

Decarbonising Smart Ports: A Complexity and Paradox Perspective of Sines and Leixões

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Abstract: The decarbonisation of maritime transport and port infrastructure has become a central challenge in the global transition towards climate neutrality. Smart ports are increasingly positioned as innovation hubs where digitalisation, energy transition, and sustainability intersect. However, the pathways through which ports adopt and implement decarbonisation strategies remain heterogeneous and theoretically underexplored, particularly regarding how different strategic approaches emerge in practice. This paper investigates how smart ports navigate decarbonisation through the combined lenses of Complexity Theory and Paradox Theory. It addresses three research questions: (1) What factors influence the adoption of decarbonisation practices in smart ports? (2) How do these factors shape strategic responses? (3) To what extent do emerging vectors, such as green hydrogen, represent innovation opportunities within port ecosystems? The study adopts a qualitative comparative case study methodology, analysing the ports of Sines and Leixões in Portugal. Data were collected from secondary sources, including strategic plans, institutional reports, and policy documents, and analysed through thematic coding across five dimensions: decarbonisation goals, technologies, public policies, partnerships, and expected outcomes. Findings reveal that both ports are aligned with European climate objectives but follow distinct strategic pathways. Sines adopts a large-scale, infrastructure-driven approach, leveraging international energy corridors and industrial integration projects. In contrast, Leixões pursues a more decentralised and innovation-oriented trajectory, emphasising earlier carbon neutrality targets and strong collaboration with research institutions. The analysis shows that decarbonisation emerges as a complex adaptive process shaped by multi-actor interactions, while also involving persistent tensions between growth and sustainability, centralisation and collaboration, and efficiency and experimentation. These tensions are actively managed as drivers of innovation rather than constraints, enabling differentiated yet effective transformation pathways. The paper contributes in three ways: (1) it integrates Complexity and Paradox Theory in the context of sustainable innovation; (2) it provides empirical insights from a comparative smart port analysis; and (3) it identifies green hydrogen as a strategic opportunity for complementary innovation ecosystems.

Keywords: Smart Ports; Decarbonisation; Green Hydrogen; Innovation; Paradox vs Complexity Theory

1. Introduction

The transition towards climate neutrality has placed increasing pressure on maritime transport and port systems to reduce their carbon footprint. Ports are evolving from logistics nodes into integrated energy and innovation platforms within global value chains.

Smart ports, characterised by digitalisation and sustainability integration, are central to this transformation. Decarbonisation strategies—including electrification, renewable energy, and alternative fuels such as green hydrogen—are reshaping operations and governance.

Despite this relevance, research remains fragmented and insufficiently attentive to the dynamic and tension-rich nature of transformation processes.

This study addresses this gap by analysing the decarbonisation strategies of the ports of Sines and Leixões through the lenses of Complexity Theory and Paradox Theory.

Portugal provides a relevant empirical setting due to its strategic positioning within European energy and logistics systems.

This paper contributes in three ways. First, it advances theoretical understanding by integrating Complexity and Paradox perspectives. Second, it offers empirical insights through a comparative analysis. Third, it identifies green hydrogen as an emerging innovation vector.

2. Literature Review

2.1 Smart Ports and Innovation

Smart ports integrate digital technologies, automation, and sustainability practices to improve efficiency and environmental performance (Belmoukari et al., 2023). They function as innovation ecosystems involving multiple stakeholders and interconnected infrastructures.

Existing literature highlights the importance of digitalisation, yet lacks empirical grounding and unified conceptualisation.

Large seaports have become strategic nodes within global logistics and energy networks, extending their traditional cargo-handling role towards multifunctional platforms integrating transport, industrial activities, digital infrastructures, and energy systems. Their scale, connectivity, and investment capacity enable them to act as innovation ecosystems capable of accelerating technological diffusion and supporting the transition towards low-carbon maritime transport (Notteboom & Rodrigue, 2005; ESPO, 2021).

Within Europe, major ports increasingly operate as integrated hubs where digitalisation, renewable energy deployment, alternative fuels, and industrial symbiosis converge. This evolution reflects a broader transition from infrastructure-based competitiveness towards ecosystem-based competitiveness, in which value creation depends on collaboration among port authorities, terminal operators, energy companies, research organisations, and public institutions (European Commission, 2021; ESPO, 2021). Consequently, large ports constitute particularly relevant empirical settings for investigating how complex innovation processes underpin decarbonisation strategies.

2.2 Decarbonisation Strategies

Decarbonisation involves electrification, renewable energy integration, and alternative fuels such as hydrogen (Holder et al., 2024). Ports are increasingly positioned as energy hubs, supporting both maritime and industrial decarbonisation.

However, strategies vary significantly depending on local context, governance, and infrastructure.

2.3 Complexity Theory

Complexity Theory conceptualises ports as adaptive systems characterised by non-linearity, emergence, and interdependence (Anderson, 1999; Arthur, 2021). Transformation emerges from interactions among multiple actors rather than centralised planning.

2.4 Paradox Theory

Paradox Theory focuses on persistent tensions such as sustainability vs. growth (Smith & Lewis, 2011). Organisations must manage rather than resolve these tensions, enabling innovation through dynamic balancing.

2.5 Port Governance and Ownership Models in Europe

The governance and ownership structures of ports constitute an important contextual factor influencing their capacity to implement innovation and decarbonisation strategies. Beyond technological capabilities and infrastructure, port governance shapes investment decisions, stakeholder coordination, regulatory flexibility, and the ability to mobilise long-term partnerships for sustainable transformation (World Bank, 2007; Verhoeven, 2010).

The European port sector is characterised by considerable institutional diversity. Nevertheless, the landlord port model has become the predominant governance structure across most major European ports (World Bank, 2007; OECD, 2011). Under this model, the port authority retains ownership of the basic infrastructure and assumes responsibility for strategic planning, environmental management, safety, and regulatory oversight, while commercial cargo-handling activities and terminal operations are undertaken by private operators through long-term concession agreements. This arrangement seeks to combine public strategic control with private-sector efficiency, investment capacity, and operational expertise.

Alternative governance models include the service port, where the port authority directly provides most operational services; the tool port, in which infrastructure and equipment remain publicly owned while cargo

operations are partially outsourced; and fully private ports, where infrastructure ownership and operational responsibilities are concentrated within private organisations (World Bank, 2007). Although these models continue to exist in specific contexts, the landlord model has progressively become the dominant institutional framework in Europe due to its ability to balance public policy objectives with commercial competitiveness (Verhoeven, 2010).

From an innovation perspective, governance arrangements influence how ports respond to emerging challenges associated with digitalisation and decarbonisation. Landlord ports typically operate within complex multi-actor ecosystems involving port authorities, terminal operators, logistics firms, energy companies, industrial tenants, research organisations, and public agencies. As a result, innovation increasingly depends on collaborative governance mechanisms rather than hierarchical decision-making alone (OECD, 2011).

This governance perspective is particularly relevant to the present study. Both the Port of Sines and the Port of Leixões operate under the landlord model, yet they exhibit different configurations of stakeholders, investment patterns, and strategic partnerships. These institutional differences provide an important contextual layer for interpreting their respective decarbonisation pathways through the lenses of Complexity Theory and Paradox Theory. Rather than determining a single trajectory, governance structures create the institutional conditions within which alternative innovation pathways emerge and evolve.

3. Methodology

This study adopts a qualitative, exploratory comparative case study design.

3.1 Data Collection

Data were collected from:

- Strategic plans (Sines, Leixões)
- Institutional reports
- EU policy frameworks (e.g., Green Deal)
- Academic literature

3.2 Data Analysis

A thematic coding approach was applied across five dimensions:

1. Decarbonisation goals
2. Technologies
3. Public policies
4. Partnerships
5. Expected outcomes

3.3 Analytical Framework

The study integrates:

- Complexity lens → adaptation, emergence, system dynamics
- Paradox lens → tensions and dualities

This dual framework enables a richer interpretation of innovation processes.

4. Results

4.1 Case Description

The Port of Sines and the Port of Leixões represent two structurally distinct but strategically relevant cases within the Portuguese port system, offering a robust basis for comparative analysis. Sines, located on the southwest Atlantic coast, is Portugal's largest deep-water port and a key node in global maritime logistics. Handling approximately 47.8 million tonnes of cargo in 2024, including around 1.9 million TEU, it is strongly integrated into international trade routes and energy corridors. Its industrial ecosystem, including the ZILS (Sines Industrial

and Logistics Zone), supports large-scale energy and petrochemical activities, positioning the port as a strategic platform for energy transition initiatives.

Consistent with the governance framework outlined in Section 2.5, both the Port of Sines and the Port of Leixões operate under the Portuguese landlord port model. In this model, port authorities retain responsibility for strategic planning, infrastructure development, regulation, safety, and environmental management, while cargo handling and terminal operations are largely undertaken by private concessionaires (World Bank, 2007; OECD, 2011).

Although both ports share the same institutional structure, their stakeholder configurations, strategic partnerships, and investment profiles differ substantially, influencing the way decarbonisation initiatives are developed and implemented. The Port of Sines hosts major international terminal operators and energy companies, reflecting its strong integration into global logistics and energy markets. This international orientation facilitates large-scale investments and long-term infrastructure projects associated with the energy transition. By contrast, the Port of Leixões operates within a more regionally embedded industrial ecosystem, where collaboration with local industries, municipalities, universities, and research centres plays a more prominent role in supporting innovation and sustainability initiatives. These institutional differences reinforce the contrasting strategic pathways identified in this study.

In contrast, the Port of Leixões operates within a dense urban and industrial environment in northern Portugal. Handling approximately 14–17 million tonnes annually, it serves as a critical logistics gateway for regional industries, including textiles, metallurgy, and agri-food sectors. Its strategic positioning within a knowledge-intensive region, with proximity to universities and research centres, reinforces its role as an innovation-oriented port.

From a decarbonisation perspective, Sines adopts a long-term, infrastructure-intensive strategy centred on large-scale projects such as the NEXUS Agenda and participation in European green corridors. These initiatives aim to integrate digitalisation, renewable energy production, and hydrogen-based value chains. Leixões, by contrast, follows a more accelerated trajectory, targeting carbon neutrality by 2035 through incremental innovation, electrification, and strong collaboration with research institutions.

These structural and strategic differences create a valuable empirical setting to explore how alternative decarbonisation pathways emerge under different institutional, geographic, and economic conditions.

4.2 Comparative Analysis

The comparative analysis reveals both convergence and divergence in decarbonisation strategies across the two ports. At a fundamental level, both Sines and Leixões adopt a common set of technological and strategic measures, including electrification of port operations, integration of renewable energy sources, digitalisation of logistics processes, and experimentation with alternative fuels such as hydrogen and biofuels. These shared elements reflect alignment with European policy frameworks, including the European Green Deal and Fit for 55.

However, the manner in which these strategies are implemented differs significantly. Sines adopts a scale-driven model, prioritising infrastructure development, energy system integration, and positioning within international logistics and energy corridors. Its strategy emphasises long-term competitiveness through large capital investments and partnerships with global energy players.

Leixões, in contrast, follows a network-driven model, characterised by agility, experimentation, and strong collaboration with regional innovation ecosystems. Its approach is more decentralised, leveraging partnerships with universities and research centres to accelerate the adoption of emerging technologies and achieve earlier decarbonisation milestones.

Differences are also evident across the five analytical dimensions. In terms of goals, Leixões sets more ambitious short-term targets, while Sines focuses on long-term systemic transformation. In technologies, Sines emphasises large-scale energy infrastructure, whereas Leixões prioritises modular and adaptable solutions. In partnerships, Sines aligns with industrial and international actors, while Leixões builds knowledge-based networks. These distinctions illustrate how context shapes strategic choices in decarbonisation pathways.

4.3 Theoretical Interpretation

From a Complexity Theory perspective, both ports can be understood as complex adaptive systems in which multiple actors—port authorities, logistics operators, energy firms, policymakers, and research institutions—

interact dynamically. Decarbonisation does not result from linear planning but emerges from iterative processes of adaptation, experimentation, and feedback. The introduction of new technologies, such as hydrogen systems or digital platforms, triggers cascading effects across organisational, infrastructural, and regulatory domains.

The comparison between Sines and Leixões highlights different modes of complexity management. Sines reflects a more orchestrated form of system evolution, where large-scale projects act as structuring mechanisms for coordinated change. Leixões, by contrast, exhibits a more distributed form of adaptation, where innovation emerges through networked interactions and local experimentation.

From a Paradox Theory perspective, the analysis reveals that both ports face persistent and interrelated tensions. These include the need to balance economic growth with environmental sustainability, centralised strategic direction with decentralised collaboration, and operational efficiency with experimentation and innovation. Rather than resolving these tensions, both ports engage in ongoing processes of balancing and reframing.

Importantly, the findings suggest that these tensions are not merely constraints but generative forces that stimulate innovation. For example, the pressure to reduce emissions while maintaining competitiveness drives investment in new technologies and business models. The ability to navigate these paradoxes effectively becomes a key organisational capability in the context of sustainable transformation.

4.4 Green Hydrogen as Innovation Opportunity

The literature review, the identification of key decarbonisation drivers (Section 4.1), and the comparative analysis between Sines and Leixões (Section 4.2) collectively point to green hydrogen as a strategic vector with high potential for sustainable innovation in smart ports.

As highlighted by Notteboom and Haralambides (2023), green hydrogen (GH₂) is increasingly integrated into port systems through three main pathways: (1) local production using renewable energy sources; (2) bunkering services for hydrogen-based maritime fuels; and (3) export and distribution of hydrogen and its derivatives (e.g., ammonia and methanol). These roles position ports not only as logistics nodes but as emerging energy hubs within decarbonised value chains.

This transformation introduces a new “secondary market” logic, in which ports expand beyond traditional cargo handling to participate actively in clean energy ecosystems. From an innovation perspective, green hydrogen enables new business models, fosters cross-sector integration between energy and logistics, and reinforces the strategic relevance of ports in the energy transition. The associated benefits include economic diversification, increased attractiveness for foreign investment, reduction of carbon emissions, industrial symbiosis, and the creation of high-skilled employment.

The empirical analysis suggests that the Ports of Sines and Leixões may assume complementary roles within this emerging hydrogen ecosystem. Sines is well positioned to act as a large-scale production and export hub, supported by its extensive industrial area (ZILS), access to renewable energy sources, existing LNG infrastructure adaptable to hydrogen, and integration into European energy corridors. Large-scale projects such as GreenH2Atlantic further reinforce this positioning.

In contrast, Leixões is better suited to operate as a regional distribution and innovation hub, focusing on local industrial applications, pilot projects, and technological experimentation. Its proximity to industrial clusters in northern Portugal, combined with strong linkages to research institutions (e.g., FEUP, INEGI, CEiiA), enables the development of a knowledge-intensive hydrogen ecosystem. The reconversion of the Matosinhos refinery into an innovation hub further strengthens this trajectory.

This complementary positioning is synthesised in Table 1, which highlights the distinct but interconnected roles of both ports within a potential hydrogen-based innovation system.

Table 1: Complementary roles of Sines and Leixões in the green hydrogen ecosystem

Dimension	Port of Sines	Port of Leixões
Scale	Large-scale	Regional and urban
Main Function	Production and export	Distribution and local consumption
Type of Projects	Industrial, international	Innovation, urban and industrial supply
Partnerships	EDP, Galp, Engie, REN	Galp, CEiiA, INEGI

Dimension	Port of Sines	Port of Leixões
Geographic Positioning	South – Atlantic corridor	North – industrial urban cluster
Energy Role	Mass production and export	Local application and technological demonstration

Source: Author's own elaboration

From a theoretical perspective, this finding reinforces the argument that decarbonisation is not a uniform process but unfolds through differentiated yet interconnected pathways. From an innovation standpoint, green hydrogen emerges as a bridging vector that connects these pathways, enabling complementarities across scales and functions.

Due to its relevance in terms of opportunities for innovation, it is important to summarize these findings relating to green Hydrogen:

1. Green hydrogen emerges as a critical innovation vector enabling new business models and energy-logistics integration.
2. In Sines, hydrogen is positioned as a large-scale production and export opportunity, supported by infrastructure, industrial integration, and international energy corridors.
3. In Leixões, hydrogen plays a more decentralised role, focusing on regional consumption, experimentation, and integration with industrial clusters and research ecosystems.
4. This complementary positioning suggests the emergence of a dual-port innovation ecosystem, where:
 - Sines operates as a production and export hub
 - Leixões functions as a distribution and application hub
5. This configuration enhances:
 - System efficiency
 - Innovation diffusion
 - Strategic resilience
6. Green hydrogen therefore represents not only a technological solution but a systemic innovation opportunity.

4.5 Integrated Framework of Decarbonisation Pathways

Building on the comparative findings and theoretical lenses, this study proposes an integrated conceptual framework of smart port decarbonisation pathways (Figure 1).

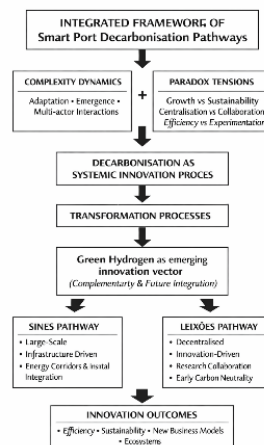


Figure 1: Integrated Conceptual Framework of Smart Port Decarbonisation Pathways

Source: Author's own elaboration

Figure 1 presents the integrated conceptual framework of smart port decarbonisation pathways developed in this study. The model conceptualises decarbonisation as a systemic innovation process emerging from the interaction between complexity dynamics (adaptation, emergence, multi-actor interactions) and persistent paradoxical tensions (e.g., growth vs sustainability; centralisation vs collaboration).

Importantly, the framework embeds the empirical findings by identifying two differentiated strategic pathways: a large-scale, infrastructure-driven trajectory (Sines) and a decentralised, innovation-driven trajectory (Leixões). A transversal vector—green hydrogen—is introduced as a bridging and future-oriented innovation pathway connecting both trajectories, illustrating how complementarities across ports can drive systemic transformation.

This highlights how ports navigate tensions not as constraints but as drivers of innovation, leading to distinct yet interconnected decarbonisation pathways.

5. Discussion

The findings of this study reinforce the view that decarbonisation in smart ports is best understood as a systemic and non-linear innovation process. Rather than following a predefined trajectory, ports develop context-specific pathways shaped by institutional conditions, resource endowments, and stakeholder configurations.

The comparative analysis of Sines and Leixões demonstrates that different strategic approaches can lead to effective decarbonisation outcomes. Sines exemplifies a scale-based pathway, where large investments and integration into global systems drive transformation. Leixões illustrates a network-based pathway, where innovation emerges through collaboration and regional ecosystems. These findings challenge the assumption of a single optimal model for port decarbonisation.

A key insight is the role of tensions as drivers of innovation. The need to reconcile competing demands forces organisations to develop hybrid strategies that combine elements of stability and change, centralisation and decentralisation, and efficiency and experimentation. This aligns with emerging perspectives in innovation studies that emphasise the importance of managing, rather than eliminating, contradictions.

Furthermore, the results highlight the importance of policy alignment and multi-level governance. European and national policies provide both direction and resources, but their impact depends on local implementation and institutional capacity. The interaction between policy frameworks and organisational strategies is therefore critical in shaping decarbonisation trajectories.

Although this study focuses on two large Portuguese ports, some of the underlying mechanisms identified may also provide useful insights for smaller ports. While smaller ports generally operate with more limited financial resources, infrastructure capacity, and institutional capabilities, they face similar challenges related to decarbonisation, digital transformation, and stakeholder coordination (ESPO, 2021).

Rather than replicating the large-scale investments observed in Sines or the extensive innovation networks developed in Leixões, smaller ports may benefit from adopting context-appropriate strategies centred on collaboration, gradual technological implementation, and regional partnerships. In this sense, the complexity and paradox perspectives developed in this paper offer analytical insights that extend beyond large ports, highlighting that successful decarbonisation depends less on scale itself than on the capacity to coordinate multiple actors, manage competing objectives, and develop adaptive governance arrangements.

Finally, the identification of green hydrogen as an emerging vector underscores the evolving role of ports as energy hubs. Beyond reducing emissions, ports are increasingly involved in the production, storage, and distribution of clean energy, creating new opportunities for value creation and innovation.

5.1 Implications for Innovation Theory

This study contributes to innovation theory by framing port decarbonisation as a form of systemic innovation that transcends organisational boundaries. It highlights the need to move beyond linear models of innovation towards more dynamic and integrative perspectives that account for complexity and interdependence.

By combining Complexity Theory and Paradox Theory, the paper offers a novel analytical lens to understand how innovation unfolds in environments characterised by uncertainty and competing demands. Complexity Theory explains how innovation emerges from interactions within adaptive systems, while Paradox Theory elucidates how organisations navigate tensions inherent in these processes.

The findings also suggest that tensions can play a productive role in innovation. Rather than hindering progress, they create conditions for creative problem-solving and strategic renewal. This perspective contributes to a growing body of literature that views paradox not as a problem to be solved but as a resource to be leveraged.

Additionally, the study highlights the importance of multi-actor ecosystems in driving innovation. Ports are not isolated entities but embedded in networks of stakeholders whose interactions shape innovation outcomes. This reinforces the relevance of ecosystem-based approaches in innovation research.

6. Conclusion

This study set out to analyse how smart ports navigate decarbonisation through the combined lenses of Complexity Theory and Paradox Theory, using a comparative case study of the ports of Sines and Leixões. The findings demonstrate that decarbonisation is a multifaceted and dynamic process that cannot be reduced to technological adoption alone.

A central conclusion is that there is no single pathway to successful decarbonisation. Instead, ports develop differentiated strategies that reflect their specific contexts, capabilities, and strategic priorities. Sines and Leixões exemplify two distinct but effective models: one based on scale and infrastructure, the other on networks and innovation ecosystems.

From an innovation perspective, the study highlights the importance of managing complexity and embracing paradox. The ability to navigate competing demands, adapt to changing conditions, and leverage multi-actor interactions emerges as a critical capability for sustainable transformation.

The identification of green hydrogen as a strategic opportunity further illustrates the evolving role of ports in the energy transition. By acting as hubs for clean energy production and distribution, ports can contribute not only to their own decarbonisation but also to broader systemic change.

In terms of future research, the study points to several avenues for further investigation. Empirical validation through primary data, including interviews with key stakeholders, would strengthen the findings and provide deeper insights into decision-making processes. Quantitative approaches, such as structural equation modelling, could also be used to test the relationships between the identified factors. Additionally, comparative studies across a larger number of ports would enhance the generalisability of the results.

Overall, this paper contributes to advancing the understanding of sustainable innovation in complex infrastructural systems, highlighting the importance of integrative theoretical approaches and context-sensitive strategies.

Furthermore, the complementary positioning of the Port of Sines as a large-scale production and export hub and the Port of Leixões as a regional distribution and innovation hub highlights a promising systemic configuration within the emerging green hydrogen economy. This complementary approach deserves further investigation in all its implications, particularly regarding its potential to foster integrated innovation ecosystems, enhance regional competitiveness, and accelerate the transition towards sustainable energy systems.

Ethics Declaration

No ethical approval was required.

AI Declaration

AI tools were used to support language refinement and structuring of the manuscript.

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