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The role of ports in the transition to low-emission trucks – a multi-system transition analysis

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ABSTRACT

Diesel-powered trucks handle most container movement between ports and the hinterland, resulting in negative externalities. Using low-emission trucks could reduce the impact of hinterland transport on global warming, but widespread diffusion remains slow. Since ports are central hubs for hinterland transport and focal points in the energy transition, we assess the conditions at ports for accelerating the transition to low-emission trucks. We employ a multi-system transition lens to examine the technology, actor, and institutional couplings between the hinterland transport system and the port energy system, under the regulatory influence of the port authority and EU policies. Drawing on data from a literature review, our findings show that ports offer 9 distinct conditions to accelerate the uptake of low-emission trucks for hinterland transport, including facilitating the diffusion of niche-technologies across systems, coordinating actors involved in energy infrastructure for low-emission trucks, and governing the transition as a focal institutional body in hinterland transport chains. Future research should incorporate primary data from port hinterland transport actors to examine diffusion barriers and deploy simulations to understand the diffusion of low-emission trucks in port hinterlands under different policy scenarios.

1. Introduction

Europe's largest port, the Port of Rotterdam, handled 13,4 million TEU in 2023, of which approximately 40% is transported annually by trucks to hinterland destinations (Gonzalez-Aregall et al., 2019; Port of Rotterdam, 2024c). This fleet of trucks accounts for approximately 34% (0.9 Mt) of the port's hinterland transport-related emissions (Lechtenböhmer et al., 2018; Otten et al., 2020). Switching to low-emission trucks could significantly reduce emissions from road freight hinterland transport. However, the diffusion of low-emission trucks remains low due to, among other factors, the unavailability of low-carbon energy distribution infrastructure and the uncertainty around energy supply and costs (Aryanpur & Rogan, 2024; Ye et al., 2024).

Historically, port decarbonisation literature has focused mainly on maritime transport and in-port operations, leaving unanswered the responsibility and capability of ports to decarbonise hinterland transport (Alamoush, 2024; Alzahrani et al., 2021; Iris & Lam, 2019). Although hinterland transport is a major contributor to port-related emissions, existing studies treat it at an aggregated level in modal shift strategies or focus on specific case studies of electrifying drayage operations, without providing an overview of port-specific conditions to facilitate low-emission truck diffusion in port hinterland transport (Liu et al., 2019; Zhong et al., 2023).

Meanwhile, the road freight transport sub-sector operates on low margins, creating strong path dependencies locking carriers to existing fossil fuel infrastructure and constraining the pace of low-emission truck diffusion (Gray et al., 2021). The transition is not self-contained, as the viability of low-emission trucks relies on the costs and availability of low-carbon energy, making progress dependent on developments in the energy sector (Müller, 2024; Noll et al., 2022). Therefore, low-carbon energy distribution infrastructure must co-evolve with the transition towards low-emission vehicles (Andersen & Geels, 2023; Nykamp et al., 2023; Rogge & Goedeking, 2024). This interdependence introduces new interactions and institutional entanglements across both systems, as energy suppliers, grid operators, fleet owners, and regulators must coordinate across sectoral boundaries (Raoofi et al., 2024a). Hence, understanding how these systems interact and identifying where and how to intervene effectively requires a multi-system transition perspective that moves beyond single-sector technological analyses (Ertelt, 2024).

As a central node for coordinating energy distribution and transport across different modes, the port can play a crucial role in this transition by mediating between energy producers, energy supply infrastructure,

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and hinterland freight transport actors (Buonomano et al., 2023; Lind et al., 2023; Steen et al., 2024). In addition, ports also offer geographical proximity to actors in low-carbon transitions, enabling exchange on best practices for the transition, diffusion of low-carbon technologies across systems, and resources to facilitate the energy transition (Bjerkan et al., 2021; Bjerkan & Seter, 2019; Damman & Steen, 2021; Loorbach & Geerlings, 2017). Based on these observations, this article investigates the following research question: **What socio-technical conditions can ports offer to support the transition to low-emission trucks for hinterland transport?**

To answer this research question, we identify the energy supply conditions at ports and analyse their impact on the diffusion of low-emission trucks in port hinterlands. The two-sided nature necessitates a multi-system lens that considers the characteristics of the port energy supply system and the road freight hinterland transport system. We apply the multi-system transition framework for identifying couplings between energy and transport subsystems at ports (Andersen & Geels, 2023; Löhr & Chlebna, 2023). We use a systematic literature review to collect relevant data. Subsequently, we synthesise the results from the multi-system transition analysis to extract the unique conditions that facilitate low-emission truck diffusion for hinterland transport. These conditions are shaped by the structural couplings between the energy and hinterland transport systems unique to ports. The application of the framework and the outlook on port conditions to accelerate the diffusion of low-emission trucks in hinterland transport constitute the main contribution. It can inform port actors in port management, policy-making, and road freight transport.

The remainder of the article is organised as follows: Section 2 provides an overview of related work on low-emission truck diffusion challenges, the port hinterland decarbonisation literature, and key concepts in multi-system transitions. Section 3 describes the applied multi-system transition framework and the data collection. Section 4 shows the main findings, structuring them according to the multi-system transition framework. Section 5 presents the synthesis of the results and their implications for low-emission truck diffusion in hinterland transport, and discusses them in light of related work. Section 6 provides the conclusion, limitations and pointers for future research.

2. Background

2.1. Transition challenges for low-emission trucks

The transition to decarbonised freight transport entails many strategies, including utilising freight transport assets, implementing energy efficiency measures, reducing freight demand, and adopting low-carbon energy technologies (McKinnon, 2018). Eventually, trucks will continue to deliver goods to consumers' doors for many years to come. Therefore, it is increasingly important to find an economically viable alternative energy carrier to reduce diesel truck emissions. The technological spectrum entails multiple options and combinations, wherein the base energy carriers are electricity, hydrogen, and biofuels (Gray et al., 2021). Electrification is on everyone's lips, but no clear technological pathway has emerged since 97% of the truck fleet is fuelled by fossil fuels (IEA, 2024; Larson et al., 2024). Multiple factors hinder the deployment of low-emission trucks, whether in Europe, the US, or China, with the latter experiencing the greatest sales gains.

The literature agrees that energy storage size, energy prices, mileage, and refuelling/charging infrastructure are the most sensitive parameters determining the diffusion of low-carbon emission technologies for trucks (Gray et al., 2021; Larson et al., 2024; Link et al., 2024; Raoofi et al., 2025). Thus, the decision on low-carbon energy drive technology depends on energy supply and infrastructure. On a more granular decision level, also intangible aspects such as actor-specific needs for different types of transport need to be considered for decarbonising trucks (Aryanpur & Rogan, 2024; Cabrera-Jiménez et al., 2025; Ertelt et al., 2024). Despite several identified diffusion challenges for low-emission trucks, the final decision often comes down to costs (Link et al., 2024; Mulholland et al., 2018; Noll et al., 2022). Table 1 lists the main challenges of low-emission truck diffusion based on a representative selection of articles.

The biggest challenge for the uptake of low-emission trucks is not the technology itself. Adoption of low-emission trucks remains low, even though new drivetrain technologies will reach cost parity with internal combustion engines beginning in 2030 (Hoekstra & Alkemade, 2025; Link et al., 2024; Rogstadius et al., 2024). The market is at a standstill because trucks cannot transition without the input of adjacent systems, such as energy supply and grid infrastructure (Mitra et al., 2025). However, these systems cannot deliver the required energy in time because of grid construction bottlenecks stalling low-emission truck diffusion (Raoofi et al., 2024b).

Given the interdependencies, alignment among stakeholders across systems is central to achieving sustainability in road freight (Nkesah, 2023). Other findings also indicate that the timing and location of interventions are crucial considerations for policymakers seeking to achieve emission-reduction goals (Y. Guo et al., 2021). The question of how and where to intervene to overcome the transition inertia and stimulate the diffusion of presumably technologically mature, low-emission trucks remains open. As such, ports, which usually provide the start and end points of central freight corridors, become increasingly important as accessible intervention points (McNeil et al., 2024; Tavasszy, 2021).

2.2. Port-hinterland transport decarbonisation

Port hinterland transport is controlled by a complex field of logistics

Table 1
Low-emission truck diffusion challenges.

Challenges	Source
Availability of energy source (electricity, H2, ammonia, e-diesel)	(Gray et al., 2021; Larson et al., 2024; Link et al., 2024; Raoofi et al., 2025; Ye et al., 2024)
Charging/refuelling infrastructure availability	(Bakker et al., 2025; Raoofi et al., 2024b; Ye et al., 2024; Zhao et al., 2024a)
Technology uncertainty (through infant maturity and little experience)	(IEA, 2024; Larson et al., 2024)
Total costs of ownership (TCO), including capital investment and operational expenditures (maintenance, insurance, energy price, equipment replacement, resale value, etc.)	(Alarcón et al., 2025; Hoekstra & Alkemade, 2025; Link et al., 2024; Mulholland et al., 2018; Noll et al., 2022)
Mileage/Range	(de Saxe et al., 2023; Nykvist and Olsson, 2021; Rogge and Goedeking, 2024; Zhao et al., 2024a)
Charging/refuelling time	(Ainalis et al., 2023; Bakker et al., 2025; de Saxe et al., 2023; Raoofi et al., 2025; Zhao et al., 2024a)
Change of routing/planning	(Ertelt et al., 2024; Ertelt and Kask, 2024; Zhao et al., 2024a)
Retraining/adapting truck drivers	(Aryanpur & Rogan, 2024; Cabrera-Jiménez et al., 2025; Ertelt et al., 2024)
Coordination complexity of logistics activities with logistics companies, shippers, grid operators (TSO & DSO), and OEMs.	(Ertelt and Kask, 2024; Hoekstra and Alkemade, 2025; Mitra et al., 2025; Raoofi et al., 2024a; Rogge & Goedeking, 2024; Rogstadius et al., 2024)
Inclusivity of the transition (SME have a disadvantage and could be left behind/ block the transition)	(Ainalis et al., 2023; Ertelt & Kask, 2024; Rogstadius et al., 2024)
Governance of heterogeneous groups of stakeholders, including trucking businesses, public and private actors, ports, local/national governments, communities, logistics hubs, cargo owners, truck drivers, utilities, and competing energy consumers.	(Alamoush et al., 2024; Aryanpur & Rogan, 2024; Bjerkan et al., 2021; Ertelt et al., 2024; Ertelt & Kask, 2024)

and transport companies involved in shipping, rail and trucking (De Langen & Chouly, 2004). Hinterland transport is often the bottleneck to port growth and efficiency, as rail and road routes are congested and infrastructure development doesn't keep pace with freight demand and containerization (Behdani et al., 2020; Van Der Horst & De Langen, 2008). As a result, ports began distributing cargo to inland ports to facilitate mode switching and improve hinterland transport efficiency (Notteboom & Rodrigue, 2005; Rodrigue, 2024). Such intermodal terminals also contributed to the growing need to reduce CO2 emissions by enabling a smoother transition to more environmentally friendly modes, such as rail and waterways.

Decarbonisation strategies at ports can be classified into port operations, maritime transport, hinterland transport, and energy (Alamoush, 2024; Bjerkan & Seter, 2019). Most of these articles examine maritime transport and in-port operations, including cleaner vessels, port call logistics, and energy consumption (Acciaro et al., 2014a; Bloemert & Saraceni, 2024; Damman & Steen, 2021; Iris & Lam, 2019; Lechtenböhmer et al., 2018). Hinterland transport decarbonisation remains comparatively underexplored (Gonzalez Aregall et al., 2018). The limited literature on port hinterland transport decarbonisation primarily addresses the abatement of negative externalities from hinterland transport, often by investigating efficiency-improving, traffic reduction, or modal switch measures in multiple case studies (Behdani et al., 2020; Liu et al., 2019, 2021; Matsuyama et al., 2024; Zhong et al., 2023).

In the energy-related port decarbonisation literature, many articles cover topics such as alternative fuels, electrification, and renewable energy cooperatives, with an emphasis on the port's central role in the transition to low-carbon energy (Alamoush, 2024; Bjerkan & Seter, 2019; Hentschel et al., 2018). Even though the transition to low-emission trucking may benefit from knowledge of low-carbon energy in ports, the link between the port energy system and sustainable road freight hinterland transport hasn't been established. Only a small set of studies has examined policies to promote low-carbon energy use to mitigate hinterland transport emissions in the context of hinterland economies and port cities, with particular focus on the electrification of drayage operations and major charging infrastructure bottlenecks (Hou & Geerlings, 2016; McNeil et al., 2024; Sharifi et al., 2024; Ye et al., 2024; P. Zhao et al., 2025). How to achieve the final objective of broad deployment of low-emission trucks for hinterland transport, and the port-specific dynamics influencing the transition process, remain unanswered.

The lack of focus on low-emission trucking for road freight hinterland transport in connection with the port's energy system limits our understanding of the port's role in facilitating this interconnected transition. Therefore, we map the port's energy system and its relations to the hinterland transport system to examine the central conditions it can provide to help overcome the adoption inertia of low-emission trucks for hinterland transport. We frame the transition challenge as a co-dependent, co-evolving transition of changes in the energy supply system and in the road freight hinterland transport system. Together with the review of relevant work, this constitutes the paper's main contribution.

2.3. Concepts applied in this study

This study examines the role of ports in the ongoing transition to sustainable hinterland transport, adopting a social science stance on the development of technologies in society (Geels, 2004; Geels et al., 2017a; Köhler et al., 2019; Loorbach, 2007). The underlying concept of sustainable transitions examines the complex process by which societal systems transition to a new sustainable state, taking into account how incumbents shape the existing socio-technical system and how new niche innovators strive to bring about change (Geels et al., 2017b).

Given the dependency on energy supply and grid infrastructure, the diffusion of low-emission trucks requires a perspective on transitions involving multiple systems. The literature defines transitions in adjacent systems as multi-system transitions (Andersen & Geels, 2023; Markard et al., 2020). It investigates the maturing of niche technologies and how the evolution of technologies in one system affects transitions in adjacent systems (Löhr & Chlebna, 2023; Nykamp et al., 2023). Such interconnected transitions evoke interactions across multiple systems, resulting in multi-system dynamics that can block or accelerate either system's transition (Andersen et al., 2020; Rosenbloom, 2020). For example, advances in hydrogen and biofuels, along with the rapid decline in battery costs, support a strong shared belief in the transition to low-emission trucks, driving cooperation across sectors.

Connected complex systems depend functionally on one another through energy, information, or material flows, facilitated through technological, actor, and institutional structural couplings (Konrad et al., 2008). These structural couplings are elements that overlap across interconnected socio-technical systems; as a result, they may lead to the integration of formerly independent systems, interference, or niche technology spillovers (Andersen et al., 2023; Bakhuis et al., 2024). Investigating the intersection of co-evolving transitions can help identify such dynamics and path dependencies between systems, potentially identifying sensitive intervention points, to accelerate the energy transition (Farmer et al., 2019; Nykamp et al., 2023). Notably, such intervention points could be central actors with strong influence on multiple systems, the proximity of complementary actors in technology value chains, or spaces for peer-/co-learning and system alignment (Andersen et al., 2020; Löhr & Chlebna, 2023; Nykamp et al., 2023).

Ports are interface nodes of transport and energy systems and create an arena for such multi-transition phenomena: the transition from fossil to renewable energy, the transition of the chemical cluster, the transition to sustainable transport, and area development connected to the hinterland collide (Loorbach & Geerlings, 2017). Segregated interventions are insufficient to change these four system transitions successfully; a multi-system approach is needed. Furthermore, the heterogeneous constellation of actor groups at ports with varying values necessitates consideration of the multi-stakeholder context of interconnected systems (Bjerkan et al., 2021). Hinterland transport is geographically linked to energy production and distribution infrastructure and industry at ports (Damman & Steen, 2021). These interdependencies between both systems and the port's unique interface position suggest that investigating the port's conditions to facilitate the transition to low-emission trucks for hinterland transport could be fruitful.

3. Methodology

3.1. Analytical multi-system transition framework

To identify the unique conditions at ports that facilitate the transition to low-emission trucking, we need to understand the existing socio-technical subsystems of port energy and hinterland transport, as well as the structural couplings that enable their interaction. We use a multi-system transition perspective to structure our analysis. Fig. 1 introduces the port-specific multi-system transition framework encompassing road freight hinterland transport and the energy supply system, drawing on the concepts of multi-system transitions (Andersen & Geels, 2023). We focus on the structural couplings that shape the interconnectivity of both system transitions, as they provide the socio-technical conditions at ports. Through the setup and maintenance of couplings, systems can be aligned to allocate resources, maintain interactions across systems, and govern a co-evolving and effective transition. The structural couplings are divided into technology, actor, and institutional dimensions.

- **Technological couplings** become visible as technologies are used across or shared between systems or diffuse to another system (Nykamp et al., 2023).

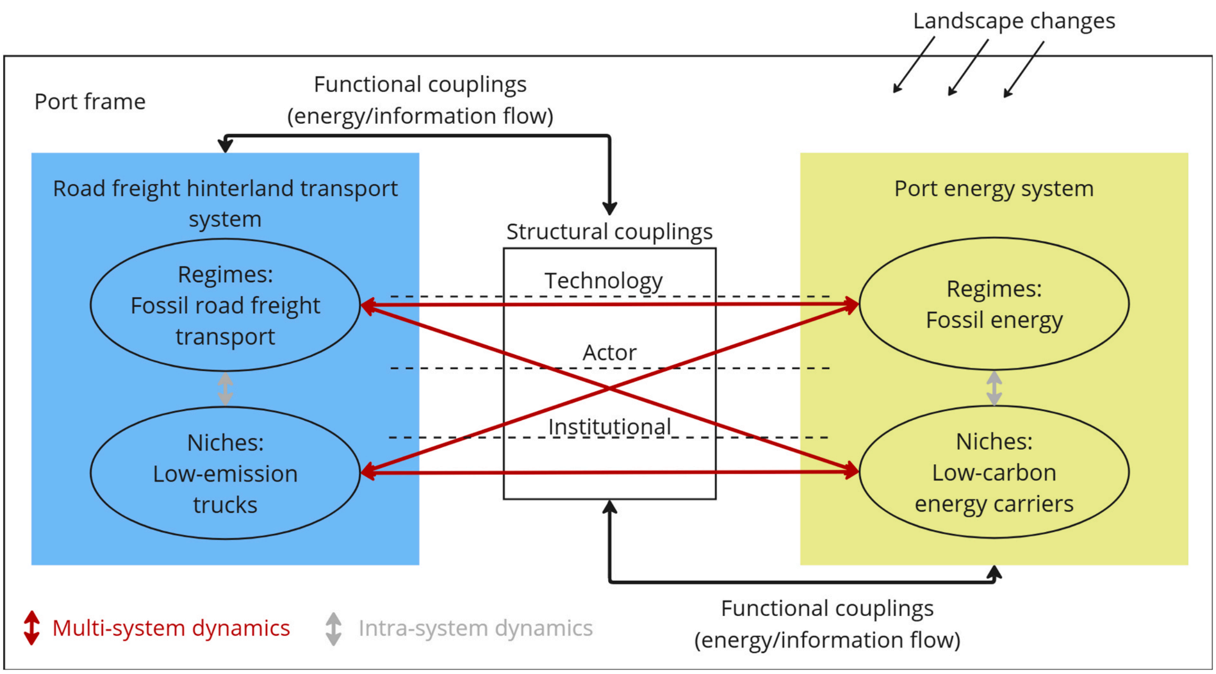

Fig. 1. Analytical multi-system transition framework describing the sociotechnical dependencies between road freight hinterland transport and energy system, adapted from Andersen & Geels (2023).

- **Actor couplings** represent actors that act or are connected to one or more systems, with the knowledge of working in multiple sectors (Löhr & Chlebna, 2023).
- **Institutional couplings** appear at the intersection of systems when the coordination of interactions of actors between systems is needed (Andersen & Geels, 2023). Generally, institutions set the rules of the game for actors and the usage of technologies; they can be formal or informal (DiMaggio & Powell, 1983). (Mis-)alignment of institutions can enable or hinder technological evolution and interactions between systems.

We use the framework in Fig. 1 to structure the literature review results in technological, actor, and institutional couplings. These structural couplings define the port's energy supply conditions to facilitate the transition to low-emission trucks and constitute the main contribution of this work. Based on this framework, we analyse the co-evolution of road freight hinterland transport and port energy system transitions to synthesise the resulting multi-system dynamics influencing the transition towards low-emission trucks. The port frame defines the framework's boundaries.

3.2. Systematic literature review

We use a literature review to identify the components of the multi-system transition of freight transport in the context of ports. We assume that the conditions at ports for niche, low-carbon energy technologies differ from those outside ports. We aim to identify the actor, institutional, and technological structures that shape the niche-regime dynamics within hinterland transport and energy systems at ports and across both systems. Literature reviews have been used in transport research for multiple purposes, among them to provide a comprehensive overview of the literature and to provide a focus for further investigation in the field of interest (Avni et al., 2015). We follow the PRISMA guidelines for conducting systematic literature reviews (Page et al., 2021). Fig. 2 delineates the data collection process.

We use the Scopus databases for scientific representation, as they cover most contributions in port and transport science. Through Google searches, skimming policy websites, and forward- and backwards-snowballing, we broaden the scope to grey literature that supports applications and practical cases for low-emission trucks in port contexts. The search string *road freight hinterland transport decarbonisation* and synonyms[1] yielded merely 15 relevant results with a focus on modal shift and electrification of drayage operations. However, to gain a better understanding of the holistic port energy system and its influence on the hinterland transport system, given that ports are the nexus of hinterland transport and the energy transition, we broaden the search to include articles on low-carbon energy systems at ports.

To do so, we used the following keywords and synonyms as the search string: *renew*/green/clean W/2 energy/power AND port*. We included papers up to 2024, resulting in 1866 outcomes after removing duplicates and irrelevant keyword clusters. We identified 168 relevant articles after title and abstract screening and included 31 for data extraction, based on the selection criteria in Table 2. In combination with the results of the initial search and grey literature, we selected 58 relevant documents. The data extraction underlies the authors' subjective judgment following keyword coding of low-carbon energy supply and integration conditions unique to ports, distinguished by technological, actor, and institutional conditions. The supplementary data provide a detailed description of the review process, the selected articles and reports, and the data extraction. To confirm the validity and rigour of the data extraction, we conducted a second extraction selecting randomly studies from the screening process and checked the data consistency across the selected studies (Kitchenham & Charters, 2007). We use the literature review as a systematic rather than an explorative tool to collect data for analysing the interdependencies of energy and road freight hinterland transport systems at ports and the resulting energy supply conditions. With the results of this analysis, we can synthesise the port-specific conditions shaping the speed and direction of the transition towards low-emission trucking in port hinterlands.

[1] Preliminary search string: TITLE-ABS-KEY (("hinterland transport*" OR drayage) AND (decarb* OR green OR electri* OR hydrogen OR "zero-emission" OR emission OR carbon)) AND PUBYEAR > 2004 AND PUBYEAR < 2025 AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "ch")) AND (LIMIT-TO (LANGUAGE , "English")).

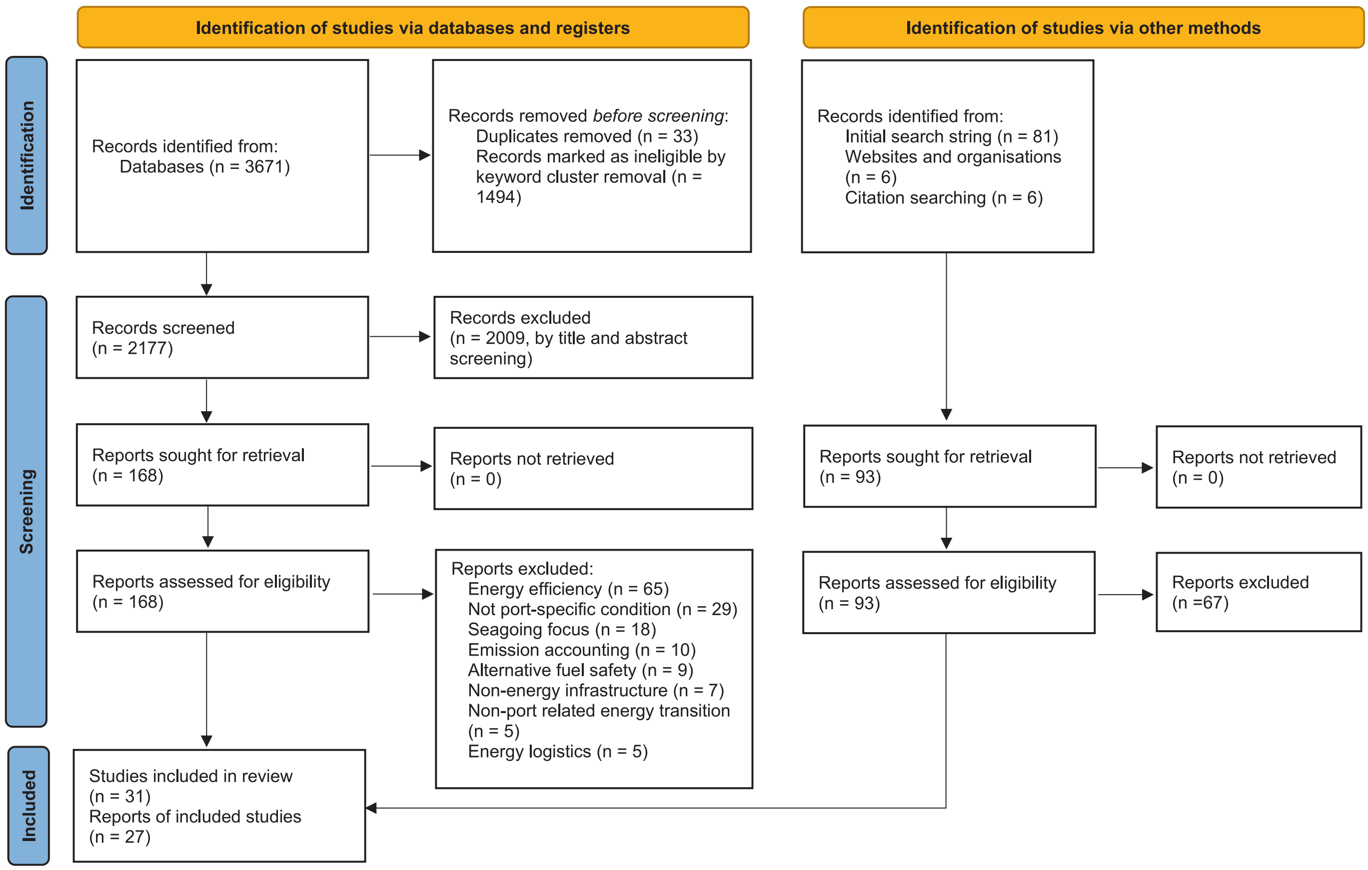

Fig. 2. PRISMA flow diagram adapted from Page et al. (2021).

Table 2
Text screening process. Inclusion and exclusion criteria for the final selection of articles, as well as keyword coding.

Exclusion criteria (multiple exclusion criteria can apply to one article)	**Inclusion criteria** (keyword coding)
- Energy efficiency/ optimisation of local energy grid (n = 65) - Not a port-specific condition for low-carbon energy (n = 29) - Focus on shipping/ low-carbon energy for shipping (n = 18) - Emission accounting and supportive information systems (n = 10) - Renewable energy risks and safety (n = 9) - Supportive infrastructure (non-energy related) (n = 7) - Non-port related operation/ low-carbon energy transition (n = 5) - Renewable energy integration logistics (n = 5)	- On the technological dimension: low-carbon energy integration with relevance to production, availability, distribution, allocation, application, or consumption; supply conditions, including price, volumes, infrastructure, storage, and application types; and specifically, application for road freight hinterland transport. - On the actor dimension: types of actors involved in port energy systems and hinterland transport, as well as their interactions and coordination. - On the institutional dimension: port policies and the influence of port authorities on policymaking, focusing on port energy systems and hinterland transport.

4. Results

In this section, we present the identified structural couplings between port hinterland transport and the port energy system, thereby defining the port's socio-technical conditions in the energy transition. As a result of the literature review, we found 58 articles and industry reports. The section is divided into conditions for each of the socio-technical dimensions: technological, actor, and institutional.

4.1. Technological couplings

We found 33 articles discussing technological couplings for deploying low-carbon energy technologies at ports. After a thorough analysis, we subdivided technological conditions at ports into energy supply and demand. The green box in Fig. 3 provides an overview of the processes and actors involved in the port energy system, and how it relates to institutional bodies and the transport system. Generally, energy is required for a range of logistics processes, including shipping, terminal operations, and hinterland transport; this study focuses on road haulage.

4.1.1. Energy supply

Beyond facilitating transport, ports import and distribute fossil fuels and balance local energy demand and supply for adjacent industries, making them a central hub for energy supply coordination (Lind et al., 2023). Operating a port requires substantial energy, mainly to power ships at berth, conduct in-port operations, and supply port industries (Iris & Lam, 2019). On top of this, visiting actors, such as transport companies, need a large quantity of energy to operate maritime and hinterland transport (Bergqvist et al., 2015; Bergqvist & Egels-Zandén, 2012). The underlying port energy system connects multiple stakeholders who rely on a stable and secure energy supply (Alamoush et al., 2024). In this way, ports connect transport systems, energy systems, and industry, making them hubs for energy distribution and production. Historically, ports have acquired energy hub properties by adding value to the processing of coal and other fossil fuels (Samadi et al., 2016). In the transition to low-carbon energy, ports seek to maintain their central energy node position by investing in and promoting low-carbon energy technologies (Alzahrani et al., 2021).

Regarding alternative fuels for use in port operations and adjacent systems, hydrogen, biodiesel, and biomass are being researched as

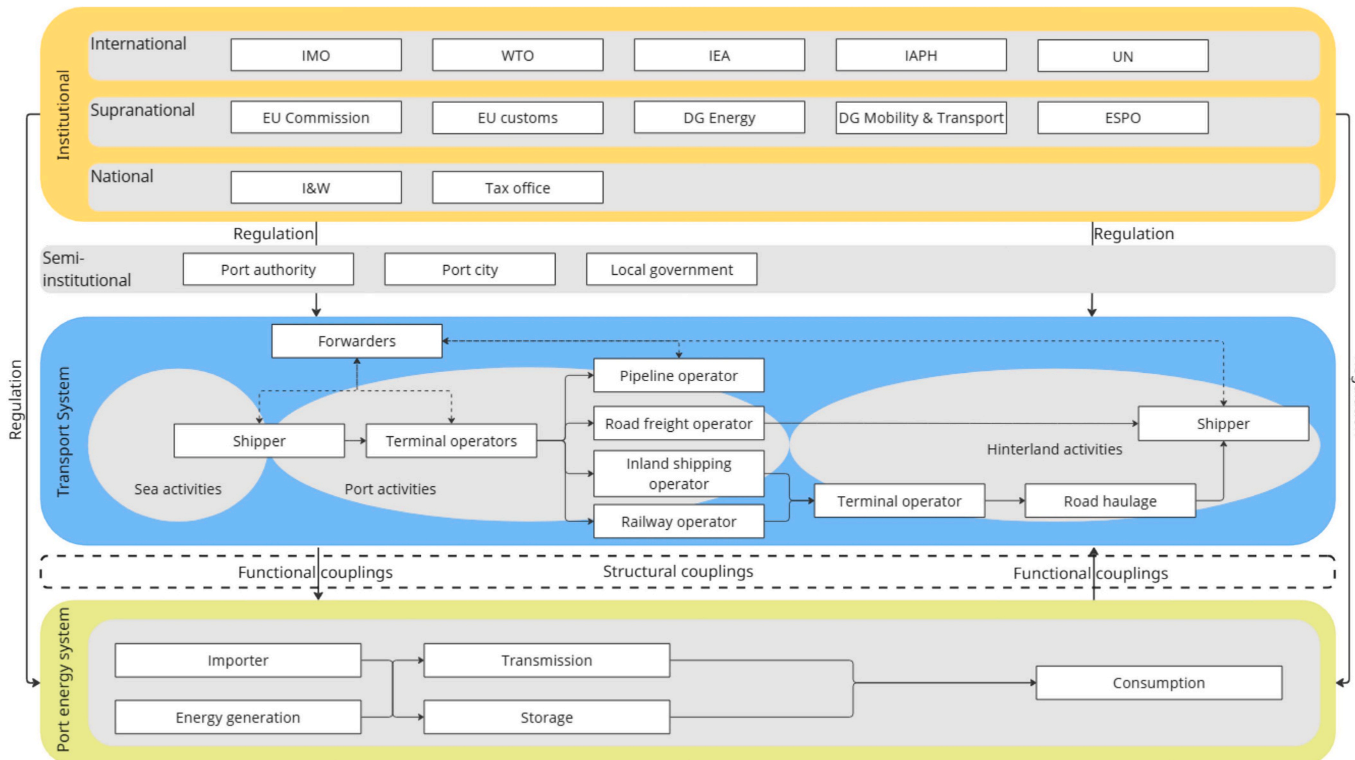

Fig. 3. Actors(IMO = International Maritime Organisation, WTO = World Trade Oragnisation, IEA = International Energy Agency, IAPH = International Association for Ports and Harbors, UN = United Nations, DG = Directorate-Generale, ESPO = European Sea Ports Organisation, I&W = Dutch Ministry for Infrastructure & Water management, Rijkswaterstraat =) and processes in the port energy-transport system multi-system transition, including the institutional dimension shaping the port landscape locally and globally (the Netherlands), transport-related activities, and energy supply-related activities. The functional flow of information and energy between systems is facilitated by structural couplings, such as charging infrastructure and power purchase agreements, and is regulated by institutions for both the transport and energy systems and their interactions. The figure is based on information from multiple sources (Bjerkan et al., 2021; Damman et al., 2025; Magnan & van der Horst, 2020; Van Der Horst & De Langen, 2008; Verhoeven & Vanoutrive, 2012).

alternatives for powering the port industry, industrial heating, and transport (Buonomano et al., 2023; Mio et al., 2023; Samadi et al., 2016). For example, ports' geographical location and cumulative power of the industrial cluster can help make green hydrogen competitive for specific energy-intensive industries (Notteboom & Haralambides, 2023). For large ports, biomass exploitation appears economically feasible for producing alternative fuels, such as sustainable aviation or shipping fuels (Thompson, 2023). Energy storage, for example, through bunkering of alternative fuels such as LNG, is an ongoing investment with the prospect of application in shipping (Notteboom et al., 2020). However, most alternative fuels (e.g., hydrogen fuel cells and small- to medium-scale biomass use) are not considered preferred or highly impactful options for ports, with low to moderate implementation probability, low impact on decarbonisation, and little desirability among port actors (Attanasio et al., 2023). Alternative fuels have only a limited contribution to a radical transition, offering only incremental steps toward carbon neutrality. Considering their application in the decarbonisation of road freight hinterland transport, their technological constraints lead to low optimism and high expected costs for near-term implementation (Lechtenböhmer et al., 2018).

More disruptive and sustainable changes can be achieved through port electrification (Lind et al., 2023). The proximity of actors striving for electrification allows for the effective deployment of energy management systems and bundling actors with energy consumption patterns (Bjerkan et al., 2021; Flikkema et al., 2023). A risk prevails through significant energy offtake from multiple consumers, increasing the load on the energy system, leading, for example, to grid congestion in the electricity systems (Wei et al., 2023). Projects could be prioritised based on their energy efficiency to maximise the number of companies switching to alternative energy, as green hydrogen production only converts about 30% of the input electricity (Lechtenböhmer et al., 2018). Comparing land- and maritime transport, port authorities prioritise high and low-voltage power infrastructure construction for ships at berth (Alamoush et al., 2020).

With scarcity in power infrastructure and supply, technological advances in finding local energy production and consumption patterns enable better electricity management among multiple consumers (Bakar et al., 2021; Iris & Lam, 2019; Kanellos, 2017). Load balancing is a key technological condition at ports that facilitates a successful electrification transition by optimally balancing grid capacities with energy demand (Zhao et al., 2024a). Especially for electric trucks, charging capacity is a major bottleneck. Having joint grid connections and energy management systems with adjacent industries can have a profound leverage on the construction speed of charging stations (Wu et al., 2023; Ye et al., 2024).

4.1.2. Energy demand

On the energy demand side, actors in shipping, terminal, and hinterland transport operations are inherently interconnected and require a steady energy supply (Bjerkan & Seter, 2019). They have heterogeneous energy requirements depending on the energy carrier needed and the consumption patterns, which increases the complexity of energy management (Bakar et al., 2022; Zhang et al., 2020). Most articles discuss the maritime dimension of energy supply, with LNG, hydrogen, and ammonia bunkering as central technological conditions for the port transport system (Attanasio et al., 2023; Thompson, 2023). Offering such technological coupling can facilitate the energy flow between transport and energy systems and increase the uptake of alternative fuels. However, little attention has been paid to the port's hinterland dimension (Gonzalez-Aregall et al., 2019). Recent literature has examined decarbonization measures in Norwegian ports, focusing on operational measures (information sharing and management), power/ fuels, maritime, and landside activities (Alamoush, 2024; Bjerkan & Seter, 2019). Only 10% of land-side decarbonisation measures are directed towards road freight transport, and renewable power and fuel usage for land-side transport operations have not been implemented at all (Steen et al., 2024).

A selection of renewable energy through wind, solar, and tidal installations, in combination with storage systems and national grid connection, forms the electricity supply in the port; mainly consumed by vessels at berth and during (un-)loading activities at terminals and the port industry (Molavi et al., 2020a; Zhao et al., 2024b). Energy technology innovations for emission reduction of electricity consumption mainly focus on energy efficiency measures and consumption optimisation (Iris & Lam, 2019). Eight articles used optimisation models to simulate the interplay between renewable energy supply and energy demand at ports. Through the geographical port boundaries, distribution and supply can be well modelled to suit the electricity demand requirements of multiple actors (Xie et al., 2024). In the port's competitive grid with projected demand bottlenecks, flexible energy consumers, such as trucks with vehicle-to-grid capabilities, could play an important role in improving energy management (Ye et al., 2024).

4.2. Actor couplings

We identified 25 documents that mention the actor dimension of the socio-technical system. Based on these documents, we analyse the actor couplings and resulting conditions for the low-carbon transition of road freight hinterland transport.

4.2.1. Focal points in energy supply chains

Literature defines ports as central nodes in energy supply chains (Lind et al., 2023; Notteboom & Haralambides, 2023). For example, the Ports of Rotterdam and Oslo primarily grew due to their advantageous position in the oil and gas industry (Damman & Steen, 2021). They now position themselves as a proactive guide in transitioning to low-carbon energy, aiming to remain the most competitive port in the energy business and, thus, engaging heavily with innovations (Port of Rotterdam, 2024a; Samadi et al., 2016). That means the port goes beyond merely implementing technology, including proactive diversification of energy production and consumption, and guiding technological and institutional development of incumbents (Acciaro et al., 2014b; Damman & Steen, 2021). At the intersection of consumers, producers, facilitators, and policymakers, the port authority often balances between incumbents and niches, with support rather evenly distributed (Notteboom & Haralambides, 2023). A co-evolving approach, where port authorities initiate change for incumbents while stimulating niches, could create a leveraged symbiotic transition space to facilitate a low-carbon transition (Loorbach & Geerlings, 2017).

4.2.2. Emerging actor couplings

A common theme across the identified articles is actor collaboration in driving niche innovations, reducing investment inertia, destabilising regimes, and bringing about systemic change (Alamoush et al., 2024; Alzahrani et al., 2021). Ports encompass a vast spectrum of stakeholders, mainly engaged in energy production, distribution, and consumption, whether to power their value-adding services or as their core business (Buonomano et al., 2023; Damman & Steen, 2021; Lind et al., 2023). In the Rhine-Delta region, major ports such as Rotterdam and Antwerp coordinate strategically to align the energy transition across sectors. Port authorities can act as orchestrators of innovation across energy and transport systems by fostering collaboration among energy producers, transport companies, policymakers, and infrastructure providers (Acciaro, Ghiara, et al., 2014; Flikkema et al., 2023; Roy et al., 2020). For example, microgrids and renewable energy installations are often the result of partnerships between port authorities, private energy firms, and logistics operators (Fadiga et al., 2024). Such dense stakeholder constellations have high capabilities to absorb innovations and knowledge from the port and surrounding industries, as well as systematic approaches to pursue and accelerate them (Alamoush et al., 2020). On top of that, the port also reacts ad hoc to innovations, testing and trialling many niche technologies, even across industries (Damman & Steen, 2021). The literature often mentions specific innovation projects, such as shore power supply for ships (Bakar et al., 2022; Notteboom et al., 2020; Zhao et al., 2024b). It is being implemented as a major contributor to cutting maritime transport-related emissions and requires the combined efforts of stakeholders, including energy providers, infrastructure providers, shipping lines, the port authority, and the local government.

In Australian seaports, environmental groups co-create environmental strategies, combine them with corporate responsibility regulations and goals, working with reporting scheme providers and the port authority (Notteboom et al., 2020). Voluntarily formed cooperatives based on similar goals can accelerate transitions through joint acceptance of alternative technologies, lower energy production, distribution, and consumption costs, and load management (Hentschel et al., 2018). Balancing interest and fairness while promoting cooperation is central to energy cooperatives, as underlying problems such as competing interests or competition for alternative energy sources can create negative feedback on the diffusion of renewable energy technologies (Buonomano et al., 2023).

4.3. Institutional couplings

We found 41 articles that address institutional complexity at ports in the context of energy systems and their management. For the port system, two different angles characterise the institutions. First, ports are a socio-technical system shaped by exogenous institutions, and second, ports can shape the socio-technical system within port boundaries and beyond through the port authority (Bjerkan & Seter, 2019; Verhoeven & Vanoutrive, 2012). Accordingly, we divide the section into two parts: first, institutions that shape ports and their systems, and second, how ports and the port authority shape institutions. Fig. 4 outlines the institutional complexity at ports, with a specific focus on the energy demand of the road freight hinterland transport system and on Dutch national institutions (similarities exist with other EU countries). It illustrates specific institutions within the energy production, distribution, and consumption sectors and their interactions.

4.3.1. Institutions shaping ports

Fig. 4 shows that, in addition to the vertical institutions of international, national, and local policymakers, including the port authority, the port also faces lateral sector-specific policies in energy supply, distribution, and demand. Port actors find themselves in the institutional sandwich between policymakers and local pressure from port authorities. At the same time, port authorities face the challenge of balancing political pressure with stakeholders' industry needs (Damman & Steen, 2021). Energy transition-related institutions, such as the Emission Trading System II or FuelEU, increase political pressure on ports to decarbonise their operations with emission caps and fines that extend beyond geographical port boundaries (EU Commission, 2023b, 2023a). For example, informal institutions, such as the port readiness framework, guide ports in developing alternative fuel availability for vessels, while formal institutions introduce renewable energy cooperatives and promote the implementation of renewable energy in ports (Hentschel et al., 2018; IAPH, 2024; Thompson, 2023). Most institutions focus on the applicability of alternative fuels for maritime shipping and the decarbonisation of port operations.

Looking at hinterland freight transport, the literature concentrates on how taxation and incentive policies at ports reduce emissions, providing specific recommendations on operationalisation and the optimal policy mix for maximum decarbonisation impact (Hasan et al.,

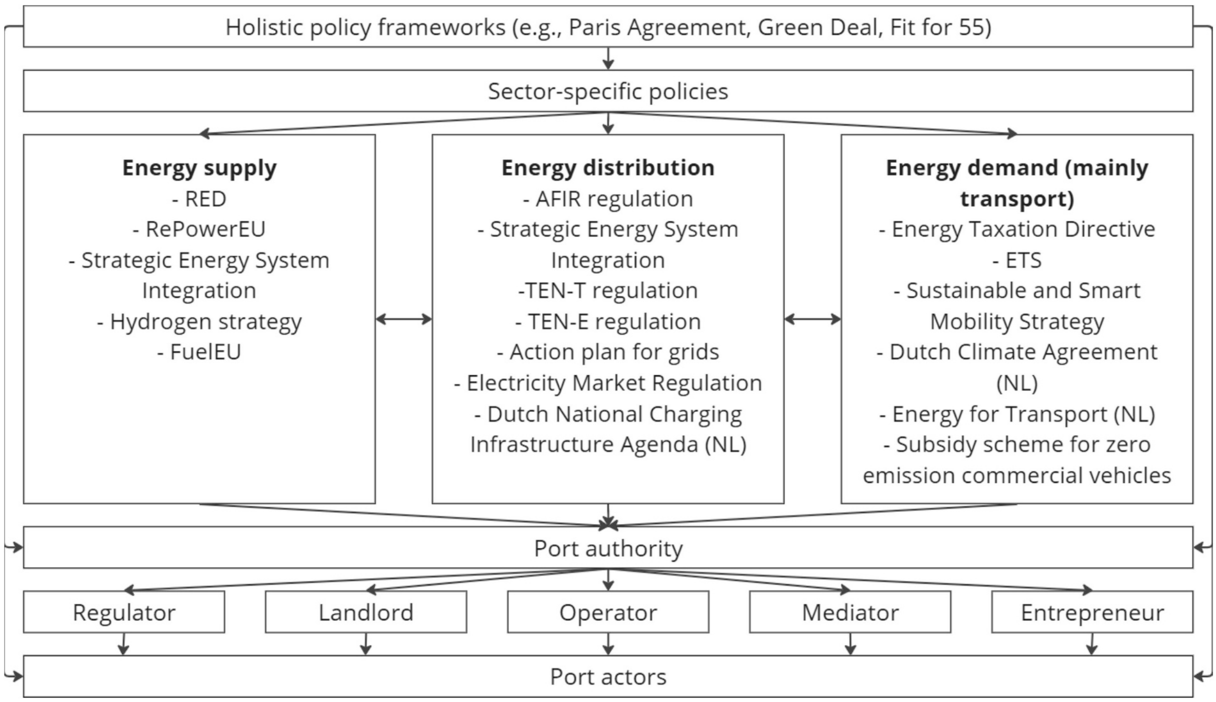

Fig. 4. Institutional landscapes shaping the port energy and hinterland transport systems(RED = Renewable Energy Directive, AFIR = Alternative Fuel Infrastructure Regulation, TEN-T = Trans-European Network for Transport, TEN-E = Trans-European Network for Energy, ETS = Emission Trading System).

2023; Liu et al., 2019; Matsuyama et al., 2024; Zhong et al., 2023). Particularly in port cities, awareness of the negative health impacts of drayage truck emissions underscores the importance of decarbonising for local governments (Ramirez-Ibarra & Saphores, 2023). Such policies focus on modal shift policies. Electrification has played a role in decarbonising drayage operations to date, with approximately 81% of pendulum trips covered by electric trucks (Tanvir et al., 2021). However, decarbonising hinterland transport is characterised by complexity and uncertainty due to its strong dependence on the hinterland economy and on infrastructure availability (Bergqvist et al., 2015). When giving policy advice on decarbonising hinterland freight transport, it is important to consider systemic constraints across systems encompassing existing road networks, fossil-based hinterland transport structures, the slow pace of grid development, and long-term economic developments towards more container-based transport (Lechtenböhmer et al., 2018; Steen et al., 2024).

4.3.2. *Port's institutional influence in global supply chains*

By definition, port authorities can be regulators (e.g. through port dues), landlords (spatial allocation), operators (self-contained or concessions), community managers (governance/mediator), and entrepreneurs (incentivising innovations) to influence in-port and adjacent industrial activities (Magnan & van der Horst, 2020; Van Der Horst & De Langen, 2008; Verhoeven & Vanoutrive, 2012). The literature views them as important institutional mediators that influence port decarbonisation through operational services, port dues, and infrastructure management, affecting the ports' energy, industry and logistics systems (Alamoush et al., 2020; Kurt, 2023; Steen et al., 2024). The measures can be directed towards port management and policies, power and fuels, operations at sea, and the hinterland (Bjerkan & Seter, 2019). The port authority can influence predominant fossil fuel regimes as a landlord by allocating land for renewable energy purposes and as an infrastructure provider for constructing charging and refuelling stations (Lind et al., 2023). As regulators, port authorities can implement measures to influence the decarbonisation of logistics operations, such as pricing, monitoring, market access controls, environmental regulation, and directed investments (Gonzalez Aregall et al., 2018). Their local measures can have a global impact on greening supply chains by bringing together shipping lines, the hinterland economy, port authorities, and energy providers to align their interests (Bjerkan et al., 2021; Bjerkan & Seter, 2019; Notteboom et al., 2020). For example, the green and digital shipping corridor between Singapore and Rotterdam, which encourages the uptake of alternative fuels and digitalised port calls for shipping (Port of Rotterdam, 2024d).

Such green corridors also apply to green trajectories with the hinterland to reduce negative externalities from trucks, thereby stimulating the uptake of low-emission trucks or modal shifts (Hasan et al., 2023; Port of Rotterdam, 2024b). The underlying green hinterland transport strategies of ports often align with regional transport and spatial planning frameworks (Poulsen et al., 2018; Ramirez-Ibarra & Saphores, 2023). Port authorities collaborate with port cities and other stakeholders in the hinterland economy to implement incentives and regulations that stimulate the adoption of low-emission trucks, while balancing the interests of affected stakeholders (Alamoush et al., 2024). Measures affect the spatial planning of transport infrastructure at ports, the planning of charging infrastructure with grid operators, logistics efficiency optimisation, and the economics of transport operators (Hasan et al., 2023; Zhao et al., 2024b). To align these goals, a holistic view of the energy system at ports is needed, including energy efficiency, a reliable energy system that operates in sync with production and consumption patterns, and a comprehensive overview of lifecycle emissions (Alzahrani et al., 2021; Iris & Lam, 2019).

Recapitulating, we found technological, actor, and institutional couplings that uniquely characterise ports in their ability to provide special energy supply conditions for energy consumers such as road freight hinterland actors. Subsequently, we discuss how these conditions affect the uptake of low-carbon energy technology for road freight hinterland transport, exploiting leverage points at the intersection of transport and energy systems.

5. Synthesis and discussion

In this section, we synthesise the results – structural couplings at ports- to describe the dynamics between port energy and the hinterland transport system, and how the port can positively influence the uptake of low-emission trucks (red arrows in Fig. 1). Through synthesis, we identify 9 socio-technical conditions that can facilitate the diffusion of low-emission trucks for hinterland transport, see Table 3. Subsequently, we discuss these conditions in light of the literature on challenges for low-emission truck diffusion and multi-system transitions.

5.1. Conditions on the technological dimension

Ports provide technological conditions for accelerating the uptake of low-emission trucks threefold: first, their energy-hub function can facilitate energy production and distribution and coordinate consumption at scale (**Condition 1** in Table 3) (Buonomano et al., 2023; Notteboom et al., 2020). Considering the scale of ports in the import/production, bunkering/storage, and distribution of low-carbon energy carriers, they have a fundamental impact on the local energy system by providing access and regulating prices for these carriers. Second, investments in energy infrastructure for offshore power generation, cold ironing, LNG bunkering, and battery storage illustrate ports' roles as energy suppliers and infrastructure providers to coordinate construction and facilitate their integration (**Condition 2** in Table 3) (Fossile et al., 2020; Molavi et al., 2020b; Wei et al., 2023; Zhang et al., 2020). And third, as investors and system entanglers, to proactively build charging infrastructure and invest in microgrid development to increase local grid capacity and independence (**Condition 5** in Table 3) (Bakar et al., 2022; Molavi et al., 2020b; Port of Rotterdam, 2024b).

Distribution infrastructure and electricity transmission are often bottlenecks in energy transition projects, as their construction can take decades and require extensive pre-planning (Nykamp et al., 2023). For example, power for vessels at berth or e-trucks for drayage operations requires megawatt-capable grid infrastructure and power supply (Bakar et al., 2022; Sharifi et al., 2024). As such, the diffusion of e-trucks depends mainly on the grid and charging infrastructure, requiring deep intervention into high and medium-voltage grids (Raoofi et al., 2024b). The transition will stagnate if charging infrastructure and power supply are unavailable, regardless of whether an imminent cost parity is achieved. Given its fingers across energy production/import, distribution, and consumption systems, ports could influence coordinated energy infrastructure development to facilitate the diffusion of low-carbon energy carriers for e-trucks or vessels at birth. In addition, the port can bridge this gap by providing geographic proximity to actors in energy production and consumption sectors to coordinate the creation of central energy management systems, innovative co-sharing concepts of grid connections, and smart grids to better plan operations that require energy (Iris & Lam, 2019, 2021; Steen et al., 2024). Companies near the port, such as road freight hinterland actors, can benefit from the resulting energy supply and price security, and infrastructure availability. For example, trucks usually queue until they can pick up their container. This time could be used to charge at local charging plazas, if aligned with pick-up timeslots. Another exemplification of such technological and actor conditions at ports is the establishment of green corridors with larger hinterland actors, such as inland ports or intermodal hubs. These are constant routes with high traffic volume, which could be gradually electrified (Lechtenböhmer et al., 2018; P. Zhao et al., 2025). The physical proximity of interdependent systems at ports can help align them and accelerate their joint transition. A central requirement, though, is well-planned grid-upgrading measures as the connecting structural element to facilitate the flow of energy between low-carbon energy generation and consumption.

Table 3
Port-specific energy supply conditions and their dynamic impact on the acceleration of the transition to low-emission trucks for hinterland transport. The last column describes the socio-technical dimension affected, as defined by the analytical MST framework in Fig. 1. It often comprises multiple dimensions. T = Technology dimension, A = Actor dimension, I = Institutional dimension.

Nr	Low-emission truck diffusion challenge	Conditions	Rationale	Dimension
1	Availability of energy sources	**Energy hub**	The scaling potential of renewable energy, whether through domestic production or imports, supports stable energy supply conditions and pricing (Buonomano et al., 2023; Hentschel et al., 2018; Notteboom et al., 2020).	T
2	Charging/ refuelling infrastructure availability	**Coordinated infrastructure development**	The port provides proximity to energy resources and centrally steered initiatives to build infrastructure, often aligned with the requirements of adjacent energy-consuming sectors and integrating multiple stakeholders. (Bakar et al., 2022; Damman & Steen, 2021; Hentschel et al., 2018; Iris & Lam, 2021; Port of Rotterdam, 2024b)	T, A
3	Technology uncertainty	**Technology-specific incentives**	Depending on the port's size, energy initiatives can be centrally driven by the port authority or by incumbents. In larger ports, port authorities can take the initiative to set regulations that promote specific technological developments and diversify innovation (Damman & Steen, 2021; Thompson, 2023).	I
4	Total costs of ownership (TCO)	**System entangler, regulator**	Ports can influence the prices of low-emission trucks through institutional measures, such as taxing diesel trucks, investing in charging and energy infrastructure, or even stimulating energy cooperatives (Bergqvist et al., 2015; Hentschel et al., 2018; Ye et al., 2024; Zhong et al., 2023).	I
5	Charging/ refuelling time	**Investor, system entangler**	Battery maturity challenge, but ports can support the construction of fast and megawatt charging stations to accelerate charging times (Port of Rotterdam, 2024b; Sharifi et al., 2024; Ye et al., 2024).	T
6	Change of routing/planning	**Fixed hinterland transport routes**	Fixed hinterland transport routes enable better planning of charging infrastructure (Gonzalez Aregall et al., 2018; Sharifi et al., 2024; Ye et al., 2024).	A, I
7	Coordination complexity of logistics activities	**Physical proximity of transport and energy systems**	Port hinterland transport/drayage often has designated routes. As a result, charging infrastructure and refuelling planning can be better aligned with logistics operations (Gonzalez-Aregall et al., 2019; Sharifi et al., 2024; Wu et al., 2023; Ye et al., 2024).	A
8	Inclusivity of the transition	**Balancing between incumbents and niche actors**	Ports can equalise market imbalances and provide charging and refuelling access for all transport companies through cross-system learning. They can also work with hinterland transport nodes to install end-to-end charging and refuelling infrastructure (Behdani et al., 2020; Bjerkan et al., 2021; Damman & Steen, 2021; Steen et al., 2024).	A, I
9	Governance of heterogeneous groups of stakeholders	**Mediator**	Ports relieve complexity by providing physical proximity and shared services that enhance energy efficiency and governance among actors in transition. (Iris & Lam, 2019; Lind et al., 2023; Wei et al., 2023)	A

5.2. Conditions on the actor dimension

We found 5 instances where ports can provide energy supply conditions on the actor dimension. Ports provide proximity to actors in energy production, distribution, and consumption (**Condition 2** in Table 3). With an overview of all three subsystems, port authorities can centrally coordinate infrastructure construction in line with energy supply and demand in port areas (Hentschel et al., 2018; Port of Rotterdam, 2024b). Illustrative of the central position in energy projects is the current development of the hydrogen conversion park or large-scale e-truck charging stations in the Port of Rotterdam (Port of Rotterdam, 2022). Energy companies, infrastructure providers, port authorities, station operators, local governments, and consumers collaborate to ensure secure wind energy production, transmission to electrolysers/batteries, hydrogen transformation, hydrogen distribution infrastructure, and energy offtake. As such, ports can coordinate infrastructure development and enable actors of heterogeneous sectors to collaborate to increase energy efficiency and share knowledge (Hentschel et al., 2018; Lind et al., 2023; Steen et al., 2024).

Ports have often established fixed freight transport routes to the hinterland, providing a central advantage for the diffusion of low-emission trucks (**Conditions 5 and 6** in Table 3). Compared to more unstructured truck trajectories across the mainland, finding optimal charging locations can be easier and ease changes in transport routing and complex logistics activities (Lechtenböhmer et al., 2018; Ye et al., 2024). Established hinterland routes and the critical mass of carriers that require low-carbon energy infrastructure lay the foundation for charging station operators to invest in infrastructure that will be used (Gonzalez-Aregall et al., 2019; Sharifi et al., 2024). Especially, drayage operations can be integrated well with infrastructure planning and the limited distance of battery-electric trucks (Wu et al., 2023).

Ports can have a profound impact on the inclusivity of the low-carbon transition of hinterland transport (**Condition 8** in Table 3). Road freight transport primarily struggles with this chicken-and-egg problem, lacking central guidance on implementing complementary niche technologies, such as charging stations, because they require a change in driving and charging behaviour (Bakker et al., 2025; Ertelt et al., 2024). Especially smaller trucking companies struggle to adopt low-emission trucks, which require fundamental changes in behaviour, rerouting, and time and payload losses, as they have few resources to compensate for these (Ainalis et al., 2023; Ertelt & Kask, 2024). They require a steady, secure energy supply and constant use of their trucks, which is difficult with lower payloads and an underdeveloped charging infrastructure. Only then will they commit to low-emission trucks. Here, port authorities could leverage their central power to drive the construction of charging infrastructure, as is done, for example, with the creation of onshore power supplies for ships, and to determine and construct optimal charging station locations and in the coordination of renewable energy cooperatives to stimulate peer-learning between actors in transition (Hentschel et al., 2018; Steen et al., 2024). In addition, the port space brings together multiple trucking companies with unsteady energy off-take patterns. If they are merged with the complementary energy consumption patterns of other energy consumers, they can achieve balanced energy offtake and better integration into energy distribution chains.

Ports can also mediate energy transitions on a larger scale (**Condition 9** in Table 3) (Bergqvist et al., 2015; Bjerkan et al., 2021). The transition to renewable electricity is often characterised by power imbalances, as grid operators usually do not depend on new grid users, whereas electrifying actors in the energy transition critically depend on new grid connections (Andersen et al., 2023; Nykamp et al., 2023). Coinciding with long-term grid-upgrading processes and rapidly developing electricity consumption markets, energy grids are notoriously underdeveloped in Europe (Raoofi et al., 2025). Given the lack of grid expansion, e.g. in the Netherlands, the need for grid sharing and innovative ways to distribute electricity among industry and transport consumers is becoming increasingly important. At this friction point between energy supply and consumption systems, system entanglers become increasingly important for governing the rising complexity (Löhr & Chlebna, 2023). The port ecosystem exhibits such complexity on a local scale, pushing port authorities to increase their efforts to coordinate this complex environment and mediate between unbalanced sectors (Bosman et al., 2018; Damman et al., 2025; Loorbach & Geerlings, 2017). Since the port provides proximity for energy distribution and consumption systems, it can enable better cooperation between them (Nykamp et al., 2023).

5.3. Conditions on the institutional dimension

We identified four ways to stimulate e-truck uptake in the hinterland transport through leveraging institutional conditions at ports. Ports can reduce the technological uncertainty through technology-specific economic and institutional incentives (**Condition 3** in Table 3). A major shortcoming in the transition to low-emission trucks is the lack of certainty about prioritising specific low-carbon technologies as future alternatives to diesel trucks (Larson et al., 2024). Ports have shown they can specifically steer technological development through local investments and the facilitation of collaboration to enable large-scale energy projects, such as energy cooperatives, large-scale green hydrogen projects, shore power initiatives, electrification of terminal operations, and the development of alternative fuels for ships (Alamoush et al., 2020; Damman et al., 2025; Iris & Lam, 2019). Although ports prioritise the decarbonisation of maritime transport and in-port operations, technological advances in adjacent industries, such as the construction of grid infrastructure for shore power, can accelerate grid expansion for e-truck charging. The establishment of formal institutions at the port to enforce shore power can stimulate the flow of niche technologies across systems and positively influence the electrification of trucking.

Ports can influence the diffusion of low-emission trucks through their regulatory measures. Since ports have a range of measures such as concession agreements, port dues, and economic incentives, they can influence behaviour in and around the port boundaries (**Condition 4** in Table 3) (Alamoush et al., 2020; Bjerkan & Seter, 2019; Damman & Steen, 2021). Low-emission truck diffusion is mainly driven by the total costs of ownership (Alarcón et al., 2025; Noll et al., 2022). Ports can leverage their landlord role to influence trucking costs by, for example, taxing diesel trucks, investing in charging and energy infrastructure, or even stimulating energy cooperatives (Hentschel et al., 2018; Ye et al., 2024). However, ports often do not proactively pursue such regulatory or entrepreneurial measures to implement radical changes, especially when unforeseen financial or competitive risks are involved (Steen et al., 2024).

Similarly, with institutional measures, ports can transform fixed transport routes into green hinterland corridors along major truck routes (**Condition 6** in Table 3). Under increasing political pressure, port authorities are working to reduce their environmental footprint, focusing mainly on maritime transport and port operations in terminals and petrochemical clusters, as well as on direct port emissions (Loorbach & Geerlings, 2017; Samadi et al., 2016). However, ports can influence green practices beyond their port boundaries through agreements with dry ports and industrial complexes in the hinterland (Bergqvist et al., 2015; Hasan et al., 2023; Lechtenböhmer et al., 2018). Hinterlands drive port throughput and encompass many important stakeholders for port authorities, such as hinterland access regimes and major freight demand companies (Liu et al., 2019; Van Der Horst & De Langen, 2008). Sitting within the same jurisdiction, they share goals for emission reduction and can jointly overcome investment barriers to changing infrastructure by establishing more sustainable hinterland transport routes. This already worked in maritime shipping to reduce emissions from heavy fuel oil, and in inland ports that help load more cargo onto inland waterways and rail instead of trucks (Behdani et al., 2020; Notteboom et al., 2020).

Notably, hinterland changes are complex and involve heterogeneous groups of actors, including shippers, customers, carriers, freight forwarders, infrastructure providers, and energy suppliers (Bjerkan & Seter, 2019). It is crucial to manage those and align their goals so all move together towards using low-emission vehicles; otherwise, their dependencies will stall one another's transition progress.

Ports can equalise market imbalances and provide inclusive charging and refuelling access for all transport companies (**Condition 8** in Table 3). The diffusion of e-trucks is, among other things, obstructed by a transport-sector-specific challenge: subcontracting activities to smaller-scale companies, which results in an unbalanced resource allocation to invest in low-emission trucks and charging infrastructure (Rogstadius et al., 2024). Port authorities can provide access to additional public charging and refuelling infrastructure for smaller-scale carriers through direct investment, in addition to depot charging infrastructure, charging opportunities from adjacent carriers, or joint investments, as mentioned in the section 5.2 (Ye et al., 2024).

5.4. Discussion

Although we identified nine potential conditions under which ports could accelerate the diffusion of low-emission trucks, their impact remains largely speculative. From the broader background literature, we have identified four critiques of the port's conditions for facilitating the diffusion of low-emission trucks, namely (1) the port's selective interventions and incremental steps towards decarbonisation, (2) the port's passiveness in the energy transition, (3) increasing transition complexity of hinterland transport, and (4) the port characteristics limit their impact on decarbonisation. Below, we discuss these conditions in light of the existing literature on e-truck diffusion and multi-system transitions.

First, existing studies suggest that ports primarily pursue decarbonisation strategies in response to external political pressure, despite positioning themselves as leaders in the energy transition (Hentschel et al., 2018; Steen et al., 2024). Consequently, their decarbonisation efforts are often selective, focusing on incremental innovations rather than transformative changes. According to the different decarbonisation pathways outlined by global and national policymakers, port authorities would support the technological alternative with the lowest marginal abatement costs (Molavi et al., 2020b). Such "minimum effort" measures are mainly directed at decarbonising in-port operations, such as yard vehicles and equipment, onshore power for ships, and the production and storage of alternative fuels (Alamoush et al., 2020; Attanasio et al., 2023; Bjerkan & Seter, 2019). At the same time, the landside logistics operations and associated negative externalities are often neglected by port decarbonisation research, since emissions from maritime transport are more visible and thus perceived as more threatening (Gonzalez-Aregall et al., 2019; Poulsen et al., 2018). Such behaviour allows only incremental steps towards carbon neutrality in hinterland transport; more stringent interventions are necessary to achieve radical change in ports (Steen et al., 2024). P. Zhao et al. (2025) extend the discussion and call for a two-sided approach: In the long term, measures should be directed at dismantling existing fossil infrastructure and transitioning to low-carbon energy-powered transport, while short-term measures should focus on incrementally improving truck fleets and road infrastructure. It is important to align incremental steps with disruptive innovations, phasing out fossil-fuel regimes to make way for low-carbon innovations (Bakhuis et al., 2024). For example, expanding the energy grid to enable mass electrification can take decades, but the technological imbalance between transport and energy systems can be bridged with institutional arrangements. Incremental changes to energy contracts could enable multiple consumers on a single grid connection, bridging the time to grid upgrades by aligning energy consumption patterns and enabling energy sharing (Nykamp et al., 2023). For policymakers and port authorities, that means existing road freight hinterland transport research and policies optimising intermodal freight networks, routing, and GHG emission minimisation must be aligned with measures supporting substantial changes in energy distribution networks and charging/refuelling infrastructure, such as in the Trans-European Transport Network directive (EU Commission, 2021). Given that the port authority and local governments share jurisdiction over hinterland transport, they can coordinate measures between the port and the hinterland to enable systemic interventions (Gonzalez Aregall et al., 2018). However, hinterland transport companies could also become trapped in an institutional sandwich between energy, transport, and port systems, threatening their economic viability. This highlights the importance of the interplay between local government and port authorities in providing a holistic, inclusive set of institutional measures to influence the uptake of low-carbon energy technologies among actors in and around ports in different timeframes.

Second, the institutional conditions for the uptake of low-emission trucks depend on the port's governance structure and its influence on the energy transition. Port authorities' institutional influence on in-port and coupled processes can take the form of regulation, landlordship, operation, community management, and entrepreneurship (Magnan & van der Horst, 2020; Van Der Horst & De Langen, 2008; Verhoeven & Vanoutrive, 2012). It is notable that port authorities primarily act passively, rather than as entrepreneurs (Steen et al., 2024). For example, hinterland transport is steered by dominant actors, including terminal operators, shipping lines, freight forwarders, port authorities, and/or regional governments, which collectively form the hinterland access regime (De Langen & Chouly, 2004). Ports take a more passive role in managing the land, collecting taxes, and maintaining competition through services (Notteboom et al., 2022). Investments in transport equipment, the use of transport modes, infrastructure construction, and freight supply are primarily influenced by incumbents. The transition to low-emission trucking depends on the energy supply and the hinterland economy; for it to be successful, ports may need to adopt a more proactive role in advocating for the energy transition, destabilising hinterland transport regimes, and supporting niche innovators (Behdani et al., 2020). In practice, restrained regulations on emission abatement and taxation won't be enough and must be accompanied by proactive actor coordination to facilitate a joint co-evolution of adjacent systems towards low-emission trucking. A vertical integration of niche and regime actors, institutions, and technologies must be combined with a lateral integration of the energy supply and demand sectors. The entrepreneurial role regains prominence as an accelerator for niche innovations in and around ports, while serving as a community manager and setting the right directions through regulations and spatial allocation.

Third, positioned at the systemic interface of transport and energy systems, ports face increasing governance complexity in preventing low-carbon energy technologies from being stranded and in steering fossil-fuel incumbents across energy and transport systems to adopt them. Our findings show that ports are focal points where energy supply, distribution, and consumption systems converge, emphasising their growing role in the energy transition and its governance across systems (Alamoush et al., 2024; Damman et al., 2025; Steen et al., 2024). To achieve greater decarbonisation, energy distribution and consumption systems must grow in step with one another (Nykamp et al., 2023). Alternative fuels and electrification were formerly independent from the transport system and have become inherently connected in the low-carbon energy transition (Bosman et al., 2018; Loorbach & Geerlings, 2017). Ports' decarbonisation strategies must therefore include the divergent socio-economic goals of heterogeneous groups of actors, the governing institutions that shape actor behaviour, and the interplay between technological innovations and prevailing regimes.

In addition, ports often depend financially on the industrial complex incumbents and the hinterland economy (Damman & Steen, 2021; T. Guo et al., 2022). If port authorities adopted strict policies to promote low-carbon energy carriers and reduce the fossil fuel industry's presence, they would risk lowering their economic competitiveness and prompting companies to leave (Alamoush et al., 2020). Relying on port authorities to be pioneers in the energy transition may conflict with their economic interests. This tension is reflected in historical decarbonization patterns, with ports focusing more on seagoing activities and terminal operations, given their direct regulatory responsibility for these emissions and the relative ease of implementing in-port changes (Behdani et al., 2020; Bjerkan & Seter, 2019). In contrast, ports enabled few technological conditions for hinterland transport companies to switch to low-emission practices, particularly charging/refuelling infrastructure or institutional support for the uptake of low-emission trucks. As electrification and alternative-fuel applications accelerate across port ecosystems, quantifying the emission-abatement potential of low-emission trucks for hinterland transport is a promising, underexplored avenue for future research.

Fourth, depending on the port's physical conditions, the energy hub character manifests in very different ways, and a port's influence should be evaluated accordingly (Notteboom & Haralambides, 2023; Steen et al., 2024). Big ports, such as the Port of Oslo or Rotterdam, evolved into oil and gas hubs, while smaller ports specialised in niche fields to maintain competitiveness (Damman & Steen, 2021; Loorbach & Geerlings, 2017). In smaller ports, the energy hub character may manifest, for example, by leveraging incumbents' advantages in renewable energy production and evaluating the most impactful emission abatement compared to the investment (Fossile et al., 2020). In contrast, big ports are taking on a more central role in the holistic energy transition, aiming to maintain their central position in the global energy supply chains, including those involving renewables (Alzahrani et al., 2021; Lechtenböhmer et al., 2018). They invest simultaneously in emission abatement, renewable production and import, alternative-fuel bunkering and electricity storage, and energy transformation and distribution infrastructure (Loorbach & Geerlings, 2017; Wei et al., 2023). In the case of Rotterdam, the port has ample influence as a landlord, large financial resources, and access to knowledge to facilitate such disruptive infrastructural innovation; in smaller ports, this might be less possible and more driven by influential incumbents (Damman & Steen, 2021; Steen et al., 2024). Through the port's central position in global logistic chains, exogenous actors such as shippers can significantly shape the port's stance on renewable energy (Bloemert & Saraceni, 2024). Additionally, the physical conditions of grid connection and renewable energy supply influence the port authorities' capability to be proactive in pushing low-emission truck uptake. Whereas, for example, the port of Rotterdam can swiftly integrate fast-charging infrastructure for e-trucks into the national high- and medium-voltage grids, remote ports such as coal ports in Australia may focus more on leveraging their location for biofuel production through access to biomass and waste sources (Flikkema et al., 2023; Schulz et al., 2025). These actor constellations must be evaluated individually in ports to identify key nodes that can leverage impact on the sustainable transition in ports (Notteboom & Haralambides, 2023). Despite their influence, port authorities sit at the interface of transport and energy systems, facilitating functional flows between the energy supply and the hinterland transport system. (Inter-)National policymakers should thus leverage the port's central position by integrating port authorities, logistics incumbents and fossil fuel regimes more fully into policy frameworks for the energy transition to enable centrally governed transitions (Steen et al., 2024).

6. Conclusions

This research examined the port's socio-technical conditions to facilitate the diffusion of low-emission trucks in road freight hinterland transport systems. Drawing on information from a literature review, we structure our findings by applying a multi-system transition framework to identify the technological, actor, and institutional couplings that shape the interconnectivity between port energy supply and road freight hinterland transport systems. We found 33 articles mentioning technological couplings, 25 actor couplings, and 41 institutional couplings. In response to the research question, we find that ports occupy a unique position at the interface of the hinterland transport and energy system, providing nine socio-technical conditions that facilitate the diffusion of low-emission trucks in port hinterland transport.

Based on the identified conditions in Table 3, we provide recommendations for the port community to leverage their influence to accelerate the diffusion of low-emission trucks in port hinterlands. On the technological dimension, ports primarily act as energy hubs, which they should leverage to scale low-carbon energy production, import, storage, and distribution for low-emission trucks (Condition 1). This can be reinforced by centrally steered infrastructure development at ports, as such projects often lack central commitment (Condition 2). Additionally, ports should act as investors and enablers by deploying fast-charging infrastructure to address key infrastructure and operational bottlenecks (Condition 5).

On the actor dimension, ports should serve as coordinators for actors of coupled systems. The concentration of energy producers, distribution infrastructure providers, and transport actors in the port should be leveraged to synchronise energy supply and demand and infrastructure construction (Condition 2). Fixed hinterland transport routes (Condition 6) and the geographic proximity of logistics and energy systems (Condition 7) should be leveraged to simplify the planning of charging/refuelling infrastructure in conjunction with logistics operations. Ports also play a crucial role in ensuring an inclusive transition (Condition 8). By providing charging infrastructure, supporting collective investment models, and facilitating cross-system learning, they can lower barriers for smaller carriers. Additionally, port authorities should serve as system entanglers, overseeing both prevalent incumbents and niche actors in the port energy and hinterland transport systems (Condition 9). Aligning hinterland access regimes with niche actors and hinterland industries can lead to joint efforts to enable a low-carbon transition. Since ports are energy-constrained, such flexible concepts of shared infrastructure and demand coordination are essential.

Institutionally, port authorities should shape the transition towards low-emission trucking through a mix of incentives, regulation, and mediation. They can reduce technological uncertainty by subsidising complementary charging and refuelling technologies, thereby reducing the migration and operational costs associated with low-emission trucks (Condition 3). Furthermore, ports can act as regulators to influence the costs of low-emission trucks (Condition 4). For example, through port dues, infrastructure investments, or subsidies for energy cooperatives. Engaging hinterland economies and transport companies (Conditions 6 and 8) enables the development of green hinterland corridors along major freight routes, demonstrating the port's influence beyond its geographical boundaries. Given their cross-border nature, national policymakers should leverage big ports to implement institutions that facilitate the diffusion of low-emission trucks. In smaller ports, they should provide institutional support.

Recapitulating, the diffusion of low-emission trucks in port hinterlands relies heavily on complementary innovations in energy supply and infrastructure to reduce costs and increase charging availability (Raoofi et al., 2025; Ye et al., 2024). This dependence on investments in related systems often slows the spread of niche technologies, requiring temporal alignment (Grubler, 2012). It entails actively involving stakeholders from both systems in energy cooperatives, proactively managing them, and governing the diffusion of low-carbon energy technologies. Ports geographically connect these systems, enabling parties from both systems to better synchronise their innovation processes. In this context, we found the multi-system transition framework a valuable tool for understanding the underlying interdependencies and the potential levers at ports. However, the port hinterland system is also influenced by the spatial transition of the port and hinterland area and the port industry, which co-evolve and inherently connect to the hinterland transport system (Bjerkan et al., 2021; Loorbach & Geerlings, 2017). Since this research is limited to the road freight hinterland transport system, future research can develop a holistic, multi-system transition framework that includes additional coupled systems and their influence on transition speed, accounting for factors such as competition for low-carbon energy with other sectors, electricity infrastructure congestion, hinterland economy, and spatial restrictions.

In this research, we use the holistic perspective of the multi-system transition framework to analyse the port's role in the diffusion of low-emission trucks; however, there are more peculiarities associated with adopting niche low-carbon technologies for road freight transport (Aryanpur & Rogan, 2024; Ertelt et al., 2024; Rogge & Goedeking, 2024). These require further investigation with empirical data from stakeholders in the hinterland transport and port energy system, as well as a quantitative evaluation of the impact of innovations on the transition to carbon–neutral road freight transport.

When it comes to the interplay of heterogeneous system components, simulations can support understanding the dynamics between complex system elements. In transition studies, the benefit of simulation models has been recognised (Köhler et al., 2018, 2019; Köhler & Brauer, 2023). The interplay of multiple systems at ports creates a dynamic field tied to the economics of hinterland markets and the port industry (T. Guo et al., 2022; Liu et al., 2019; Zhong et al., 2023). In this context, system dynamics models can support understanding the second-order effects of decarbonisation measures on adjacent systems (Köhler & Brauer, 2023). To reach carbon neutrality, it is not only important to analyse the interactions between systems, but also to include the quantified temporal impact on system transitions (Geels et al., 2017b; Köhler et al., 2019; Sovacool et al., 2025). Future research can investigate the dynamics of adjacent systems during the transition to low-emission trucks for hinterland transport, building on this study's findings. Specifically, it should consider the port authority as an institutional medium to leverage low-carbon energy technology and exploit the spatial proximity of energy systems at ports.

CRediT authorship contribution statement

Jonathan Schmid: Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Samantha Eleanor Tanzer:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Lórant Antal Tavasszy:** Writing – review & editing, Validation, Supervision, Project administration, Funding acquisition, Conceptualization.

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Declaration of competing interest

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trip.2026.102152.

Data availability

Data will be made available on request.

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