resilience & peak control
Grid dependency	Energy diversification strategy	Security of supply
Permitting complexity	Pre-zoned “energy areas” in ports	Faster approval
Investment risk	Energy-as-a-Service models	Reduces CAPEX burden
Variability of RES	Large-scale thermal storage	Seasonal balancing
Hydrogen uncertainty	Ammonia / methanol pilots	Alternative fuels
Stakeholder conflicts	Participatory energy planning	Social acceptance
Fragmented governance	Port Energy Transition Office	Coordination
Lack of flexibility	Mobile / modular OPS & H2 units	Phased deployment

These are the examples on how the collected data from South Baltic Region Ports could be used in the DeCoInter Digital Tool energy transition planning. Theoretically speaking, the digital tool could use the data from these tables with good practice real life examples and after evaluating the ports data and depending on the specific ports’ situation and needs - offer to implement some of the good practices in their port solving the limiting factor as well as upgrading the ports infrastructure. The good practice data from surrounding ports in the same region would be very useful information in the energy transition planning.

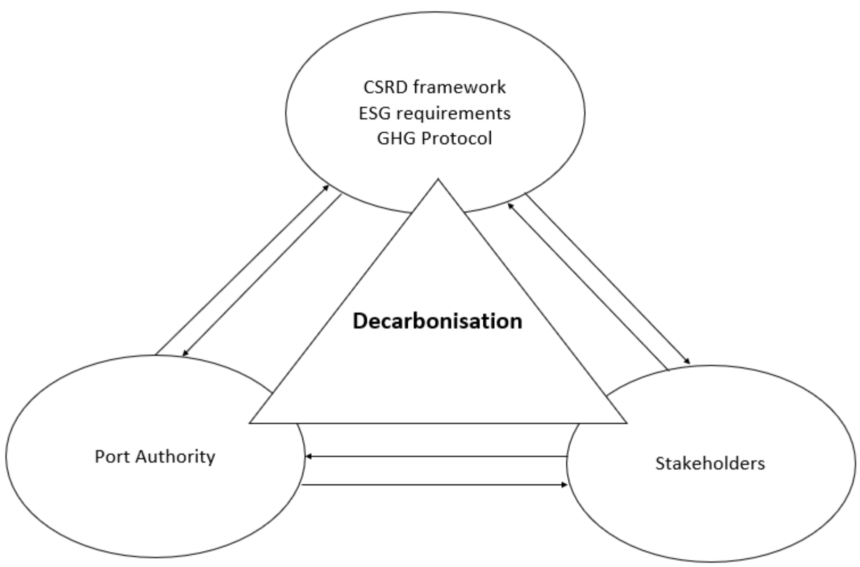
Description of the DeCoInter Digital tool stakeholders

Like any complex project, the DeCoInter digital tool is being developed to address the needs and expectations of three main stakeholder groups. The concept of stakeholders, as well as the importance of their inclusion and their role in project governance, have been discussed earlier in this work. Building on that foundation, this section focuses on explaining the three principal stakeholder groups that are taken into account in the design and development of the DeCoInter digital tool for port energy transition planning.

Since the success of such a tool depends on its ability to support decision-making across different parts of the maritime and logistics system, it is essential to consider the perspectives and operational realities of all relevant actors. For this reason, the tool is designed to serve three core stakeholder categories, each representing a key component of the port energy transition ecosystem: Ships, Ports, Inland stakeholders.

4 Picture

The port energy transition ecosystem



Together, these stakeholder groups cover the full scope of activities and interactions involved in port operations and hinterland connections, ensuring that the digital tool supports a coordinated, inclusive, and effective approach to energy transition planning.

In this context, the stakeholder categories are intentionally defined in broad and abstract terms. Rather than referring to individual entities, these labels represent complex groups of actors and systems. To properly understand their role in the DeCoInter digital tool, it is therefore necessary to explain what is encompassed within each of these stakeholder categories.

The stakeholder group referred to as "Ship" represents the wide variety of vessels involved in maritime transport, each of which consumes different amounts of energy depending on the distance travelled and the nature of its operations. Ships differ significantly in their technical and operational characteristics, including fuel type and consumption, crew size, physical dimensions, cargo capacity, and the type of goods they carry. In addition, vessels are operated by companies from different countries, each subject to distinct regulatory frameworks and corporate priorities. This diversity means that energy demand and operational behaviour can vary considerably from one ship to another, making it essential for the digital tool to be able to account for these differences in its analyses and planning functions.

The "Port" stakeholder represents the wide range of ports that may be involved in the energy transition process. Each port has a unique territorial layout, spatial structure, and geographical context. Some ports are located far from urban areas, while others are embedded within the city and function as an integral part of a smart city ecosystem. Ports also differ in terms of their infrastructure, including machinery, buildings, terminals, docks, and other equipment operating within their boundaries. Furthermore, ports vary in size and activity level: some handle very high traffic volumes, while others operate at a more modest scale. As a result, their energy needs differ substantially, which makes energy planning tools particularly important. As highlighted in the WP2.1 analysis, not all ports have the same ability to access or deploy green energy solutions, due to factors such as regulatory frameworks, geographical location, grid connectivity, environmental permitting procedures, and spatial planning constraints.

In order to properly capture this diversity, a port should not be viewed as a single, uniform entity, but rather as a system that can be segmented both functionally and structurally. From a functional perspective, port activities can be divided into three main operational areas: maritime operations, terminal operations, and hinterland operations. Maritime operations include activities related to vessel access, navigation, berthing, and safety; terminal operations focus on cargo handling, storage, and internal logistics; while hinterland operations cover the connections between the port and inland transport networks, such as road and rail systems. Each of these operational areas has distinct processes, infrastructure, and energy consumption profiles that must be considered separately within the digital tool.

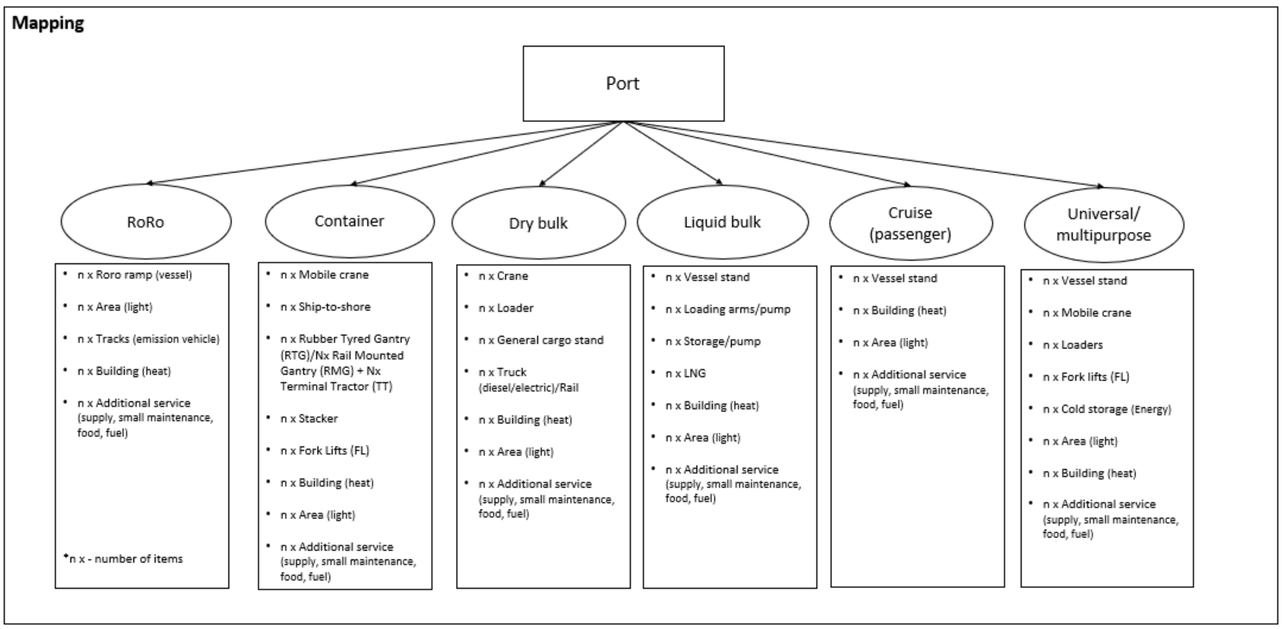
In addition to this functional segmentation, ports can also be classified according to different structural and organizational archetypes. A port may be a sea port or a river port; it may host a container terminal, RoRo terminal, bulk or break-bulk terminal, or liquid and gas terminal, and in many cases, a single port may include several of these segments simultaneously. From a governance and business perspective, a port may be publicly owned, privately operated, or dedicated to a specific industrial or factory purpose. Moreover, ports can play different roles within the global logistics network: some function primarily as gateway ports, serving a specific hinterland, while others operate mainly as transshipment hubs connecting international shipping routes.

Ports can also be categorized by size and throughput, for example as large ports (with annual throughput equal to or greater than 30 million tons per annum, MTPA ≥ 30) or small ports (with throughput below 30 MTPA). This classification further influences their operational complexity, infrastructure requirements, and overall energy demand.

Each of these port segments and operational areas can perform a wide range of activities that either contribute to energy efficiency or support energy monitoring and optimization. Examples include real-time draft monitoring for access channels and berthing, real-time monitoring of under-keel clearance, continuous monitoring of weather, ocean, and tidal conditions, monitoring of energy usage across port facilities, and monitoring of entry and exit gates for trains and trucks. These digital and operational capabilities play an increasingly important role in improving efficiency, reducing unnecessary energy consumption, and supporting more informed operational and strategic decision-making.

5 Picture

Terminals operating in the port



For this reason, the DeCoInter digital tool must be capable of representing ports not only as single entities, but as complex, multi-layered systems composed of maritime, terminal, and hinterland operations, each with its own characteristics, constraints, and energy profiles. Only by accounting for this internal diversity can the tool provide realistic, accurate, and useful support for port energy transition planning.

The “Inland” stakeholder represents the entire hinterland transport and logistics system, including road and rail networks, cities, logistics hubs, and the distances between them. This stakeholder category is especially important for energy calculations, as the energy required to transport goods does not end at the port gate. In order to estimate the total energy demand associated with a shipment, the digital tool must take into account the distances between origins and destinations, as well as the transport modes used within the inland network. By incorporating these elements, the tool can provide a more comprehensive and realistic assessment of energy consumption across the full transport chain.

In addition to the structural and operational differences between ships, ports, and inland transport systems, the developers of the DeCoInter digital tool must also take into account a range of external and dynamic factors that can significantly influence energy consumption and operational performance. Among the factors are weather conditions and port traffic, both of which can affect all three stakeholder groups. Adverse weather, such as storms or strong winds, can delay ship arrivals, make docking temporarily impossible, or require vessels to use additional energy in order to reach the port safely. Similarly, congestion and traffic within ports can lead to longer waiting times, inefficient manoeuvring, and increased energy use for both ships and port equipment. These effects propagate further into the inland transport system, causing delays and additional energy consumption along the entire logistics chain.

Seasonal variations also play a crucial role in energy planning, particularly with regard to renewable energy generation. For example, during the winter period, wind energy production is often higher, while solar energy generation tends to be lower due to shorter daylight hours and reduced solar radiation. These seasonal patterns directly influence the availability and reliability of different renewable energy sources. At the same time, it must be recognized that each port is located in a unique geographical and climatic context. As a result, local weather conditions and renewable energy potential can differ significantly from one location to another. Some ports may benefit from strong and consistent winds, while others may have better conditions for solar or other renewable sources.

For this reason, the DeCoInter digital tool must be designed to incorporate location-specific data, seasonal variability, and short-term operational conditions into its calculations and planning functions. By doing so, the tool can provide more accurate, realistic, and robust assessments of energy demand and supply for ships, ports, and inland transport systems, thereby supporting more effective and resilient energy transition planning.

Digital tool technical specifications

1. Purpose of the tool

The Digital tool shall be designed, developed, tested, deployed and documented as a web-based digital decision-support system for simulation, forecasting and planning of energy transition in port ecosystems using a digital twin approach. It must be a secure and role-based system supporting concurrent users. It must be scalable, maintainable and well documented. The system should be created following modern web technologies and best practices, and provide acceptable performance for multi-year simulations. It is recommended that contractors provide user manuals, administrator manuals, and training workshops.

The system shall support South Baltic region ports and their stakeholders in:

1.1 Quantifying energy consumption and generation;
1.2 Simulating transition pathways;
1.3 Evaluating decarbonisation measures;

1.4 Supporting investment and policy decisions;
1.5 Integrating spatial, technical, operational and environmental dimensions.

2. Scope of Delivery

The contractor shall deliver a fully functional web-based application with:

2.1 Modular simulation and calculation engine;
2.2 GIS-enabled spatial component;
2.3 Scenario and forecasting engine;
2.4 KPI, reporting and dashboard system;
2.5 Knowledge base of transition measures;
2.6 User documentation and administrator documentation;
2.7 Source code and deployment package;
2.8 Training and handover.

3. System Architecture Requirements

The system shall:

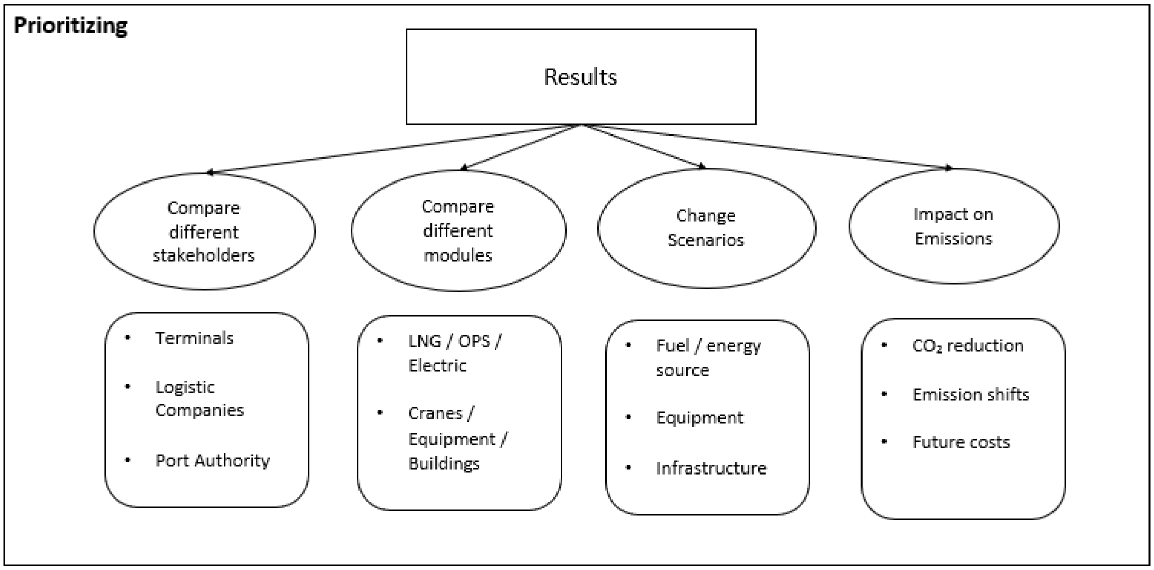
3.1 Be web-based and have multi-user connection availability;
3.2 Support role-based access control;
3.3 Use modular architecture:

- Data & sensing layer;
- Energy twin & Simulation layer;
- Optimization & decision support layer;
- Transition & Policy layer;
- Stakeholder & Market Layer;
- User Interface & Visualization layer;

3.4 Support multi-port deployment;
3.5 Be scalable and extensible;
3.6 Support API-based data exchange;
3.7 Allow local or cloud deployment.

6 Picture

The main results delivered by the digital tool



6 Table

Functional Requirements for the DeCoInter Digital tool

Digital Twin Core	
Represent ports as a digital twin including:	- Infrastructure; - Machinery; - Terminals; - Energy systems; - Ships; - Hinterland transport;
Data Management	
Support manual data input and bulk import	
Store:	- Asset inventories; - Energy systems; - Transport flows; - Spatial data; - Emission factors; - Cost parameters;
Track:	- Data sources; - Data quality; - Assumptions; - Scenario versions;

Energy & Emissions Calculation	
Calculate:	- Energy consumption by sector, asset, terminal and stakeholder (ton/km); - If possible, separately calculate emissions by GHG Protocol , the global standard for carbon accounting, where scope 1 stands for Direct emissions, scope 2 stands for indirect emissions from purchased energy, and scope 3 stands for other indirect emissions; - Energy intensity (ton/km); - Energy generation by source (ton/km); - CO_2, NOx, SOx, PM;
Support:	- Time-series profiles; - Peak load analysis; - Seasonal variations; - Weather variations;
Decision Support & Optimization	
Rank measures by:	- CO_2 reduction; - Cost efficiency; - Feasibility; - Implementation time;
Identify:	- Bottlenecks; - Grid constraints; - Space constraints;
Generate:	- Transition roadmaps; - Phased investment plans;
Knowledge Base of Measures & Good Practices	
Structured database of:	- Transition measures; - Barriers; - Mitigation actions; - Reference projects;
Multi-Stakeholder Analysis	
Represent:	- Port authority; - Terminal operators; - Ship operators; - Energy providers; - Grid operators; - City / hinterland;

Allocate:	- Costs; - Benefits; - Impacts per stakeholder;
KPI, Monitoring & Reporting	
Provide dashboards for:	- Energy; - Emissions; - Progress vs targets; - Investments;
Support:	- Export of reports; - Scenario comparison reports; - Graphical and tabular outputs;
Interoperability	
Support:	- CSV, Excel import/export; - GIS formats; - API interfaces;
Be prepared for:	- Sensor data integration; - External databases; - Energy systems data;

Discussions

The theoretical framework established in A2.3 provides the intellectual foundation for developing a scalable digital twin tool under A2.4. By integrating socio-technical analysis, multi-level transition theory, spatial analytics and sustainability metrics, while also drawing on published papers related to this body of work, the framework offers a holistic approach to support green transition pathways in ports.

The digital tool will serve as both a diagnostic and decision-support instrument, helping port stakeholders identify high-impact actions, align institutional strategies and accelerate the shift toward low-carbon, resilient maritime ecosystems across the South Baltic Region.

Conclusions

The theoretical assumptions developed in this study highlights how the port energy transition can be effectively supported when structured around an integrated, sequential digital ecosystem. At the foundation lies the data sensing layer, where harmonised, spatially explicit, and real-time data streams - derived from energy systems, port operations, environmental sensors, and GIS infrastructure - ensure a reliable representation of the physical port environment. Building upon this foundation, the energy twin and simulation layer transforms raw data into dynamic digital models capable of reproducing physical processes, evaluating infrastructure configurations, and running “what-if” scenarios across energy, operational, and environmental domains.

These insights feed directly into the optimisation and decision-support layer, where analytics, forecasting models, multi-criteria assessments, and sustainability indicators help identify high-impact actions, anticipate operational constraints, and optimise energy flows. When embedded within broader governance structures, these outputs inform the transition and policy layer, enabling ports to align strategies with regulatory requirements, future energy pathways, and climate targets. This evidence-based approach strengthens planning, supports compliance, and clarifies investment priorities.

The subsequent stakeholder and market layer ensures that transition processes remain socio-technically robust by facilitating collaboration across port authorities, utilities, terminal operators, municipalities, and other actors. Harmonised data exchange, transparent KPI frameworks, and shared governance mechanisms help coordinate actions and mitigate risks of misalignment. Finally, the entire system is rendered accessible through a user interface and visualisation layer, which provides dashboards, spatial representations, and interactive digital-twin tools that communicate scenarios, KPIs, and system states in an intuitive manner.

By linking these layers into a coherent digital ecosystem, the study demonstrates how the DeCoInter digital tool can support operational efficiency, energy transition, decarbonisation progress, and strategic decision-making. This layered perspective underscores that the success of port energy transitions depends not only on technological capability, but on integrated data architecture, coordinated governance, and user-centered visualisation tools.

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