Content, Structure and Governance of Transactions
A Business Model

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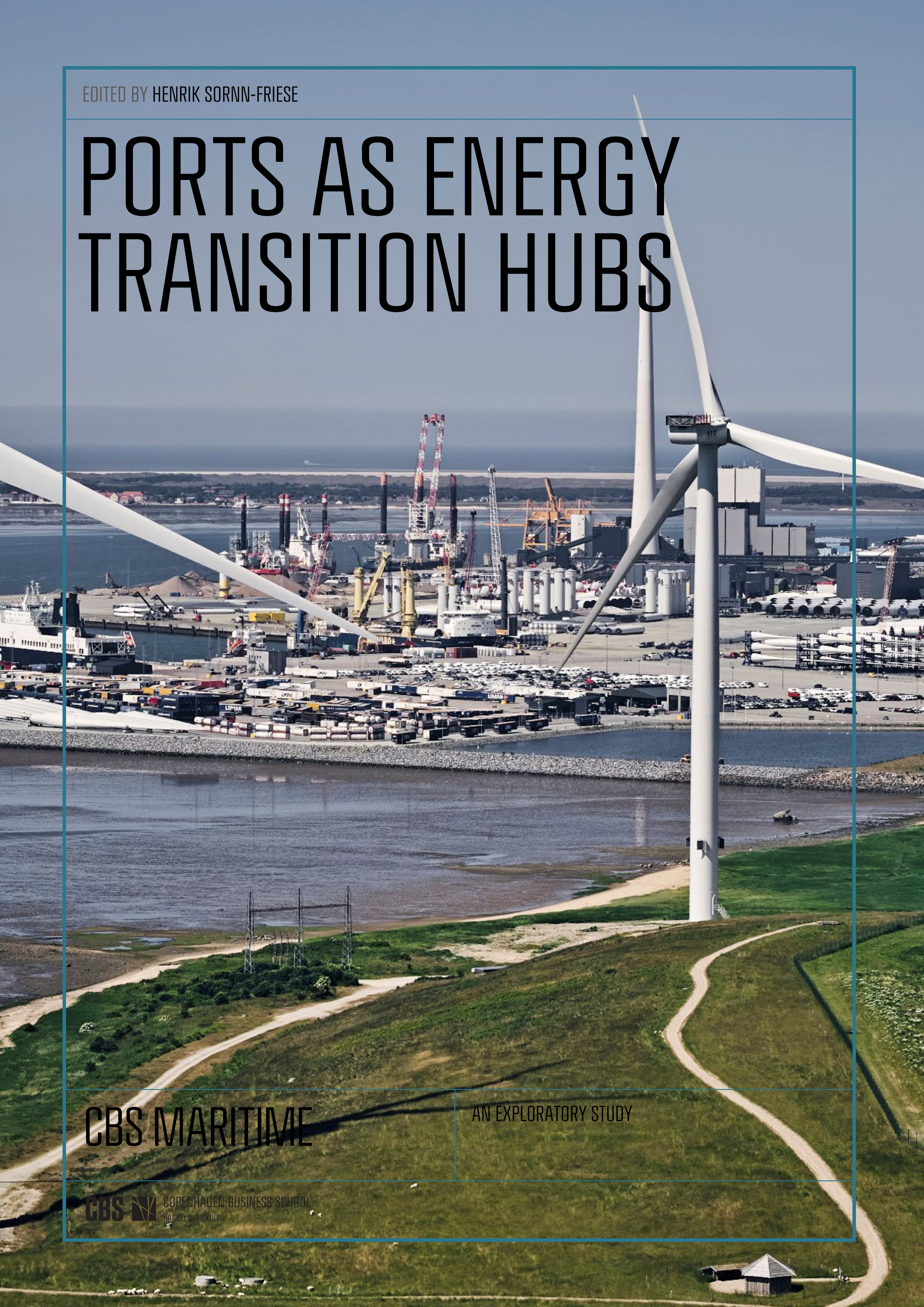
EDITED BY HENRIK SORNN-FRIESE

PORTS AS ENERGY TRANSITION HUBS



CBS MARITIME

AN EXPLORATORY STUDY

CBS COPENHAGEN BUSINESS SCHOOL
HANDELSHØJSKOLEN

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This research was supported by the Danish Maritime Fund; projects: 'Accelerating the Energy Transition at Sea and on Land: Ports as Hubs' [#2021-037] and 'Accelerating the Energy Transition at Sea and on Land: Governance of Hubs, Valleys, and Corridors' [#2022-044]

PUBLISHED BY
CBS MARITIME
NOVEMBER 2024

CBSMARITIME@CBS.DK
WWW.CBS.DK/MARITIME

FRONT PAGE PHOTO
CHRISTER HOLTE/ESBJERG HAVN

PRODUCTION
CBS MARITIME

GRAPHIC PRODUCTION
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ISBN
978-87-93262-16-4

PARTNERS:

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CHAPTER 1. EXPLORING PORTS AS ENERGY TRANSITION HUBS

Henrik Sornn-Friese

1. INTRODUCTION

This report is the outcome of a collaborative effort between researchers from Copenhagen Business School's *CBS Maritime* and *Copenhagen School of Energy Infrastructure* (CSEI) and the Technical University of Denmark's *Maritime DTU*, as part of our joint work in the mPATH project. The report presents a tentative and transdisciplinary inquiry into the emerging role of ports as hubs for the clean energy transition and is exploratory in nature. The aim of the report is not to meticulously describe and document how ports can or do facilitate the transition from fossils to renewable energy and green fuels, nor to uncover underlying causes and factors. Instead, it focuses on identifying knowledge gaps, formulating challenges and problems, and developing new scholarly ideas and approaches for addressing them. By identifying key issues and generating preliminary evidence, the report aims to stimulate further investigation and support the strategic planning necessary for ports to effectively contribute to and benefit from the clean energy transition.

Ports play a critical role in the global economy, acting as major hubs for industry, trade, and transportation. As the world moves towards renewable energy and green fuels, ports are positioned to be key facilitators in the transition due to their strategic locations, infrastructure, and ability to influence multiple sectors, including shipping, logistics, and industrial activities. The importance of ports as hubs for the clean energy transition generally relies on three interrelated functions (Notteboom et al., 2022):

- Ports can be *energy transport platforms*, acting as gateways for the import and export of energy products (including their temporary storage)
- Ports can be *energy transformation platforms*, acting as sites for all the industries involved in the production, distribution and sales of energy and energy-related products to perform their activities
- Ports can be *energy generation platforms* that provide conventional and alternative energy sources to port tenants and users

We already see the favorable locational aspect of ports playing out in the current commercial and policy visions to develop port-centric business ecosystems for the clean energy transition. Several major ports, such as, Antwerp-Zeebrugge, Houston, Rotterdam, Singapore, and Tokyo are already advanced in gas-powered electricity generation and liquefied natural gas (LNG) bunkering for ships. It should be noted that while LNG is cleaner than traditional fossil fuels, it remains a carbon-based energy source, and reliance on LNG could be seen as an intermediate rather than a transformational approach.

In recent years, the focus has turned to the role of ports in accelerating the transition to truly renewable energy sources and the so-called hydrogen economy.

1. The Port of Hamburg is spearheading significant initiatives to establish itself as a central hub in the clean energy transition, particularly focusing on hydrogen as a key energy carrier (Port of Hamburg, 2023). By 2026, the Blumensand tank farm will thus host Germany's first import terminal for green ammonia, crucial for transporting hydrogen. Major infrastructure upgrades include replacing oil tanks with ammonia tanks and installing ammonia crackers. International partnerships with countries like Chile, Uruguay, and regions like Scotland and Canada bolster hydrogen import capabilities. Locally, the port is developing a hydrogen distribution center and an electrolysis plant at the Moorburg site, expected to produce up to 800 megawatts.
2. The Port of Rotterdam envisions to become the place where the energy transition takes shape (Sok, 2016) with the long-term aim of becoming a leading hydrogen hub in Northwest Europe (Stam et al., 2023).

3. Shoreham Port in West Sussex has launched a public-private partnership for producing high-purity hydrogen for use in fuel-cells onboard ships and aiming to transform the UK's southern coast into a national hub for green transport and energy.
4. In Denmark, Copenhagen Infrastructure Partners (CIP) has for the past few years worked on developing a massive power-to-X (PtX) facility in Esbjerg, in the so-called Høst project. Esbjerg is favorably located as gateway to the North Sea and is home to one of the leading offshore ports in Northern Europe.

In addition to the locational advantages enabling ports to become facilitators of the clean energy transition, ports are also under increasing pressure from a range of stakeholders to decarbonize their own operations and develop environmental strategies to better manage the negative externalities emanating from their operations and improve stakeholder relations as part of their business model (Acciaro et al., 2014). For example, given their common location near cities, ports are increasingly compelled to reduce their own emissions as well as emissions from the ships and trucks calling at them. As an example of a response to the latter, Singapore's (energy consuming) Jurong Port, which primarily handles major bulks such as cement or steel, has recently assembled a 9.65 MW solar farm capable of covering most of its own annual electricity needs. Ports may thus have social legitimacy incentives for being involved in accelerating energy transitions, an issue that is dealt with in chapter 6 of this report.

The clean energy transition thus presents both an opportunity and an imperative for ports to become energy transition hubs. The notion of ports as energy transition hubs raises the question of how to transform the key ports in global trade, which – among other things – would involve electrification of port and port user activities and fuel switch for ocean shipping, land-based transport, and industry (DNV GL, 2020) and require change in the use of land and the infrastructure landscape in the port as well as in port cargo flows (Royal HaskoningDHV, 2022).

1.1 Different roles and approaches of ports

Ports can assume various facilitating roles in the clean energy transition, each with different levels of foresight and strategic intention (please table 1 for an overview). They might be passive providers of clean energy infrastructure, intermediaries bringing together relevant stakeholders, or system-builders strategically creating and shaping clean energy and green fuel value-driven chain structures or business ecosystems. The latter role involves ports becoming genuine institutional entrepreneurs, proactively driving innovation in business models, technologies, and value chains to enable the transition to renewable energy and green fuels for shipping and other sectors.

Some ports may adopt a conservative approach to the transition, slowly integrating new technologies, practices, and business models, while others may take a proactive, entrepreneurial role. In the conservative approach, change is undertaken reluctantly, mainly in response to serious challenges, while a more entrepreneurial approach is characterized by aggressive enactment of innovation (Miller and Friesen, 1982). As proactive institutional entrepreneurs and system-builders, ports will drive systemic change by purposely developing new organizational capabilities, knowledge resources, and collaborative networks to shape the transition.

Table 1. How ports can facilitate the clean energy transition

Role	Description
Supportive facilitators	Ports act as infrastructure providers without active involvement in shaping the transition. They offer clean energy infrastructure but do not drive innovation.
Adaptive integrators	Ports take a reactive approach, integrating new technologies and practices slowly, monitoring industry trends and regulatory changes before adapting.
Intermediaries	Ports bring together relevant stakeholders, facilitating the transition by acting as a bridge but not actively shaping the ecosystem.
Strategic adapters	Ports adopt a balanced approach, selectively integrating innovative practices and technologies, enhancing infrastructure incrementally, and fostering partnerships.
Proactive entrepreneurs	Ports drive systemic change by developing new capabilities, resources, and networks, playing a proactive role in shaping the transition.

System-builders	Ports strategically create and shape clean energy and green fuel value-driven chain structures or business ecosystems.

Between these two extremes, ports can take on a more balanced approach, neither passively waiting for changes to happen nor aggressively leading the charge in systemic transformations. Instead, they act as strategic adapters, selectively adopting innovative practices and technologies as they become viable. These ports recognize the importance of staying competitive and sustainable without overextending their resources or taking significant risks. They may incrementally enhance their infrastructure to support clean energy and green fuels, foster partnerships with stakeholders to share knowledge and resources, and pilot projects that align with the evolving energy landscape.

2. A SYSTEMS PERSPECTIVE AND INTERDISCIPLINARY COLLABORATION

Transitioning from fossils to renewable energy and green fuels is key for decarbonization and climate change mitigation and for maintaining global temperatures within the goals of the Paris Agreement. Energy production and use are responsible for a significant portion of global greenhouse gas (GHG) emissions. According to the International Energy Agency (IEA), more than 75 percent of total GHG emissions globally are attributed to energy-related activities. This includes emissions from the combustion of fuels for electricity and heat production, transportation, industrial processes, and residential use, as well as fugitive emissions from the extraction and processing of fossil fuels.

The energy transition is a subsection of broader sustainable development and is intertwined with goals such as reducing carbon emissions, enhancing energy security, promoting economic resilience, and ensuring social equity (Sachs et al., 2019). It encompasses a wide array of changes aimed at creating more sustainable economic, social, and environmental systems and will involve profound structural changes across all sectors of society. Achieving a successful energy transition thus requires recognizing its multifaceted and systemic nature, involving interconnected changes across technology, policy, societal sectors, market structures, social behavior, and environmental practices (Geels et al., 2023). This requires coordinated efforts across governments, industries, and stakeholders to address technological, economic, and social challenges in a systemic way (IRENA, 2020).

The present report enquires into the emerging role of ports as facilitators (or, bottlenecks) of this transition, a problem that remains ill-defined and complex. By examining the issue through a systems perspective, we endeavor to enhance our understanding of the challenges and opportunities ports face as they adapt to and facilitate the transition towards clean energy. Developing ports as energy transitions hubs involves more than just technological, spatial, and infrastructure developments. It also requires rethinking economic regulation of the port sector, port governance structures, business models, and key stakeholder relations and partnerships.

Recognizing that ports operate within a complex web of economic, social, and environmental systems, we employ systems thinking to understand and address the interdependencies and interactions among these elements in the context of the clean energy transition. By addressing the clean energy transition as a complex system involving multi-level interactions, we wish to emphasize the interconnectedness of various factors influencing the facilitating roles of ports. We acknowledge that ports operate within a dynamic network of economic, environmental, and regulatory dimensions, all of which must be considered to understand their evolving functions in the clean energy landscape. This approach allows us to identify intervention points where ports can most effectively contribute to the clean energy transition, anticipate potential challenges, and develop solutions that maximize positive outcomes while minimizing unintended consequences.

3. RESEARCH DESIGN AND DATA

The energy transition requires insights and expertise from a range of fields, including the physical and social sciences as well as humanities research (Franklin and Blyton, 2013). The present study brings together experts from engineering, business and management, and regulatory economics to create a comprehensive understanding of the role ports can play. To explore the (potential and emergent) role of ports in the clean energy transition, we adopt an eclectic approach, utilizing a diverse array of methods to collect data and gather insights. By integrating these diverse methods, this report not only captures a broad spectrum of information but also ensures that our propositions are grounded in real-world experiences and stakeholder perspectives. We believe that this approach provides a robust foundation for understanding the potential roles of ports in the clean energy transition and highlights key areas for future research and policy development.

3.1 Interdisciplinary research and transdisciplinary approach

We define *interdisciplinary research* as research carried out by discipline-specific teams working collaboratively to address a common problem (Rosenfield, 1992). By integrating technical knowledge with economic analysis and social considerations, we seek to address the full spectrum of challenges and opportunities associated with the role of ports in the clean energy transition.

While Rosenfield (1992) distinguished interdisciplinary research from multidisciplinary research by its higher level of integration and collaboration among the teams involved, we have opted for a hybrid approach. This approach aims to leverage the strengths of both independent and collaborative efforts. We began this exploratory study with an initial joint planning phase, where the participating researchers came together to define research questions, goals, and methodologies, ensuring a shared vision and alignment of efforts. After this collaborative planning, we worked independently within each our disciplines to conduct in-depth analysis and gather data, allowing us to focus on our specialized expertise and generate detailed insights. We then scheduled regular integration meetings and workshops where we shared our findings, discussed progress, and identified overlaps and connections, fostering alignment, ongoing communication, and cross-pollination of ideas.

Moreover, to foster closer collaboration between the research teams and relevant non-academic stakeholders across the maritime and energy value chains, we have adopted a *transdisciplinary research* approach. This has worked to ensure 1) that the study captures a holistic view on the role of ports in the clean energy transition, 2) that the issues and problems under investigation remain relevant for practice, and 3) that the quest is for solution-oriented knowledge that can be applied to both science and practice.

We define transdisciplinary research as not only transcending separate disciplinary perspectives but also as being trans-sector, problem-oriented research involving a wider range of stakeholders in society (Klein, 2008). We have engaged with stakeholders from a broad range of societal groups with a stake in the clean energy transition, and particularly representing the maritime and energy value chains, in different parts of the research process and in different types of conversation (personalized and direct conversation with individual stakeholders, multi-lateral stakeholder workshops). This has allowed us to integrate the best available knowledge, reconcile values and preferences, and create a sense of ownership for the issues being addressed (Lang et al., 2012).

Table 2 provides an overview of all the stakeholders engaged in this process.

Table 2. Stakeholders involved in the research

AUTHORITIES	
Columbia's National Planning Department (DNP)	Danish Ministry of Higher Education and Science
Danish Utility Regular	Ministry of Foreign Affairs of Denmark
Embassy of Denmark in Singapore	Municipality of Fredericia
Italian National Agency for New Technologies, Energy and Sustainable Economic Development	Transport & Environment (T&E)
Maritime and Port Authority of Singapore (MPA)	UNCTAD, Division on Technology and Logistics
PORT MANAGING AND OPERATING COMPANIES	
Copenhagen Malmö Port (CMP)	Port of Antwerp
Associated Danish Ports (ADP)	Port of Esbjerg

Fundación Valenciaport	Port of Marseille-Fos
Hamburg Port Authority	Port Metro Vancouver
HAROPA Port	Port of Rotterdam
Jurong Port	Port of Rønne
Kenya Ports Authority	PSA International (Singapore)
OTHER COMPANIES	
Chiyoda Corporation	Fortum Power and Heat
Copenhagen Infrastructure Partners (CIP)	Maersk
Danfoss Power Electronics	Ramboll
DFDS	World Bank Group
Energinet	
INDUSTRY ASSOCIATIONS	
Danish Maritime	Danish Shipping
Danish Ports	European Sea Ports Organisation (ESPO)
OTHER ORGANIZATIONS	
American Bureau of Shipping (ABS)	Global Centre for Maritime Decarbonisation (GCMD)
Center Denmark	Global Maritime Forum
DNV	Lloyd’s Register Maritime Decarbonization Hub
C40 Cities	MMM Center for Zero Carbon Shipping
European Inland Waterway Transport Platform (IWT)	North Sea Hydrogen Maritime and Ports Community (NS HyMaP)
Fundacion Conecta Logistica	Singapore Maritime Institute (SMI)
German Maritime Centre	Waterborne TP
UNIVERSITIES	
Chalmers University of Technology	Kühne Logistics University
Copenhagen Business School (CBS)	Norwegian School of Economics
Denmark’s Technical University (DTU)	Norwegian University of Science and Technology (NTNU)
Kedge Business School	World Maritime University (WMU)

3.2 Data and data collection

Our study has employed a transdisciplinary approach, engaging representatives from various societal sectors in the research process. By combining desk research, stakeholder workshops and engagement, site visits, and interviews our research has provided a comprehensive and practice-relevant understanding of the multifaceted role of ports in the clean energy transition.

A large part of the exploratory research outlined in this report has relied primarily on extensive desk research and systematic reviews of the scientific literature. This provided a foundational understanding of the current state of knowledge, theoretical frameworks, and research gaps related to ports and the clean energy transition.

To collect valuable insights, we examined key learnings from other industries that, while different, offer comparable lessons for ports in terms of their transition to clean energy, including airports, electricity networks, and large infrastructure projects. It has also included sectors like logistics, manufacturing, and energy production, where innovative practices and technologies have been successfully implemented.

We analyzed a range of secondary data sources to contextualize our findings. This included industry statistics, providing quantitative benchmarks and trends, as well as newsletters and online communications from relevant stakeholders. These sources offered timely updates and industry perspectives that enriched our understanding of ongoing developments and stakeholder sentiments.

Table 3. Stakeholder workshops conducted at Copenhagen Business School (CBS) and Port Esbjerg headquarters

	Time and Place	**Main themes**	**Scope of workshop**	**No. of participants**
1	Full-day workshop at CBS, Nov. 5, 2021	Ports as energy transition hubs	• Presentation by research team: 'Project scope and deliveries' • Presentation by Anne-Rieke Stuhlmann, Senior Advisor at ESPO: 'The role of ports in the energy transition' • Presentation by Dennis Jul Pedersen, CEO at Port Esbjerg: 'The view from an energy port' • Sub-group discussions on project themes • Plenary discussion on key research needs and research questions of high industry relevance	31
2	3-hours workshop at CBS, Dec. 8, 2021	Social acceptance and community inclusion	• Presentation by research team: 'Project scope, deliveries and main take-aways from Workshop 1′ • Plenary discussion of the social aspects of ports as energy transition hubs and identifying research questions of high industry relevance	17
3	3-hours workshop at CBS, May 12, 2022	Refining research questions and building research partnership	• Presentation by research team: 'Project overview and preliminary results of main research themes and questions' • Open discussion on developing partnership opportunities	14
4	Full-day workshop at Port Esbjerg, May 30, 2022	Port Esbjerg in sustainability transition	1. Port Esbjerg's strategies and visions for sustainability and offshore wind 2. Dock workers' view on sustainability and offshore wind 3. Civil society view on sustainability and offshore wind 4. Guided tour of the port	20
5	3-hours workshop at CBS, October 13, 2022	Closing workshop	Presentation by research team: 'Project overview, preliminary findings, and open questions' Presentation by Maaike Dalhuisen, Strategy Advisor at Port of Rotterdam: 'The MAGPIE project'	51

Another crucial component of our research relied more heavily on engaging with a broad spectrum of policymakers and industry stakeholders across the maritime and energy value chains. We conducted discussions and participated in panel debates to gather diverse viewpoints and insights (see table 3 for an overview of stakeholder workshops). These interactions helped us understand the practical challenges, opportunities, and strategic priorities of those directly involved in the clean energy transition.

To complement our desk-based research, we conducted participant observations during visits to various ports. These on-site observations allowed us to witness firsthand the operational realities, infrastructure, and innovative practices being employed. This immersive approach provided contextual depth and practical examples of how ports are positioning themselves within the clean energy landscape.

Broader perspectives on the role of ports in the energy transition were collected at stakeholder workshops held in Copenhagen, where the research teams were able to discuss with almost 30 different stakeholders representing shipping, ports, classification societies, offshore companies, energy companies, renewable infrastructure investors, research and development organizations, consultancies, and universities. These workshops served to hone the research questions for the present study, scope the theoretical framework, and prepare the research team for the interview with port executives and subsequent stakeholder dialogue.

A stakeholder workshop was organized at Port of Esbjerg and engaged several academics, students, and key professionals from the port community and civil society interest organizations (port executives and staff, representatives of the Esbjerg dock workers' union, representatives of two port companies, and a representative of a local civil society group) in an informal and unstructured discussion. The workshop was opened by the CEO of Port Esbjerg, who presented the port's strategic visions and actual development initiatives, particularly within the area of offshore wind. The subsequent conversation revolved around the strategic visions and development of the port and broader and more general reflections on port sustainability issues, but with no predetermined questions and without a fixed agenda. The conversation to a certain extent resembled narrative interviewing, where particularly the participating dock workers gave personal reports from everyday life and events in the port, but the informal nature of the workshop allowed for follow-up questions from the research team (probing) and other workshop participants.

A final closing workshop was held at CBS on October 13, 2022, where the research teams presented their initial findings and perspectives to an audience representing academia, industry, and policymakers. This event served to validate the project outcomes and led to further refinement and new insights.

Several semi-structured interviews were carried out in the fall of 2022 and spring of 2023 with executive officers from different ports and stakeholder companies. These interviews relied on open-ended thematic questions identified prior to the interviews. The interviews typically started with broad, contextual questions on the role of ports as enablers of the energy transition before narrowing down to specific questions on the individual ports and companies.

Port site visits to Port of Esbjerg, CMP in Copenhagen, Port Metro Vancouver and Singapore's PSA International and Jurong Port gave the research teams the opportunity to interact with informants in their natural setting and can be conceived of as a form of participant observation. Several of these visits included tours of the ports, where the research teams were able to observe and to gain first-hand understanding of the massive scale required and high complexity of port operations in the context of the clean energy transition, the physical layout of port infrastructure, and the private companies located in several of the ports.

4. OVERVIEW OF REPORT

The chapters in this report all highlight the evolving role of ports in the clean energy transition and discuss the challenges and opportunities for ports as they transition from traditional roles to becoming integral parts of the global renewable energy and green fuel infrastructure. The report brings together diverse perspectives to provide a deep understanding of the multifaceted nature of this transition and offers a wide-ranging and to some extent integrative view that is crucial for stakeholders in the maritime and energy sectors.

Chapter 2 provides an interdisciplinary perspective on the transition of ports into energy hubs, integrating insights from engineering, environmental science, and digitalization and emphasizing technical, operational, and strategic dimensions. This discussion revolves around the integration of renewable energy systems and the decarbonization of traditional port operations. Ports, as complex multi-modal systems, are shifting towards incorporating advanced technologies like Internet of Things (IoT) and digital solutions to enhance efficiency and sustainability. The chapter outlines the technical aspects of this transition and explores the technical requirements for ports to manage and distribute renewable energy, particularly emphasizing the need for extensive automatization and decision support tools. Based on this discussion, the chapter identifies current knowledge gaps and suggests corresponding research questions in four areas: 1) Decarbonizing traditional port functions, 2) power-to-gas technologies, 3) digitalization and automatization in ports, and 4) development of a strategic decision support tool that could assist ports in selecting energy transition activities that optimize value creation while taking the priorities of the local stakeholders into consideration.

Chapter 3 synthesizes existing knowledge within the area of regulatory economics, pulling together insights from previous studies, regulatory frameworks, and theoretical models to identify emerging issues concerning the expected transformation of ports into future energy hubs. This transformation is expected to integrate ports more closely with the energy sector, particularly in generating offshore electricity and producing green fuels like hydrogen and ammonia. Ports, along with energy islands, will become crucial infrastructure elements in the energy system, playing a significant role in supplying and exporting green fuels to various industries. This new role will have economic implications, requiring ports to adapt to economic regulations like those in other infrastructure sectors, facing scrutiny for local and environmental impacts. The chapter explores economic regulation, public acceptance, and efficiency analysis of ports, drawing lessons from other regulated industries like airports and energy networks. It highlights the importance of economic efficiency, ownership structures, and the necessity for new governance frameworks as ports undertake significant investments and face the challenge of gaining public acceptance for clean energy infrastructure projects. On this basis, the chapter outlines several knowledge gaps and proposes research questions in six areas: 1) Economic regulation models; 2) economic methods to study and enhance public acceptance; 3) applying efficiency and productivity analysis to ports as energy hubs; 4) cost-benefit analysis applied to port expansion and development; 5) comparative studies; and 6) social and economic impact.

Chapter 4 explores the role of ports as energy transition hubs within the context of global maritime supply chains, which are responsible for carrying over 80 percent of the volume of international trade in goods (approximately 36 percent of which are energy products) and have a key facilitating role in promoting cooperation between maritime and energy systems. The chapter begins by examining how macroeconomic and regulatory pressures create vulnerabilities in global supply chains and how such pressure underscores the need for ports to transition. Ports are described as critical nodes that not only facilitate energy trade but also act as significant consumers of energy, emphasizing their dual role. The chapter explores how ports can support the transition to low- and zero-carbon fuels by implementing innovative technologies and adjusting operating practices, including their capacity to store and distribute alternative fuels.

Regulatory frameworks and incentives are crucial in this process, pushing ports to adapt to and comply with new standards and requirements. The chapter proposes several key research questions concerning fuel application processes, regulatory frameworks, legacy capacity issues, and the spatial implications of fuel production and usage: 1) who initiates the process to allocate a suitable fuel type, considering first-mover advantages versus disadvantages in value chains?, 2) which regulatory frameworks (e.g., carbon levy, subsidies) would contribute most to the progress of the energy transition?, 3) how should the maritime sector address legacy capacity issues and operate with foresight along policy ambitions?, and 4) what are the spatial implications of fuel production and usage, evaluating possible supply chain network changes?

Chapter 5 complements the discussions in the previous chapters by offering a framework for studying business model innovation in ports. This includes specific strategies for stakeholder engagement, new revenue streams, and the development of integrated service offerings. The chapter discusses the role of ports as physical locations and as complex organizations in the energy transition, focusing on port governance and business models. Effective port governance is essential due to the complex nature of port operations involving multiple stakeholders and significant externalities, but a broader focus on port business models is essential for the clean energy transition. Particularly, ports must adapt their business models to facilitate renewable energy development, attract investment, and foster innovation. The chapter identifies key knowledge gaps in understanding ports as energy transition hubs and proposes relevant research questions revolving around the 1) content, 2) structure, and 3) governance of ports' economic transactions.

Content of transactions focuses on what activities ports undertake (e.g., the specific services ports offer in the context of the clean energy transition), the structure of transactions focuses on how these activities are linked and sequenced (including the network of entities participating in the exchange and their roles and relationships), and governance of transactions concerns the mechanisms and systems that regulate the conduct and terms of transactions, including the structure and composition of the port's Board of Directors. In addition, the chapter identifies research questions of relevance to 4) the port revenue model accompanying the transactional aspects, i.e., how ports can generate revenue from clean energy activities and the financial implications of the clean energy transition on ports.

Chapter 6 discusses the role of ports as energy transition hubs with a key focus on the social dimensions of this transition. The adoption of green fuels at ports is expected to positively impact the climate and local environment. However, public acceptance and social implications need to be managed effectively. Ports traditionally interact with stakeholders within the port area, but the green transition requires closer cooperation with external stakeholders. Conflicts of interest among stakeholders, such as environmental protection versus port development, highlight the need for transparent, equitable, and efficient port management. Ports must balance economic, social, and environmental benefits to gain community support and mitigate negative externalities locally, such as air, soil, and water pollution.

The relationship between ports and cities is evolving, with ports playing a crucial role in urban transport systems and energy supply. Effective community engagement, transparent communication, and proactive measures are essential for building strong relationships between ports and their communities. The chapter highlights the need for future research to include comparative analyses of public acceptance across different countries, explore the intersection of social acceptance in both ports and renewable infrastructure, and incorporate a broader range of variables influencing social acceptance, which could provide a deeper understanding of emerging trends.

CHAPTER 2. TECHNICAL ASPECTS TO BE CONSIDERED BY PORTS FOR EVOLVING INTO ENERGY TRANSITION

Maximilian Schroer and George Panagakos

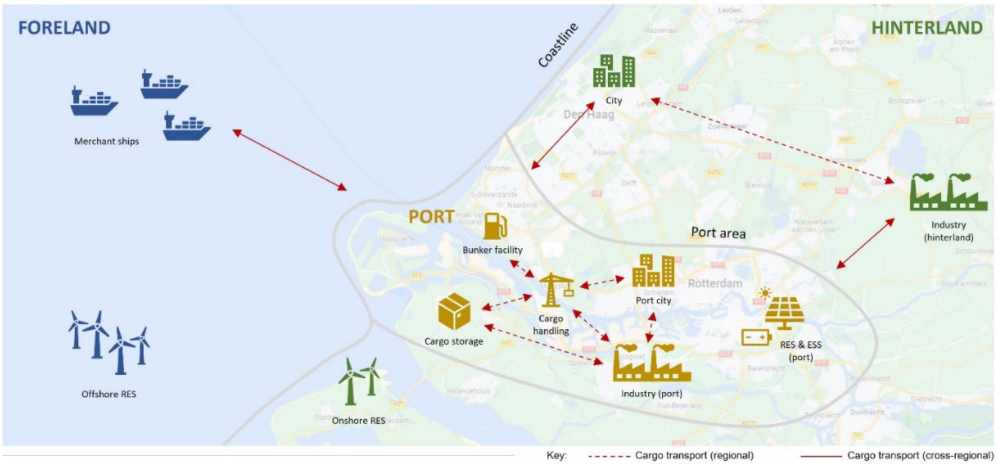
1. INTRODUCTION

A port represents a complex multi-modal and multi-actor system constantly evolving over time. Lee et al. (2016) referred to five port generations closely related to technological advances, among others. The current generation (customer-centric and community-focused modern port) arose from implementing digital solutions such as the Internet of Things (IoT) (Sadiq et al., 2021). This correlation between port characteristics and technological progress renders shifting towards an energy transition hub a natural development pathway. The technical dimension of this shift calls for exploring the current technical status-quo of a port, the state-of-the-art in research, and technical aspects beyond traditional port systems and operations. This is the purpose of this chapter.

Nowadays, ports act as multi-modal links connecting maritime with landside transport (Papaefthimiou et al., 2017). The port triptych model defines connections between a port's foreland (sea) and hinterland, the port itself being the third component (Charlier, 1992). In this pivotal role, the primary task is the transshipment of goods of all kinds, end-consumer products, semi-finished parts, resources, and passengers (see Figure 1). This already requires a high degree of technologization and organization for cargo handling and intermediate transporting.

On top, various vehicles and cargo handling and transporting equipment are exposed to efficiency and decarbonization requirements deriving from the energy transition. Electrification and hybridization of technologies like yard trucks (YT), rail-mounted gantry cranes (RMG), and forklifts locate at the forefront of potential solutions (Alamoush et al., 2020). Similarly, rail, road, and waterborne transport to hinter- and foreland considers alternative propulsion systems, further intensified through port dues, standards, and incentives (Acciaro et al., 2014b; Du et al., 2018; Gibbs et al., 2014; Poulsen et al., 2018). Less specific attempts focus on the positive correlation between operational and energy efficiency by improving, e.g., cargo handling time or ship and truck idle time (Chen et al., 2013; Yun et al., 2018).

Figure 1. Cross-Regional and Regional Cargo Transport Connections in the Port Triptych Model

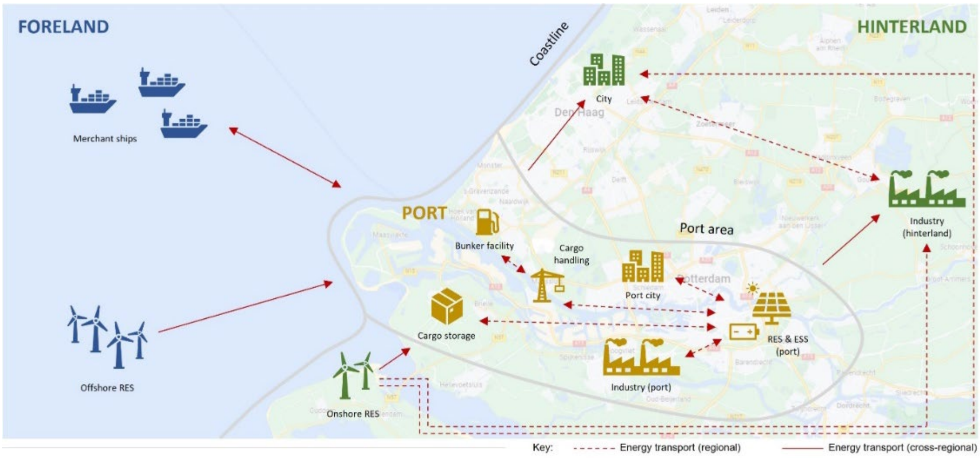


Source: Authors inspired by Rodrigue and Notteboom (2006)

Adding to these demanding technical challenges of the traditional operations, the energy transition inflicts completely new technical aspects on ports, primarily concerning renewable energy systems (RES). While ports have always been entry points for seaborne hydrocarbon energy transport, they will also function as focal points for integrating offshore RES and alternative fuels. The dimension of the integration is twofold: (a) the port must transship the renewable energy to adjacent areas, ships, the port city, and the hinterland, and (b) the port must utilize renewable energy for its operations requiring energy management and energy storage solutions (ESS) due to the renewables' volatility (see Figure 2).

A successful integration demands technical knowledge outside ports' current expertise, for example, concerning smart and micro grids or reusing existing infrastructure for alternative fuels (Quintino et al., 2021; Sadiq et al., 2021). Data and control technologies come to the fore when handling these issues altogether (Sadiq et al., 2021).

Figure 2: Cross-Regional and Regional Energy Transport Connections in the Port Triptych Model



Source: Authors inspired by Rodrigue and Notteboom (2006)

In summary, the complex challenges faced by ports during the upcoming energy transition-dominated generation concern both traditional and new port functions and require extensive automatization and digitalization. Additionally, the wide variety of potential technologies calls for decision support for finding the most appropriate solutions. These aspects are precisely what will be explored in this chapter oriented along the below-listed categories:

1. Decarbonization and energy efficiency of traditional port operations and infra-/superstructure
2. Renewable energy integration and distribution
3. Digitalization and automatization of traditional and new port functions
4. Decision support tool concerning port transition strategies.

A selection of interesting research opportunities in each of these areas is highlighted in a blue box following the main text.

2. METHODOLOGY

Before diving into the above aspects of ports as energy transition hubs, the review methodology applied in this chapter is introduced. The process aligns with reviews using the snowballing approach, explained in, for example, Wohlin (2014). As a foundation, the procedure requires a start set of papers. To account for the broadness of this chapter, the start set includes a diverse group of studies concerning different publication years, authors, journals, and content focuses. Wohlin (2014) underlines the importance of diversity in a start set.

Table 1 depicts the start set used for this chapter. The publication years range between 2019 and 2022, accounting for the fast research development in engineering sciences. All sources are literature reviews providing a broad foundation for the snowballing approach. Seven out of eight papers exhibit FWCIs above

1 (1.59 to 5.9), rendering them highly-cited works. The set of associated universities and journals further justifies the sources' research excellence. Lastly, none of the authors is included twice in the start set, again underlining the set's diversity.

According to Wohlin's (2014) procedure, backward snowballing was applied on the way forward, meaning that the reference lists of the start set were searched for additional sources. Relevant search criteria were title, authors, publication year, and language. A potential set of documents remained after further removing papers already identified in previous reference lists. Then, the group was examined in detail by checking the abstract and potentially the main text until deciding on inclusion or exclusion.

In a final step, the presented chapter underwent a revision process, including leading scholars in the field who were asked to suggest, if any, additional sources worth including.

Table 1: Start Set for the Snowballing Procedure Applied in the Study

Source	Associated universities	Journal	FWCI*	Content focus
Iris and Lam (2019)	Nanyang Technological University	Renewable and Sustainable Energy Reviews	2.1	Energy efficiency
Alamoush et al. (2020)	World Maritime University	Marine Pollution Bulletin	0.87	Energy efficiency; GHG emission reduction
Bjerkan and Seter (2019)	Norwegian University of Science and Technology	Transportation Research Part D	4.39	Sustainability; Decision making
Sadiq et al. (2021)	National Kaohsiung University of Science and Technology Aalborg University National Chiao Tung University Nanyang Technological University	IEEE Access	1.59	Energy efficiency; Infrastructure, and related challenges
D'Amico et al. (2021)	University of Messina University of Szczecin Maritime University of Szczecin	Sustainable Cities and Society	5.9	Sustainability; Port city
Puig et al. (2022)	Universitat Politecnica de Catalunya BarcelonaTech Cardiff University	Science of the Total Environment	2.6	Environmental management
Trivyza et al. (2022)	University of Strathclyde National Technical University of Athens	Energy	-	Decision making; Sustainability
de la Peña Zarzuelo et al. (2020)	University Polytechnical of Madrid University of A Coruna	Journal of Industrial Information Integration	3.31	Digitalization; Automation

*The field-weighted citation impact (FCWI) justifies how well cited a paper is. Values greater than 1 represent an above-average citation count. The FCWI factors were obtained from Scopus.

3. DECARBONIZATION AND ENERGY EFFICIENCY OF TRADITIONAL PORT FUNCTIONS AND INFRA/SUPERSTRUCTURE

The port sector cannot abstain from society's general movement towards decarbonization and energy efficiency improvements. In 2020, the European Sea Port Organization's (ESPO) listing of top 10 environmental priorities placed 'climate change' and 'air quality' in the 2nd and 1st position, respectively. In all annual reports of the period 2013 - 2020, 'energy efficiency' features in the 2nd or 3rd ranking (ESPO, 2020).

Ports can address energy efficiency and decarbonization of their traditional functions through two levels of improvement: (a) port infrastructure and superstructure, and (b) port operations. The former mainly concerns the technical efficiency of equipment and buildings, for example, the hybridization of cargo handling devices (Hangga and Shinoda, 2015). The latter concerns optimizing activities such as berth allocation or equipment handling and scheduling (Chang et al., 2010; Iris et al., 2018, 2015). The following subsections explore both levels of improvement in detail.

3.1 Port infra- and superstructure

A port's traditional cargo handling areas [GP1] can be divided into quayside, yardside, and landside (Iris and Lam, 2019). The required equipment and infrastructure distributed over these functional areas are numerous (refer to Table 2). The loading and unloading of cargo is usually done by ship-to-shore (STS) cranes or quay cranes (QC). On the yardside, the cargo is transported via conveyor belts, YTs, or automated guided vehicles (AGV). Cargo transported in containers is staked by RMGs or rubber-tired (RTG) gantry cranes. Note that the cargo (e.g., bulk or container) and the individual port structure strongly influence the required infrastructure and equipment (Sadiq et al., 2021).

Table 2: Overview of cargo handling and transporting equipment distributed over the functional areas of a port

Quayside	Yardside	Landside
Ship-to-shore cranes	Automated guided vehicles	Rail-mounted gantry cranes
Quay cranes	Stacking crane	Rubber-tired gantry cranes
Quay grabs	Straddle carriers	Reach stackers
Stacker reclaimers	Yard cranes	Inter-terminal transport vehicles
Loading arms and hoses	Conveyor belts	Trucks
Merchant ships	Yard trucks	Trains
	Bobcats	Inland waterway vessels
	Forklifts	Pipelines

The equipment electrification and hybridization are primary and widely recognized objectives for addressing the energy efficiency and decarbonization challenges of ports (Alamoush et al., 2020). It can be distinguished between full electrification of the equipment's energy source or partial (Alamoush et al., 2020). The latter includes, for example, diesel-electric drivetrains. Yang and Chang (2013) showed the advantages of installing diesel-electric hybrid RTGs (E-RTGs) instead of conventional RTGs. The source's case study considers historical data (2008 to 2011) of 61 RTGs in the Port of Kaohsiung (Taiwan). The calculated energy consumption and CO_2 emission reductions of employing E-RTGs are remarkable (86.60% and 67.79%, respectively). Similar energy savings (73.9%) using hybrid RTGs were identified by Wei et al. (2019). The electric power supply of these E-RTGs can either be realized through an overhead conductor system (like electric trains), a cable reel system allowing high flexibility, or a bus bar system using power transmission from slide rails (Yang and Chang, 2013). Fully electric RTGs are also possible and operated in, for example, the Port of Long Beach (POLB) and the Port of Koper (SPBP, 2017; Twrdy and Zanne, 2020). The energy efficiency of E-RTGs can further be improved by the application of active front-ends (AFE) stabilizing the power supply (Pietrosanti et al., 2016). Most importantly, Pietrosanti et al. (2016) show that AFEs allow E-RTGs to recover energy while hoisting down. Similar recuperation has also been reported beneficial for QCs and RMGs (APEC, 2014; Zhao et al., 2014).

In addition to various port cranes, AGVs, YTs, and other smaller equipment, like forklifts, can also be electrified mainly through batteries (SPBP, 2017). Schmidt et al. (2015) found that B-AGV fleets have several advantages over AGV fleets, including reduced energy and maintenance costs. Even more advanced are intelligent autonomous vehicles (IAV), a class that allows vehicle pairing and unpairing for transporting containers of various sizes providing higher operational flexibility (refer to Figure 1 in Gelareh et al. (2013)). Gelareh et al. (2013) used a mixed integer programming (MIP) model and simulated the handling time of an IAV compared to an AGV fleet for 400 containers. The resulting improvement by employing IAVs was 22.26%.

Other major, already electrified energy consumers in ports are refrigerated containers (reefers), accounting for about 40% of a container terminal's energy consumption (Wilmsmeier and Froese, 2014). Generally, the energy demand of reefers in a port reduces with a decreasing dwell time, but in reality the consumption is influenced by environmental effects and as such is volatile. Rijsenbrij and Wieschemann (2011) propose the installation of sun protection roofs to reduce the dynamic negative impact of solar radiation. Filina-Dawidowicz and Filin (2019) study the effect of elastic sealing between stacked reefers. In a small-scale experimental set-up, the suggested solution reduced the model's energy consumption by 7.6%.

Whereas almost all of the above options concern container handling, Alamoush et al. (2020) conclude that electrification of bulk equipment is scarce due to a more challenging electric infrastructure. The source only lists two ports (POLB and POLA) that have already introduced related measures (conveyor belt resistance reduction, electric liquid bulk pumps, tank and pipeline insulation).

While terminal equipment represents the most prominent energy consumer, the port superstructure (buildings, lighting, etc.) makes up 23% of a port's energy consumption (Fahdi et al., 2019). Starting with the building itself, Hippinen and Federley (2014) listed the passive house design used at the Port of Aalborg as a potential energy efficiency measure. The same study further mentions the application of new roofing technologies for warehouses. These reduce the building cooling demand and, correspondingly, the heating, ventilation, and air condition (HVAC) energy consumption. An HVAC temperature control (usually 26°C) can further increase the system's efficiency (Liu and Gong, 2010). Talking about control, motion and twilight sensors can reduce the energy required for lighting and have been installed, for example, in the Finnish ports of HaminaKotka and Pori (Hippinen and Federley, 2014). Finally, changing the light source to LED lamps reduces energy demand while also reducing maintenance costs. In 2014, the Rietlanden Terminals (Port of Amsterdam) achieved a 60% decrease in energy consumption due to entirely substituting existing with LED lamps (Hippinen and Federley, 2014).

Recent regulatory developments, first and foremost the FuelEU Maritime Initiative, require ports to offer onshore power supply (OPS), also called 'cold ironing,' to berthed ships from 2030 onwards (EC, 2021). OPS allows ships to turn off their auxiliary engines in port, thus complimenting ports' energy efficiency and decarbonization efforts (Zis, 2019). OPS implementation imposes challenges especially on port grids (Zis, 2019). For further information, refer to Chris' chapter.

A circular economy (CE) is a broader approach denoting ports' distributor and matchmaker role concerning production, recycling, and waste (de Langen and Sornn-Friese, 2019). It concerns establishing a circular value creation chain while reducing the chain's inputs and outputs and ultimately preventing waste creation (Carpenter et al., 2018). Yuan et al. (2006) refer to three CE levels: micro (individual firm), meso (second), and macro (third) level. The first focuses on the individual firm, especially internal cleaner production. The second points toward forming eco-industrial networks, for example, through sharing of local infrastructure. The third concerns eco-cities, representing not only industrial but also municipality-related aspects.

The unique colocation of several CE stakeholders in a port fosters synergies in the CE approach primarily related to the meso and macro level (Carpenter et al., 2018). A meso-level example is the 'Warm CO_2' partnership in the Zeeland Seaports, enhancing energy and CO_2 exchange between a fertilizer plant and an agricultural greenhouse business (de Langen and Sornn-Friese, 2019). The European Commission (EC) further emphasizes the need for connecting CE with biomasses (EC, 2016). Alamoush et al. (2020) mention the option of either burning biomass for heat or electrical energy or fermenting it for biofuels and biogas. The Waste Management Centre in the Port of Koper secures the conversion of all bio-degradable waste into compost (Twrdy and Zanne, 2020). A port-specific CE issue relates to dredging, the deepening and widening of waterways to allow larger ships to access a port. The dredged sediments are usually contaminated and not directly reusable. Yet, the Port of Gävle has adopted a land creation process that allows reusing dredged material through local decontamination in collaboration with energy producers and steel manufacturers (Carpenter et al., 2018). Although CE fits nicely into ports' energy efficiency and decarbonization agendas and compliments their distributor and matchmaker role, de Langen and Sornn-Friese (2019) conclude that literature on CE in ports is scarce.

From an overall perspective, energy and environmental management and related software and systems help reduce emissions and increase energy efficiency (Sadiq et al., 2021). International certifications like ISO 50001 and 14001 allow approval of a successful management system and require constant improvements assessed by corresponding audits (Roy et al., 2020; Sadiq et al., 2021). A detailed description of energy management systems in the context of smart and microgrids is provided in Section 4. A comprehensive exploration of digital decarbonization and energy-related management system solutions is performed in Section 5.

3.2 Port operations

The distinction between quayside, yardside, and landside infrastructure applies also to port operations. Quayside operations mainly include loading/unloading cargo linked to the foreland. These operations can be influenced directly (e.g., improved berth allocation) and indirectly (e.g., port dues) (Alamoush et al., 2020). Yardside focuses on efficiently storing and transporting cargo concerning, for example, warehouse and storage management or yard crane (YC) scheduling (He et al., 2015a; Mao and Zhang, 2019). Landside operations are characterized by inter-terminal and intermodal cargo transport to the hinterland.

3.2.1 Quayside operations

The primary operation at the quay is the loading/unloading of ships. QCs carry transported cargo from vessels to distribution vehicles, like AGVs. Optimized scheduling of this operation is recognized as an option for increasing energy efficiency and reducing emissions at the quayside (Liu and Ge, 2018). The latter is an essential target for ports considering that 27% of all 2010 port emissions originated from vessels (Hu et al., 2014). This challenge is mirrored in the literature. Liu and Ge (2018) researched optimizing the number of QCs to minimize CO_2 emissions during unloading containers to AGVs. For this, they developed a convex mathematical programming model. They found that the optimal number of QCs for reducing CO_2 emissions grows with the expected arrival rate and the mean hourly fuel consumption of AGVs. In contrast, it falls with the mean queue service rate and hourly electricity consumption of QCs.

Berth assignment is another improvement challenge faced by ports at the quayside. It primarily influences the seaside emissions of ships in port proximity (Venturini et al., 2017). Normally, ships arriving at a port wait at anchor before their cargo is handled at berth (Poulsen and Sampson, 2019). The berth assignment problem (BAP) represents an attempt to improve this operational inefficiency. Various formulations of the BAP with spatial and temporal differences exist (see, for example, Imai et al. (2005) and Imai et al. (2001)). Only a few sources research the effect of the BAP on ships' GHG emissions. An early attempt to integrate fuel consumption in the BAP was made by Du et al. (2011). The source further applied emission factors to measure achieved emission reductions.

The conducted numerical experiments considered 10 test problems with randomly or equation-based generated parameters using three different departure delay limits (0, 1, and 2 hours) and 10 to 28 containerships of three size classes (feeder, medium, and jumbo) assigned along a 1200m long wharf over a week time. Using the suggested variable arrival time strategy and the ship arrival time as a decision variable, the calculated average CO_2 reduction for a single ship arrival ranged between 49.58 to 143.22 tons. Venturini et al. (2017) combine a multi-port berth allocation with a speed optimization problem and calculate the resulting fuel and emission savings to be around 40%. Their model considers 3 to 4 ports and 4 to 20 vessels (1,700 TEU feeders).

Given the relation between berth and QC assignment, combining both problems for comprehensively improving quayside operations represents a widely adopted approach. Hu et al. (2014) developed a new berth and quay-crane allocation strategy applying MIP and introducing the vessels' arrival time as a decision variable. The source claims that the average emission reduction using this optimization approach is 21.21 tons of CO_2. The value originates from numerical experiments considering a 72-hours' time window, a 1200m long wharf, and 10 test problems with 6 to 40 containerships in three size classes (feeder, medium, and jumbo). Besides Hu et al. (2014), Chang et al. (2010) and He (2016) made a comparable attempt.

Virtual arrival aspires to improve seaside emissions through enhancing the port-ship communication by informing the ship about its berth assignment before reaching the port. This allows the vessel to reduce its speed to arrive just in time (Poulsen and Sampson, 2019). Jia et al. (2017) state that fuel savings resulting from a VA application can range between 7.26 and 19%. The values originate from an AIS-based bottom-up approach considering 483 Very Large Crude Carriers (VLCC). Johnson and Styhre (2015) followed a voyage report-based method for two 5,000 GT dry bulk vessels. They constituted a potential energy efficiency increase of 2 to 8% if each port call was reduced by 1, 2, or 4 hours respectively.

On top of these two main port options for reducing seaside emissions, diverse less widespread options exist. Ports can introduce incentive programs of various dimensions to foster environmental ship performance. The Port of Los Angeles (POLA) offers a vessel speed reduction program providing incentives like reduced port fees or pre-assigned berths for ships reducing their speed at a specific distance to the port (Gibbs et al., 2014). The Port of Vancouver incentivizes timely arrivals of ships (Poulsen et al., 2018). Besides such programs, Lalla-Ruiz et al. (2018) underline the importance of waterborne traffic management approached with the waterway ship scheduling problem.

3.2.2 Yardside operations

Scheduling is also a significant energy efficiency challenge for yardside operations. For example, YC scheduling directly influences the energy consumption of YCs, which are solely responsible for about 25 to 35% of the total energy costs in a container yard (He et al., 2015a). Similar optimization problems to the above are objected to research concerning yard allocation, yard equipment handling, and yard scheduling. An early attempt to optimize loading time considering a yardside system of two transtainers and a quay crane was made by Lee et al. (2007). Later studies explicitly focused on reducing the associated energy consumption. He et al. (2015a) introduced a MIP model optimizing the YCs' operational efficiency and energy consumption. When tested with actual data from the Tianjin Port, the model reduced the energy costs by 25.53%.

Considering the interdependencies of yard and quayside operations, a combined scheduling problem is also researched (He et al., 2015b; Iris et al., 2018). He et al. (2015b) proposed a MIP model for the integrated approach of combining QC, YC, and internal truck (IT) scheduling. Similar to the previously cited work, the model's objective was to decrease energy consumption combined with the vessel departure delay.

In addition to operations optimization, eco-driving techniques or double loading cycles of QCs, YCs, and vehicles can also improve energy efficiency and emission reduction of quay and yardside functions. Double loading or dual cycles refer to handling activities without empty movement, e.g., loading one vehicle and unloading another back and forth (Lee et al., 2015). Using a dual-cycle instead of a single-cycle strategy resulted in 42.2% fewer cycles for QCs, 0.42% for YCs, and 37.9% for vehicles. (Hippinen and Federley, 2014; Lee et al., 2015).

3.2.3 Landside operations

As for quay and yardside operations, scheduling and equipment allocation constitute key challenges when it comes to ports' landside energy efficiency and emissions. On a regional scale, inter-terminal transport scheduling is researched in the literature. He et al. (2013) focus on internal truck sharing. Zheng et al. (2017) study the energy-efficient employment of waterborne AGVs for inter-terminal transport. Zooming out, terminal and hinterland transport coordination represents another option for addressing the port challenges. A good example is a toll pricing program charging higher toll fees at peak times, e.g., implemented at the POLA (PIERPASS) and the Port of New York and New Jersey (NY/NJ) (Chen et al., 2013; Ozbay et al., 2006). Another coordination possibility is represented by time windows grouping trucks for a specific vessel (Chen et al., 2013).

Similar to the enhanced port-ship communication of virtual arrival, truck appointment systems (TAS) can improve coordination by fostering communication between trucks and ports (Caballini et al., 2018). More ambitious approaches like Zehendner et al. (2011) even attempt to include all three actors (ships, ports, and trucks). Controlling the truck arrival times in ports enables scheduling required cargo handling and reduces truck congestion (Li et al., 2018). The TAS allows truckers to choose a preferred entry window out of available ones specified by the port (Li et al., 2018). The Port of Vancouver, POLA, and the POLB apply a TAS scheme (Giuliano and O'Brien, 2007; Morais and Lord, 2006).

Schemes such as these are also studied by scientific literature. Phan and Kim (2015) developed a centralized and decentralized decision model to minimize trucks' inconvenience and waiting costs associated with their arrival in port. Zehendner and Feillet (2014) combined various transport modes in a MIP model. They tested it for scenarios with different straddle carrier handling and traveling times and stated that the average truck service time could be decreased by around 14% realistically.

Lastly, hinterland operations include diverse modes of transport, trucks, rail, and inland waterway. Utilizing this diversity is another improvement option. A modal split of cargo volumes distributed over all three transport modes enables increased efficiency in port infrastructure usage (Bergqvist and Egels-Zandén, 2012). A measure for enhancing the modal shift is the green corridor concept aiming at improving the attractiveness of the less emission intense rail and waterborne transport modes (Panagakos and Psaraftis, 2017).

Although the emissions of landside and hinterland operations are higher than those of port operations (landside: 138 kt CO_2 / port: 71.5 kt CO_2 - Port of Felixstowe), only a limited number of ports apply measures for energy efficiency and emission reduction of landside operations (Gibbs et al., 2014; Gonzalez Aregall et al., 2018). As shown above, the main actions concern truck congestion and equipment scheduling. Only a few focus on modal shifts (e.g., Panagakos and Psaraftis (2017)), and very few solely involve rail and inland waterway transport efficiency.

Box 1. Research opportunities in the area of decarbonizing traditional port functions

- Derived demand for alternative fuels for all transport modes using the port resulting from developments outside the port area
- Constraints due to the capacity of local/regional electricity grids
- The use of fuel cells for the provision of onshore and floating power supply to ships

4. TECHNICAL REQUIREMENTS IMPOSED BY THE ROLE OF PORTS AS ENERGY TRANSITION HUBS

While ports are already key players in national and international energy trade, introducing RES and alternative fuels can only elevate their prominence. Offshore wind parks or the more advanced Danish energy islands require distributing the offshore-generated energy to the landside. Countries like Germany even aim to change their entire energy infrastructure from natural gas (NG) to hydrogen (BMWi, 2020). Developments such as this impose technical requirements, often beyond traditional port expertise, in five key areas separately explored below:

1. Energy management
2. Power-to-gas transition and distribution
3. Multi-fuel supply to sea- and landside transport
4. Renewable energy and energy storage systems
5. Carbon capture, utilization, and storage

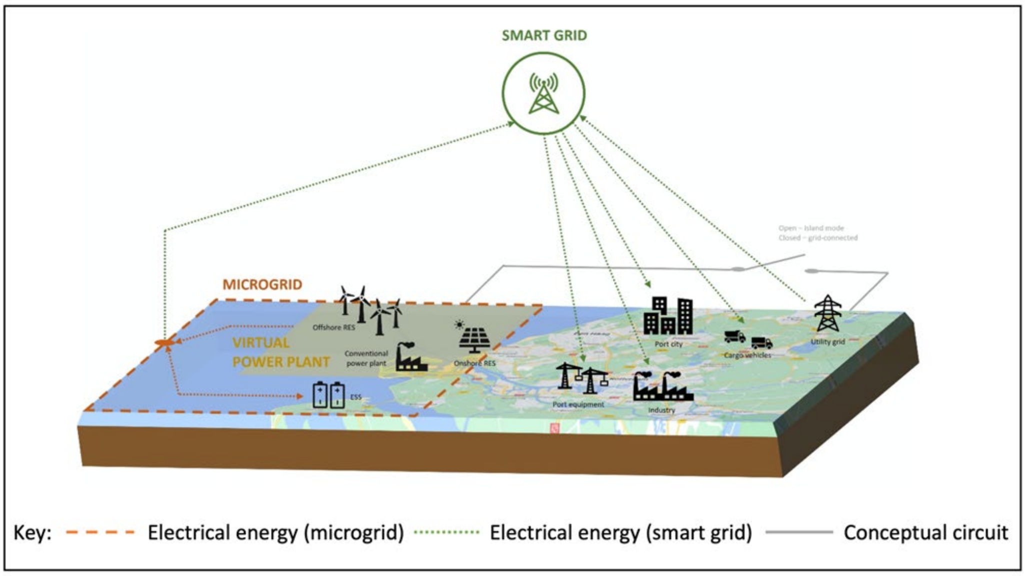
Note that this chapter splits the energy distribution role of ports into two parts: power-to-gas transition and multi-fuel supply. This allows a distinction between national and international energy distribution tasks for various non-port-related consumers, including cities and industries that will likely rely on power-to-gas systems (Song et al., 2022), and the distribution of transport energy carriers, namely fuels, to all modes of transport to, out of, and within the port.

4.1 Energy management

Li et al. (2019) and Sadiq et al. (2021) identify a highly dynamic energy supply and demand as a significant challenge when integrating RESs. Li et al. (2019) further point toward identifying appropriate optimization strategies for the comprehensive integration of RESs, for example, through energy management systems. These systems help reduce energy consumption and emissions and improve load distribution (Parise et al., 2016). A controlled grid represents a suitable solution for smart energy management in ports. Such grids, commonly known as smart grids, actively coordinate energy storage systems (ESS) and generators (Parise et al., 2016). On top, integrated data collection systems enable predictions for efficiently balancing energy supply and demand (Bayindir et al., 2016). Smart grids, usually applied for high and mid-voltage networks, further subdivide into microgrids and virtual power plants (VPP). The former represent networks that can operate independently ('island mode') or grid-connected (Singh and Surjan, 2014). They manage the energy supply to local consumers like port industries and cities (Ahamad et al., 2018a).

Ahamad et al. (2018b) found that a microgrid integrating RES and ESS can effectively manage energy provision in the Copenhagen Malmo Port (CMP), providing 75% of the required energy through RES and 25% through the grid. The latter (VPP) integrate various energy generators and actively control their activation and deactivation depending on availability (Alamoush et al., 2020). They represent a suitable solution for combining conventional power sources with renewables. Underlying control strategies of these smart energy management systems can, for example, follow a multi-agent approach (Sadiq et al., 2021). Figure 3 depicts a comprehensive smart energy management solution for future ports combining the above approaches to control conventional and renewable energy sources.

Figure 3. Exemplary Combination of Smart Energy Management Systems in a Port



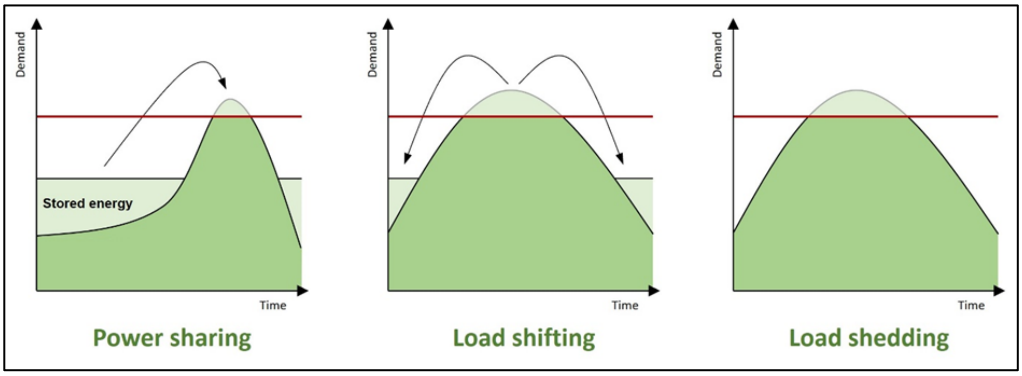
Source: Based on Alamoush et al. (2020) and Li et al. (2019)

Roy et al. (2020) provide an overview of planned and executed microgrid projects in ports. The elements covered by each project differ. The Port of Rotterdam and the Port of Antwerp focus on including a variety of RES and ESS, including lithium-ion batteries, biomass, and solar-thermal energy. The POLA and the Port of San Diego projects additionally consider electric-vehicle charging. Interestingly, only the POLB pairs renewable with traditional energy sources (diesel generators).

Peak shaving

One remaining aspect with regard to energy management concerns peak energy reduction. This is particularly true considering ports' highly dynamic consumption and production profiles (Li et al., 2019). The operational method of peak shaving represents a solution that can be applied within the smart energy management system introduced above. Generally, peak shaving concerns reducing peak energy consumption and can appear in three forms (refer to Figure 4): power sharing, load shifting, and load shedding (Iris and Lam, 2019). The first feeds previously stored energy to the consumers whenever the energy demand passes a certain threshold. The second uses, for example, planning and scheduling, to distribute energy demand over a specific period preventing peaks. The third distinguishes between critical and non-critical energy consumers and turns off the latter if required.

Figure 4. Peak Shaving Methods



Source: Iris and Lam (2019)

Cost reduction is the leading driver for peak shaving, allowing higher energy demands during periods (e.g., nights) when energy costs are lower. Geerlings et al. (2018) researched the effect of peak shaving strategies on the energy consumption and handling time of eight STS cranes based on a discrete event simulation model. The authors found that the maximum allowable energy demand for the set-up can be reduced by about 47% (equal to 10,000 kW) without experiencing considerable handling time increases (up to 0.1%). This is remarkable, especially considering that STS cranes are one of the primary energy consumers in ports (Sadiq et al., 2021).

4.2 Power-to-gas transition and distribution

Moving away from the overall approach of smart energy management systems, the energy distribution role and infrastructure is likely to change, adapting to new energy carriers (Preuster et al., 2017). Currently, ports, pipelines, railways, grids, and road transport of energy products mirror the coal, gas, and oil distribution requirements. While in 2020, 64% and 40% of the global coal and gas demand respectively was used for power generation, an uptake of RES will decrease dependability on coal and gas and impact the existing distribution infrastructure (Song et al., 2022). In a case study concerning China, Song et al. (2022) emphasize this future change prospect by comparing a business-as-usual with a carbon-neutral energy system scenario. The study finds that by 2060, power and hydrogen systems will strongly dominate China’s energy system, also changing the spatial dimension of the country’s energy infrastructure. Power generation from RES and hydrogen production will locate in environmentally beneficial areas for renewable energies. The generated energy will then be distributed to areas with less renewable resources. In this respect, the proximity of ports to offshore RES constitutes a significant advantage. As an entry point for offshore renewable energy, ports can provide the required hydrogen production facilities and, if applicable, methanation technology to enable distribution pathways consisting of centrally and renewably electrolyzed hydrogen or methane transported via pipelines (refer to Figure 5). According to Kurtz et al. (2019), such a hydrogen pathway has the lowest GHG emissions out of all possible ones. Still, if ports are to play their new advanced role, they must deploy technology mostly alien to their managers. This new technology can be broken down into:

- Electrolyzer and fuel cell technology
- Storage technology
- Grid integration technology
- Pipeline and distribution technology
- Methanation technology.

4.2.1 Electrolyzer and fuel cell technology

In an energy system that combines power and hydrogen production, often called ‘power-to-gas,’ the energy carrier gas is produced by electricity and stored or distributed afterward (Stančin et al., 2020). The electricity will be generated by RES and used to either feed the utility grid or produce hydrogen. Nowadays, hydrogen is mainly produced by steam reforming or coal gasification processes which are not emission-free (Messaoudani et al., 2016). On the contrary, the water electrolysis principle allows zero-emission hydrogen production (Alshehri et al., 2019). Such electrolyzers utilize electrical energy to split water (H_2O) into oxygen (O_2) and hydrogen (H_2) (Gondal, 2019). Currently available types are, among others, alkaline electrolyzers (AEL), proton exchange membrane electrolyzers (PEMEL), and solid oxide electrolyzers (SOEL). The types differ in technology maturity level, operating temperature, and stack voltage efficiency (Yue et al., 2021). Beyond these options, technologies like water biophotolysis or photochemical water splitting are still in research and development stages (Yue et al., 2021). Future ports storing energy in the form of hydrogen require the opposite of an electrolyzer, a fuel cell, to produce electricity. Current fuel cell types include solid oxide fuel cells (SOFC) and polymer electrolyte membrane fuel cells (PEMFC) and provide efficiencies of 60 to 80%, outperforming usual small-scale energy generators in ports, like internal combustion engines (ICE) (Mekhilef et al., 2012). Additionally, the high operating temperatures of some fuel cells (e.g., SOFC around 800 °C) allow combined heat and power generation (CHP) (Yue et al., 2021).

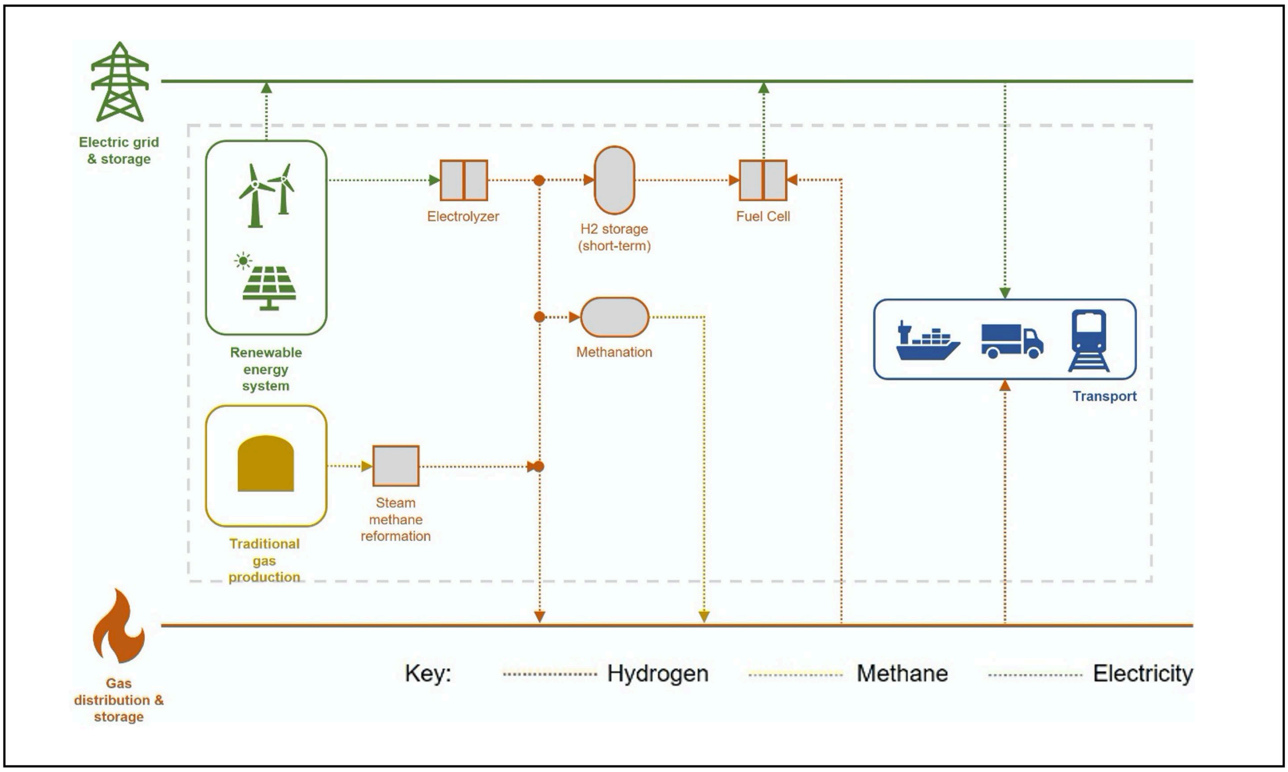
4.2.2 Storage technology

Hydrogen storage solutions are essential for large-scale centralized and small-scale decentralized energy distribution to balance energy supply and demand while accounting for RES volatility. However, hydrogen requires storage facilities different from those of fossil fuels mainly due to its lower volumetric energy density and important safety issues. These facilities can be categorized based on hydrogen’s aggregation state, liquid, solid, or gaseous. Steel gas cylinders can store compressed gaseous hydrogen (Preuster et al., 2017). Typical pressure levels can reach up to 700 bar (Stančin et al., 2020). At ambient pressure, hydrogen liquefies at the temperature of -253.15 °C (Mallouppas and Yfantis, 2021). Storing liquid hydrogen, thus, comes with a high energy consumption (Stančin et al., 2020). An option that provides a sizeable volumetric density is solid hydrogen storage. This technology allows the absorption and adsorption of hydrogen in solid materials, e.g., metal hydrides (Durbin and Malardier-Jugroot, 2013). Lastly, as Song et al. (2022) pointed out, a functioning energy system additionally requires large-scale medium and long-term hydrogen storage options. Current research focuses on using salt caverns, aquifers, or previous oil and gas deposits (Quintino et al., 2021).

4.2.3 Grid integration technology

Grid challenges associated with including RES relate to grid frequency, voltage, and energy security (blackout) (Yue et al., 2021). Grid frequency (typically 50 or 60 Hz) depends on the current demand and supply. It is usually maintained through continuous and adaptable energy supply via conventional producers (e.g., gas power plants) (Yue et al., 2021). Flexible hydrogen technology like fuel cells can overtake this task in a future energy system. The same applies to voltage control (Alshehri et al., 2019). Shehzad et al. (2019) introduce an example of the beneficial integration of an electrolyzer, storage, and fuel cell system in a wind energy-based microgrid for maintaining a constant power supply and demand balance. In the case of local electricity blackouts, a completely new power-up of the systems, the so-called black start, is required (Yue et al., 2021). Again, conventional and flexible energy producers are traditionally used for powering up. Similarly, the task cannot be solved by volatile RES but by hydrogen equipment. Other options for flexible renewable energy supply are hydropower and biomass solutions (Stančin et al., 2020). Stančin et al. (2020) state that a 30% integration of volatile RES is possible in current grids. 80% can only be achieved through short-term storage solutions, and a 100% integration requires long-term storage solutions like the previously mentioned aquifer storage.

Figure 5. Exemplary Power-to-Gas System



Source: Based on Gondal (2019) and Quarton and Samsatli (2018)

4.2.4 Pipeline and distribution technology

While local hydrogen equipment can support the integration of RES in specific areas, a comprehensive power-to-gas energy system requires gas distribution technology like piping and stations (Gondal, 2019). Current research focuses on reusing the already available natural gas infrastructure for hydrogen distribution (e.g., Gondal, 2019; Quarton and Samsatli, 2018; Quintino et al., 2021). If transporting pure hydrogen, several issues occur mainly related to hydrogen embrittlement, a long-term phenomenon that degrades the mechanical properties of, for example, hydrogen-containing pipelines (Messaoudani et al., 2016). A high-pressure gas transmission further increases related effects (Quarton and Samsatli, 2018). To resolve these issues, numerous studies researched the distribution of hydrogen mixtures. Gondal (2019) elevates the benefits of converting hydrogen into methane or synthetic natural gas. Based on Preuster et al. (2017), hydrogen blends with up to 50% hydrogen content do not harm existing pipelines. Quarton and Samsatli (2018) name a 15 to 20% volumetric hydrogen content uncritical for existing infrastructure. Distinguishing the different elements of a gas grid is essential in this regard. Pipelines can withstand H2-NG blends of up to 30% without adjustments and up to 50% with technical adjustments (Gondal, 2019). Gas compression stations can handle a

20% hydrogen content with additional adjustments, and gas turbines 10% (Gondal, 2019).

Methanation technology

As mentioned above, hydrogen conversion into methane provides benefits regarding compatibility with existing infrastructure, safety, and volumetric energy density (Lewandowska-Bernat and Desideri, 2018; Quarton and Samsatli, 2018). The respective conversion is usually performed with a fixed bed methanation reactor. The inputs, carbon dioxide (CO_2) and hydrogen (H_2), react to methane (CH_4) and water (H_2O) (Lewandowska-Bernat and Desideri, 2018). Another option with the same in- and outputs is the Sabatier reaction resulting in substitute natural gas (SNG), a composition mainly based on methane (Lewandowska-Bernat and Desideri, 2018). A disadvantage of methane is its CO_2 emission in usage, which elevates the importance of carbon capture and storage (CCS), described in a later section (Quarton and Samsatli, 2018). Despite this, the power-to-gas project database introduced by Thema et al. (2019) reports that only 35% of the projects feeding gas into the gas grid use hydrogen, while 65% feed in methane underlining the importance of methanation.

4.3 Multi-Fuel Supply to Sea- and Landside Transport and Equipment

Regardless of the energy carrier used in the future energy systems, fossil fuels will be substituted with alternative ones (Mallouppas and Yfantis, 2021). The decarbonization of port equipment has been addressed in Section 3. Focus here is shifted to other cargo vessels/vehicles using the port, mainly ships, trucks, and trains (Iris and Lam, 2019). Their decarbonization will require replacing current bunkering and station facilities. In view of the uncertainties concerning energy transition, this effort will likely lead to a multi-fuel reality. Alternative fuels include, among others, biofuels, hydrogen, and ammonia (Lamb and Austbø, 2020). These and corresponding changes are explored below:

4.3.1 Shipping

Decarbonization is a crucial task for international shipping, accounting for 2.89% of the global anthropogenic CO_2 emissions in 2018 (Faber et al., 2020). The IMO introduced significant emission reduction goals, including a 50% GHG emission reduction until 2050, and developed a three-step approach to fulfill the goals successfully (MEPC, 2018). Alternative fuels are vital enablers for IMO's strategy (MEPC, 2018). Active port participation is mandatory for achieving this target as ships need access to bunker facilities, either stationary or mobile (Styhre et al., 2017).

When it comes to alternative fuels, liquefied natural gas (LNG) emerged first from the set of possible ones, although not being carbon-free. Shipping already has prior experience with LNG-based propulsion through existing LNG tankers, and the fuel can be used in commercially available ICEs. Like shipping, ports too have expertise in LNG handling since they already serve as LNG trade points (Acciaro et al., 2014a). On the negative side, LNG is not GHG emission-free and suffers from methane slips. Balcombe et al. (2019) picture LNG's emission diversity by stating that CO_2 emissions can be reduced by 20 to 30%, but if the methane slip is just 5.5% over the fuel's entire life cycle, its global warming potential (GWP) would equal that of fossil fuels like HFO.

This is because the GWP of methane is 25 times higher than CO_2 (Forster et al., 2007). Although LNG is presumably more straightforward to implement than other alternative fuels, Poulsen et al. (2018) summarize that LNG adoption in ports is limited. This contradicts Article 6 in EC's Alternative Fuels Infrastructure Directive demanding that all member states shall ensure appropriate LNG bunkering for waterborne transport between the TEN-T network ports by the end of 2025 (maritime ports) and 2030 (inland ports) (EC, 2014). Recently, the importance of LNG for states' energy sovereignty has been elevated by Russia's war against Ukraine. The German government announced the construction of two LNG import terminals to reduce the country's reliance on Russian energy (Wettengel, 2022). Yet, Alamoush et al. (2020) and Acciaro et al. (2014a) argue that ports still face safety, market, and distribution challenges related to LNG bunkering and infrastructure.

Blending fossil fuels with biofuels is another short-term option. Geerlings and Van Duin (2011) report that the Port of Rotterdam blends diesel fuel with 30% biofuel. Most ICEs allow blending with biofuels to a certain degree. Acciaro et al. (2014a) name several interesting port roles within the biofuel supply chain ranging from biofuel raw material handling to biofuel production and storage. In fact, the Port of Rotterdam is already a leading biofuel hub, having handled 4.8 million tons in 2016 (Iris and Lam, 2019). The port also utilizes harbor waste for biofuel production, elevating biofuel benefits for a circular economy (Roy et al., 2020).

More advanced options pointing towards a zero-emission future are e-fuels, first and foremost e-methanol, ammonia, and hydrogen (Bicer and Dincer, 2018). The Danish ship owner, A.P. Moller-Maersk, recently (2021) announced an order of eight 16,000 TEU dual-fuel containerships, of which the first is expected to be operating in 2024, and the entry into operation of a 2,000 TEU dual-fuel containership in 2023 (A.P. Moller-Maersk, 2021a, 2021b). All vessels are expected to be methanol-fueled with the option of also operating on very low sulphur oil (VLSFO). Similarly, the German engine manufacturer, MAN Energy Solutions, aims to provide a commercially available ammonia-based ICE option for shipping in 2024 (MAN Energy Solutions, n.d.). Both examples underline the uptake of solutions beyond LNG and biofuels. Hydrogen as a third option provides synergies with a future power-to-gas energy system, as introduced in the previous subsection. While hydrogen combustion in ICEs faces difficulties regarding the fuel's minimum ignition and autoignition temperatures and is still under research, fuel cells, primarily PEMFC, are already in operation (Mallouppas and Yfantis, 2021). The replacement of ICEs with fuel cells can also reduce emissions of ammonia drivetrains, especially regarding high NO_x emissions (Mallouppas and Yfantis, 2021). Further advantages of fuel cells are reduced noise and higher efficiencies (Mekhilef et al., 2012). For all three mentioned fuels, the fuel life cycle and, most importantly, their production pathway define them as emission-free or not (refer to the subsection on alternative fuel pathways).

With the variety of potential alternative fuels, ports must adapt current bunker and storage facilities and account for a multi-fuel supply requiring different facilities for different fuels. The previous subsection already drew a diverse storage and bunker landscape (liquid hydrogen storage tanks, solid metal hydride storage, compressed hydrogen storage tanks, etc.) just for hydrogen, which will diversify further if considering additional fuels like ammonia. Table 3 depicts the different handling parameters for methanol, ammonia, and hydrogen, rendering the extra storage and bunker requirements imperative.

Table 3: Alternative fuel handling parameters

Fuel	**Chem. formula**	**Lower heating value [MJ/kg]**	**Vol. energy density [GJ/m³]**	**Storage pressure [bar]**	**Liq. storage temperature [°C]**
Compressed hydrogen	H_2	120	4.7	700	20
Liquid hydrogen	H_2	120	8.5	1	-253
Methanol	CH_3OH	19.9	15.8	1	20
Liquid ammonia	NH_3	18.6	12.7	1 or 10	-34 or 20

Source: Mallouppas and Yfantis (2021)

4.3.2 Landside transport and equipment

In cases where the electrification/hybridization of traditional port equipment (Section 3) is not applicable, equipment can be powered by the various alternative fuels introduced above (Martínez-Moya et al., 2019). Again, LNG represents a natural choice that can even utilize existing LNG infrastructure in ports (e.g., by using LNG vapor from large storage tanks) (Alamoush et al., 2020). Terminal equipment like RTGs and tractors are also objected to change. Martínez-Moya et al. (2019) researched the potential emission reduction from replacing a diesel with an LNG-powered tractor by a prototype study in the Port of Valencia. The study concludes that the CO_2 emission reduction can reach up to 24%. Iris and Lam (2019) state that the use of LNG for fueling terminal tractors can nullify associated NO_x emissions and reduce CO_2 emissions by 16%.

Hydrogen represents another option discussed for landside applications. The Ports of Hamburg, Los Angeles, and Long Beach operate hydrogen-powered fuel cell-based forklifts (Iris and Lam, 2019). The Valencia Port tests fuel cells in reach stackers (Alamoush et al., 2020). A hydrogen provision for landside transport, primarily trucks, can also be predicted for the future. In this respect, Kurtz et al. (2019) note that, depending on the vehicle type, different hydrogen pressure levels (mostly 35 or 70 MPa) are required and add to the diversity of available storage and bunkering options. The provision of electricity to long-distance transport like heavy-duty trucks and trains is also a foreseeable development (Acciaro et al., 2014a).

4.3.3 Alternative fuel pathways

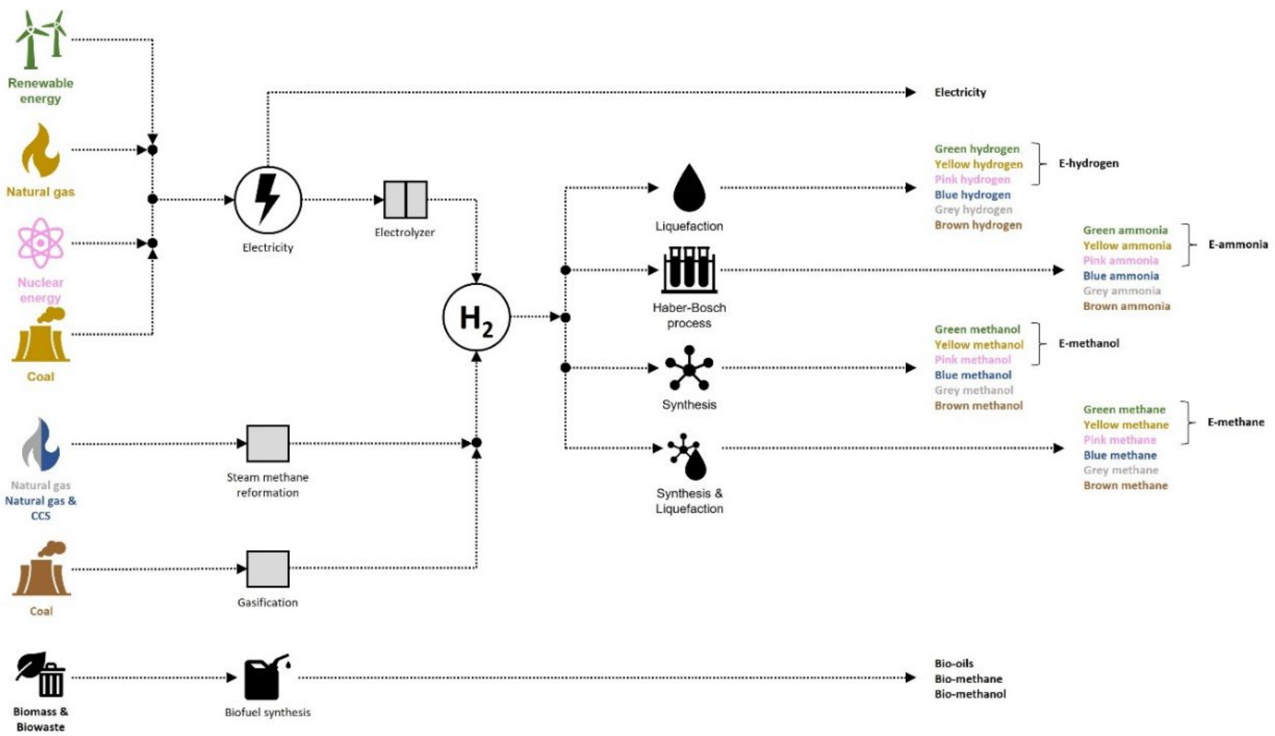
Summarizing the potential future energy carriers a port likely must provide to sea- and landside transport, the list adds up to hydrogen, ammonia, methanol, LNG, biofuels, and electricity. Previous paragraphs described their benefits over fossil fuels like heavy fuel oil (HFO) in a Tank-to-Wake (TtW) application. However, it has been pointed out that production pathways, and thus, a comprehensive life-cycle assessment defines the fuels' actual emission reduction potential and prevents misleading conclusions about a fuel's emission abatement potential (Bilgili, 2021). This includes the TtW and the Well-to-Tank (WtT) emissions (Bilgili, 2021). An assessment that is currently discussed but not adopted on a global (IMO) scale. Only EC's regional FuelEU Maritime Initiative proposal includes emission factors based on a comprehensive Well-to-Wake (WtW) assessment (EC, 2021b). For this study, it is essential to distinguish between the production pathways for each alternative fuel to support ports in choosing the best options for their energy efficiency and decarbonization goals (see also Table 4).

Table 4: Well-to-Tank emissions of conventional and alternative fuels (EC, 2021b)

Fuel	Pathway	Well-to-Tank emissions []
HFO	ISO 8217 RME to RMK	13.5
LNG	-	18.5
H_2	Grey	132.0
H_2	e-H_2*	3.6
NH_3	Grey	121.0
NH_3	e-NH_3*	0.0
CH_3OH	Grey	31.3
Electricity	EU mix 2020	106.3
Electricity	EU mix 2030	72

**To the authors' knowledge, the exact fuel pathway is not specified in EC (2021b)*

Figure 6. ***Production pathways of alternative fuels***



Source: Based on Medlock (2021) and MMMCZCS (2021)

4.4 Renewable energy sources and energy storage systems

The virtual power plant composition depicted in Figure 3 emphasizes the future uptake of renewable energy sources in and outside ports. The microgrid further justifies the enhanced application of energy storage systems within the future port energy system. In this respect, Ramos et al. (2014) underline ports' increased interest in RES, and Iris and Lam (2019) even link the 'percentage of energy from renewable energy sources' as a KPI with the sustainability of ports.

4.4.1 Renewable energy sources in and outside the port

The location of ports provides excellent environmental prerequisites for the application of wind, ocean, and solar energy (Alamoush et al., 2020).

Wind energy systems can either be off- or onshore installations. Their energy supply is weather-dependent and volatile (Vivas et al., 2018). Thus, locations with high wind speeds are preferred (Li et al., 2019). In contrast to other RES, wind energy usually has large space requirements, which might not be available in the port itself (Alamoush et al., 2020). Regions like Bavaria in Germany even prescribe minimum distances (10 times the turbine's tip height) to residential buildings (WindEurope, 2020). Yet, many ports have already installed wind energy generators, among others, the Port of Rotterdam (200 MW) and the Port of Antwerp (45 MW) (Alamoush et al., 2020). Offshore wind energy often represents a considerable solution if, for example, space availability is scarce. Although offshore solutions are more costly, they benefit from higher wind speeds and societal acceptance (Kaldellis and Apostolou, 2017).

Solar energy does not require large spaces. Both photovoltaic (PV) and solar water heating (SWH) can easily be scaled up or down (Alamoush et al., 2020). Their scalability allows small-scale applications like buoys and large-scale installations on rooftops and free land. Covering warehouses with PVs is a practice followed by several ports, including the Jurong Port of Singapore (12,000 MWh per year) and the Port of Hamburg (500 MWh per year) (Iris and Lam, 2019). Synergetic effects can be obtained if, for example, the sun protection roofs for reefer areas suggested by Rijsenbrij and Wieschemann (2011) are combined with PV or SWH installations (Iris and Lam, 2019). Acciaro et al. (2014a) further introduce a port's option of fostering the uptake of solar energy in its area through support schemes.

As a third RES option, ports can apply ocean energy. Two main types can be distinguished, tidal energy and wave energy (Alamoush et al., 2020). The former is more predictable than the latter (Ramos et al., 2014). Although Acciaro et al. (2014a) name three examples of tidal energy (Nova Scotia, Dover, and Digby) and two examples of wave energy (Mutriku and Kembla) production in ports, the solutions generally have low technology maturity (Ramos et al., 2014). However, their application is promising. Through a modeling exercise, Ramos et al. (2014) proved that the installation of 25 tidal energy turbines (400 kW each) could provide sufficient energy for the Port of Ribadeo throughout an entire year.

Finally, geothermal energy is also possible for harnessing renewable energy in ports. A further distinction can be made on the bore depth and corresponding available heat energy (Kanoglu et al., 2007). The applicability of geothermal energy relies on the geological temperature levels in the port area. High-temperature reservoirs (above 150 °C) can be used for power generation, whereas moderate (90 to 150 °C) and low (below 90 °C) reservoirs can only be directly used for heating (Kanoglu et al., 2007). Yet, near-surface geothermal energy is, for example, used in the Port of Hamburg and can provide advantages in base load applications due to its constant availability (Acciaro et al., 2014b; Cetin et al., 2019).

4.4.2 Energy storage systems

While previous subsections have introduced hydrogen storage solutions in large-scale power-to-gas energy systems, short-term energy storage within a port's microgrid is required to stabilize the local grid and balance renewable energy production (Vivas et al., 2018). Batteries, supercapacitors, and flywheels represent the most prominent solutions in this regard (Alamoush et al., 2020). From a system design perspective, the main differences between these three are their power and energy densities per mass unit (Trieste et al., 2015). Batteries generally provide larger energy densities, whereas flywheels and supercapacitors provide larger power densities (Trieste et al., 2015). Also, supercapacitors and flywheels provide larger cycle lifetimes, and batteries have superior response times (refer to Table 5) (Bocklisch, 2016).

Table 5: Characteristics of different energy storage systems

	Supercapacitor	Flywheel	Lead-acid battery	Lithium-ion battery
Energy density [Wh/l]	2 to 20	20 to 200	50 to 100	200 to 350
Power density [W/l]	15,000 to 50,000	5,000 to 15,000	10 to 500	10 to 350
Cycle efficiency [%]	77 to 83	80 to 95	70 to 75	80 to 85
Response time [ms]	< 10	> 10	3 to 5	3 to 5
Lifetime [yrs.]	15	15	5 to 15	5 to 20
Cycle lifetime [no. of full cycles]	< 1 million	> 1 million	500 to 2,000	2,000 to 7,000

Source: Bocklisch (2016)

Batteries are widely used electrochemical energy storage options (Luo et al., 2015). Generally, lead-acid and lithium-ion batteries are the battery types mostly applied. Using lead-based cathodes and anodes in sulfuric acid, lead-acid batteries can have higher power densities than their lithium-ion counterparts but lack their cycle lifetime and efficiency values. Lithium-ion batteries' superior energy density values further qualify them for applications with space or weight limitations, e.g., in vehicles. Yet, this battery type has already been installed for stationary grid frequency regulation purposes, such as a 16 MW solution by AES Energy Storage in New York (Luo et al., 2015). In addition to stationary batteries used in ports, integrating batteries in vehicles like AGVs connected to the grid while not operating represents another solution for short-term energy storage (vehicle-to-grid) (Alamoush et al., 2020).

In contrast to a capacitor's usual set-up (two metallic conductors separated by an insulation layer), supercapacitors further include a separator that, combined with an electrolyte and the typical electrodes, represents an electric double-layer (Díaz-González et al., 2012). This structure allows for having capacitor (power density) and battery characteristics (energy density). Adding to this, supercapacitors provide long lifetimes and reasonable cycle efficiencies. Their major drawbacks are significant self-discharge rates and high capital costs (Luo et al., 2015).

Lastly, flywheels are mechanical energy storage solutions storing kinetic energy by combining a composite flywheel with a motor/generator unit. Besides their large power density and cycle efficiency, their advantages include less maintenance and long lifetimes compared to the other options. Further, they are not temperature sensitive and can be quickly recharged. However, their efficiency decreases with storage time, making them inefficient for long-term storage, and, finally, their low maturity and high costs make them currently uncompetitive (Al Shaqsi et al., 2020).

4.4.3 Other power production opportunities in port

Besides the introduced RES options, wind, solar, ocean, and geothermal energy, ports can further utilize waste energy from their entities and adjacent industries. In this case, waste energy can take the form of either energy that would be lost in processes if not harnessed, e.g., waste heat, or energy generated from waste. The former is, for example, addressed by cogeneration through waste heat recovery solutions (Iris and Lam, 2019). The latter, energy from wastes, relates to the previously discussed circular economy approach and biofuel production.

4.5 Carbon capture, utilization, and storage in ports

The paragraph on methanation technology already pointed toward the importance of carbon capture and storage solutions in future energy systems. Acciaro et al. (2014a) underline the future key role of ports in CCS. Alamoush et al. (2020) further mention the ports' potential for carbon capture and utilization (CCU), including carbon dioxide utilization in the methanation process. Available technologies for carbon capture include chemical absorption, physical separation, membrane separation, calcium looping, chemical looping, direct separation, and oxy-fuel separation (Al Baroudi et al., 2021). Besides local capture options in ports, waterborne transport and pipelines arise as a cost-efficient solution for transporting CO_2, a likely scenario considering that emitters and geological storage solutions are usually not nearby (Al Baroudi et al., 2021). It even allows access to geological storage for countries emitting CO_2 but not having the required preconditions for storing. Currently, the shipping of CO_2 is only performed on a small scale for the food and beverage industry (Al Baroudi et al., 2021). Although promising, example projects and literature on CCS and

CCU in ports are scarce. The Port of Antwerp conducts engineering studies for such an installation (Port Technology, 2022). The Port of Rotterdam envisions deciding on a CCS project storing 2.5 million tons of CO_2 by spring 2022 (Pekic, 2021). Lastly, the Swedish Energy Agency founded a project looking into developing a CCS facility in the Port of Gothenburg capable of storing 2 million tons of CO_2 (Prevljak, 2021).

Box 2. Research opportunities in the area of power-to-gas technologies

- Scaling and costing of infrastructure requirements in relation to power-to-gas technologies
- Green shipping corridor design on the basis of alternative fuel availability considering local renewable energy resources and potential synergies with other sectors
- Zero carbon certification of alternative fuels

5. DIGITALIZATION AND AUTOMATION IN PORTS

The reference of Section 4 on smart energy management systems has already introduced the relevance of digital solutions in relation to the energy and decarbonization challenges of ports. In fact, de la Peña Zarzuelo et al. (2020) name digitalization as a prerequisite for logistics and underline that ports are obliged to upgrade some of the inefficient procedures. A comprehensive concept for a digitalized port is the so-called ‘smart port’ or ‘Port 4.0’, in which an exhaustive collection of sensors, actuators, communication technology, and data handling and storage units allows more efficient operations (de la Peña Zarzuelo et al., 2020; Yang et al., 2018). The efficiency benefits result from three primary smart port functions: identifying, monitoring, and aggregating data for efficiency improvement (Sadiq et al., 2021). How these functions can be addressed through technology is explored below.

5.1 Automatization and autonomous systems

As of 2021, 53 container terminals around the globe are automated to a certain extent which equals 4% of the world’s container terminal capacity. None of these is fully automated, and none operates fully automated quay cranes. The terminals mostly employ automated yard equipment and merely yard-quay transport (ITF, 2021). Yet, de la Peña Zarzuelo et al. (2020) name the benefits of automated port functions to be 24/7 operations, reduced workforce, and fewer human errors.

Some port automatization options have already been mentioned in Section 1, including AGVs, operating between quay and yard, and IAVs, the more flexible and connected successor of AGVs. Another option mostly applicable on ships calling frequently at specific ports is automated mooring (AMS), which operates with remotely-controlled vacuum pads and hydraulic arms (Alamoush et al., 2020). Its employment reduces the number of maneuvers required by ships and allows turning off the main engines about 30 minutes earlier (Gibbs et al., 2014; Iris and Lam, 2019). Díaz-Ruiz-Navamuel et al. (2018) applied two different bottom-up emission calculation methods (EPA and ENTEC) to compare mooring emissions of 18 Ro-Ro/Pax vessels undertaking traditional and AMS maneuvers. Both calculation methods conclude an emission reduction of 96.67% for mooring. Further, the maneuver time is significantly shorter, 15 minutes for traditional mooring and 20 seconds for AMS. The system is installed in several Finnish, Dutch, and Danish ports (Díaz-Ruiz-Navamuel et al., 2018).

5.2 Big data and data analytics

A reduced turnaround time (TAT), as obtained by AMS, can further be improved by data sharing through information and communication technology and port community systems (Alamoush et al., 2020). D’Amico et al. (2021) elevate the importance of data for shippers and logistics carriers while at the same time pointing towards ports’ lack of equipment for real-time data collection, monitoring, and analysis. Applications of data tools in ports are numerous, including weather, tidal, and current data for ensuring safe and efficient operations (Solari et al., 2012), health monitoring of cranes for reducing maintenance costs (de la Peña Zarzuelo et al., 2020), vacant berth identification (Kamolov and Park, 2019), and container location for automated processes (de la Peña Zarzuelo et al., 2020). Current examples of data technologies in ports are sensor-equipped buoys and docks in the Port of Rotterdam and air and weather monitoring stations in the POLA and POLB (D’Amico et al., 2021; Gonzalez Aregall et al., 2018).

5.3 Drones

Sensor and data technology also plays a vital role in remotely operating systems, like drones. The application cases of such systems are numerous in ports. Bexiga (2019) lists inspection for maintenance of port equipment, security patrols in port areas, detection of abnormalities, mapping of construction sites, measurements for bulk inventory, and delivery to non-docked ships. The same author also provides examples of drone use in ports. In the Port of Singapore, drones are tested for spare part delivery to vessels. The Port of Haifa employs drones for mapping and inspecting a construction site. The terminal operator, APM Terminal, performs supervision tasks with drones on their Chile sites. D'Amico et al. (2021) further mention the Port of Hamburg's drone application for speed and location identification within their road management system. On the downside, however, drones can be misused (e.g., fly-hacking), requiring airspace control and cybersecurity precautions (Bexiga, 2019).

5.4 Blockchain

Another digitalization option for ports that rely on data is blockchain technology, which utilizes a shared real-time data infrastructure for applications like intelligent assets or digital contracts (Wang et al., 2019). Its disruptiveness primarily evolves from making mediators or third-party verifications obsolete (Wang et al., 2019). Beyond this benefit, de la Peña Zarzuelo et al. (2020) mention increased security based on encryption mechanisms, real-time transaction visibility, network extension regarding ports' multistakeholder environment, and enhanced integration of supply flows. Difficulties of the technology include governance and legal uncertainty, trust, and adaptation issues. Still, companies such as T-Mining, Circle, or Blockfreight already test port-specific blockchain prototype solutions, given their promising applicability for supply chains (de la Peña Zarzuelo et al., 2020). The Danish shipping company, A.P. Moller-Maersk, and the Port of Valencia already operate the TradeLens Blockchain platform to improve port multistakeholder communication (D'Amico et al., 2021).

5.5 Simulation and forecasting

In terms of simulation and forecasting, Section 2 already introduced the TAS, a system for truck queue management. The terminal operation system (TOS) represents another simulation and management option that includes the analysis of several of the problems mentioned in Section 2, for example, berth and yard allocation (Alamoush et al., 2020). Machine learning techniques can further improve these systems (de la Peña Zarzuelo et al., 2020). While TOS applications are standard in large container terminals, de la Peña Zarzuelo et al. (2020) refer to a less established market for bulk terminals. Lastly, ports can employ a so-called Digital Twin model, which mirrors the real port environment through real-time data connections with sensors all over the port. Its benefit lies within its virtuality that allows constant prediction and scenario analysis (Wang et al., 2021). Eight digital twin port projects of various characteristics are mentioned by Wang et al. (2021), including the Port of Rotterdam's cargo handling and transportation twin and the Port of Singapore's traffic monitoring twin.

5.6 Additive manufacturing

Additive Manufacturing (AM) is another option associated with smart ports. The method allows fast and decentralized production of individual metal, ceramic, and plastic parts and reduces material transport and stock (Rüßmann et al., 2015). A recognized AM technology port application is spare part production for docked ships, e.g., within the RAMLAB in the Port of Rotterdam (de la Peña Zarzuelo et al., 2020).

5.7 Augmented reality

Employee-focused improvements can be obtained through augmented reality (AR). The terminal operator, APM Terminal, uses a smartphone AR application to inform employees, visitors, and contractors about risk and safety issues on their Brazil sites (de la Peña Zarzuelo et al., 2020). Generally, AR can combine real and virtual environments to show data in actual situations and simplify human decision-making in, for example, docking procedures (de la Peña Zarzuelo et al., 2020; Denktaş Şakar and Sürücü, 2018). Several possible AR port applications beyond employee training and docking procedures are discussed by Denktaş Şakar and Sürücü (2018). They include visualizing planned construction projects in natural environments, location tagging for repair personnel, and scanning visual markers on cargo for further information on, among others, unit number, weight, and assigned position.

5.8 Horizontal and vertical integration through management and information systems

The digital integration of smart port operational functions (horizontal) and with other non-operation-related processes (vertical) is another important dimension in optimal use of real-time data (Alcácer and Cruz-Machado, 2019). In this sense, integration is not only meant to be intra- but also inter-company, accounting for ports' multistakeholder environments (Alcácer and Cruz-Machado, 2019). Crucial for such integration is a reliable and secure data sharing communication through technologies like WiFi, RF, 4G, or 5G (de la Peña Zarzuelo et al., 2020; Jardas et al., 2018). Multistakeholder integration and standardization is also a solution that is requested by the EU through their single window regulation (EU, 2019).

Applicable management and information systems serving this integration were listed by Dong et al. (2013) as, among others, intelligent production scheduling (IPS), intelligent warehouse (IW), intelligent vehicle (IV), and smart ship (SM) management systems. Further, de la Peña Zarzuelo et al. (2020) mention asset (AMT) and smart asset management tools (SAMT).

The IPS system is described as a cargo handling, scheduling, and visualization tool that combines communication technologies attached to the yard and quay equipment with real-time data exchange between personnel and a control center system (Dong et al., 2013). IW systems keep track of stored cargo through communication and sensor tools. They compare the storage location of goods with the planned ones and can, for example, identify false placements (Dong et al., 2013). The IV systems support terminal vehicles and help identify and track them (Dong et al., 2013). The same functions are also part of the SM systems utilizing the automatic identification system (AIS) data, GPS, or comparable technology (Dong et al., 2013). AMT and SMAT concern numerous assets in ports, including mooring facilities, port pavements, and dock gates (de la Peña Zarzuelo et al., 2020). Sensors on these assets can help measure loads and forces or identify abnormalities (Siror et al., 2011). The Port of Hamburg uses smart asset management tools on its bridges providing the port authority with real-time data on structural loads, traffic, and weather influences (de la Peña Zarzuelo et al., 2020).

Despite the importance of comprehensive integration, communication, and data sharing, de la Peña Zarzuelo et al. (2020) point out that literature targeting ports on these issues is scarce.

Box 3. Research opportunities in the area of digitalization and automation in ports

- Digital twin modelling to support energy transition technologies
- Provision of smart on-demand services to offshore wind parks, energy islands and other energy-related coastal facilities by small autonomous vessels

6. DECISION SUPPORT TOOL CONCERNING PORT TRANSITION STRATEGIES

A variety of port-related decision support tools exist today. The vast majority of them concern the traditional cargo-handling operations. Numerous examples of them have been mentioned in Section 3.2 in relation to quayside, yardside, and landside port operations. At a tactical level, scenario analysis can be supported by the digital twin applications of Section 5. At the highest strategic level, port planning and development has been a popular subject since the late 1970s (UNCTAD, 1978). However, even the most recent publications (Notteboom, 2022) pay little attention to the ports' role in energy transition.

The wide-ranging expertise brought together by the stakeholder network that the present project develops constitutes an inviting opportunity for developing a specialized decision support tool on the energy transition strategies a port can pursue. There are two large European research projects funded by the H2020 program ongoing in this area: PIONEERS, led by the Port of Antwerp-Bruges (https://pioneers-ports.eu/); and MAGPIE, led by the Port of Rotterdam (https://www.magpie-ports.eu/). However, both these projects aim at demonstrating technical, operational, and procedural energy supply and digital solutions in a living lab environment, their Master Plans for the European Green Port are not expected before 2026, and they do not include a Danish port in their partnership.

The tool envisioned here addresses strategic decisions and aims at identifying the energy transition activities that a port can undertake in order to maximize value creation as this is perceived by the local stakeholders. Methodologically, it is expected to deploy a combination of cost-benefit analysis for the financial assessment and multi-criteria decision analysis tools for assessing the societal impact. Assessment will be based on a set of KPIs concerning all sustainability dimensions.

Tentatively, the development of the tool could include the following activities:

1. Identification of stakeholders
2. Selection of KPIs for different levels of detail based on literature findings and preliminary outputs of the other activities of the project
3. Definition of stakeholder priorities
4. Development of tool components concerning specific energy transition measures

4.1 Identification of tool components concerning specific technical measures

4.2 Identification of tool components concerning specific operational measures

5. Consolidation of tool components into a functional tool
6. Tool application on two specific case studies (a Danish port and a port in a developing country)

CHAPTER 3. REGULATORY ECONOMICS AND THE FUTURE OF PORTS AS ENERGY HUBS

Tooraj Jamasb

1. INTRODUCTION

The anticipated transition of some ports to future energy hubs will have implications for aspects of the economic nature of ports and their activities. The new economic role of ports will see them as an integrated part or an extension of the energy sector. This will mean that ports will occupy a significant role in the new energy transition supply chain that encompasses generation of offshore electricity and production of green fuels such as hydrogen and ammonia the demand for green fuels.

Crucially, ports together with energy islands will constitute two new infrastructure elements in the energy system. As a result, ports will have a central role in the supply, export, and meeting of demand for green fuels for various industry, shipping, and aviation sectors. Ports as hubs for energy supply and demand will also attract and host new industrial activities and clusters on and around their premises.

The enhanced economic role of ports as energy hubs as a new key infrastructure in the energy system will have economic implications for the ports themselves as well as for other components of the energy system and supply chain. Energy and other key infrastructure sectors are often natural monopolies and as a result subject to economic regulation. Also, due to their importance for the wider economy, the performance of infrastructure is an important consideration. Finally, the development and expansion of infrastructure facilities are increasing subject to public and community scrutiny for their possible local and environmental impact. Ports as energy will not be an exception and the above concerns will also be important for their future development. In this chapter we focus on the above three key economic aspects concerning ports and the energy transition.

This chapter summarizes selected key research areas and economic methods that can be relevant for the study of ports of future energy hubs. The three key areas covered in this review are economic regulation, public acceptance, and efficiency and productivity analysis of ports and related infrastructure sectors. Where relevant, we also point to the state of knowledge in literature.

This chapter proceeds as follows. Section 2 describes economic regulation options for ports as energy hubs and discusses them against the background of economic regulations in other sectors. Section 3 addresses how social acceptance of sustainable ports can be examined using economic methods. Section 4 describes how efficiency analyses, space and network aspects of ports and key contextual aspects can be examined.

2. ECONOMIC REGULATION FOR PORTS AS ENERGY HUBS AND LESSONS FROM OTHER INFRASTRUCTURE INDUSTRIES?

For the most part of the twentieth century, seaports (such as airports) have been state-owned enterprises, providing infrastructure and services that have a public policy objective such as making passenger and freight services more accessible. States have traditionally focused on the primary function of these natural monopolies while other aspects of their commercial activity and value have received less attention. Ports fit the conventional definition of natural monopolies in that they are capital intensive in relation to their operating expenditures resulting in declining marginal costs as the scale of operation increases.

The traditional responses to infrastructure industries with natural monopoly economic characteristics include outright public ownership, economic regulation, or, if possible, subject them to competition and market discipline. As these infrastructures tend to grow and increase their services over time, their efficiency and the ability to attract new capital have become central issues for governments with debates around ownership structure and forms of regulation. The outcome has been different across jurisdictions leading to different forms of governance and economic regulation as, for instance, in the case of the airport sector (Georges Assaf and Gillen, 2012).

Findings from the literature on economic regulations are important to consider when discussing economic regulation options for ports as energy hubs. Distributed energy in hubs provides economic and environmental advantages enabling a network for energy exchange and results in efficiency advantages from both a financial and environmental point of view (Maroufmashat et al., 2015). This section reviews the economic regulation, ownership, and governance aspects of other relevant infrastructure, focusing on how they are regulated and what lessons they can provide to seaports.

2.1 Natural monopolies as regulated infrastructure

Some sectors of the economy such as ports, airports, and energy transmission and distribution networks have economic properties that designate them as natural monopolies and leading to economic regulation of them. Natural monopolies tend to be capital intensive resulting in high fixed cost while they enjoy low marginal cost of expansion. As a result, natural monopolies exhibit declining average costs. This means that a given market and quantity of output can be provided more efficiently by a single firm than several competing firms. In the case of airports "the monopoly argument claims that the economics of airline operations favor high levels of concentration' (Tretheway and Waters II, 1998, p. 48). The same argument to a large extent also applies to seaports.

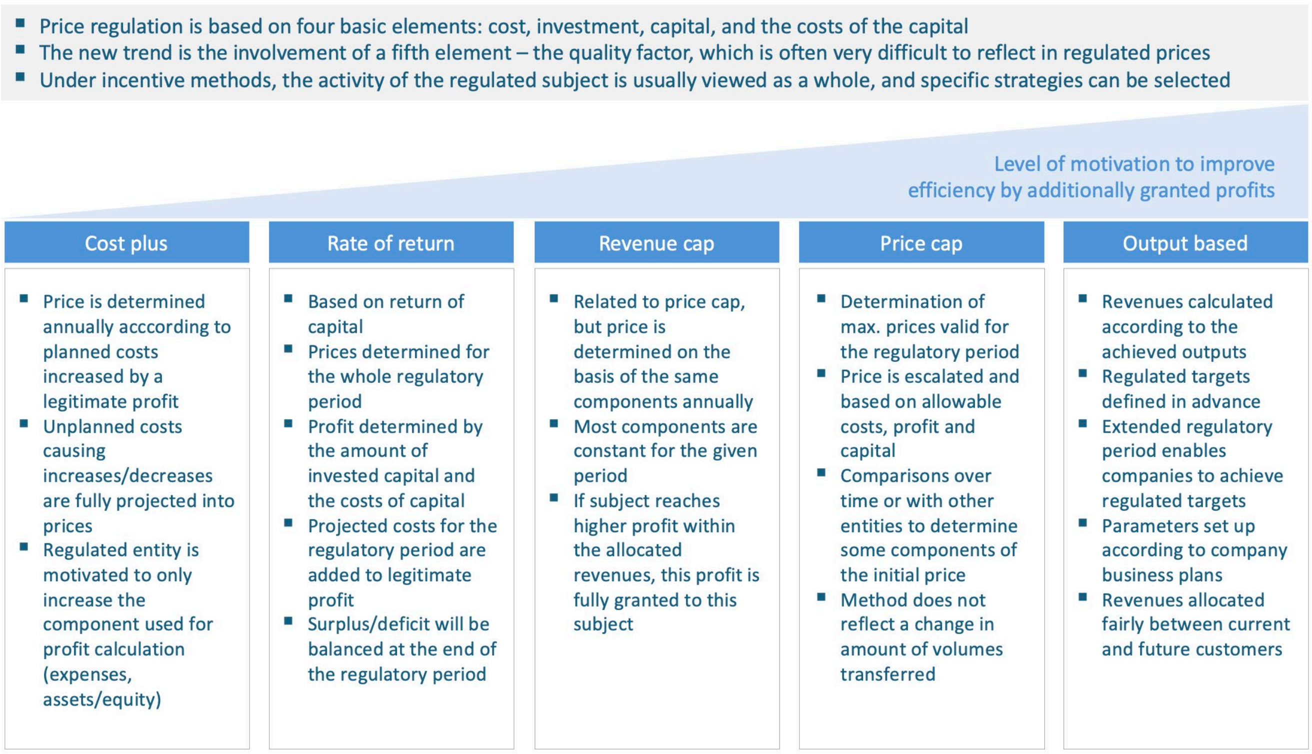
This contradicts the notion of efficient contestable and competitive markets with entry and exit (Jahanshahi, 1998). In the absence of competitive markets, the conduct of natural monopolies tends to be subject to regulatory oversight and economic regulation some of which aims to mimic, in the absence of competitive markets, the competitive market outcome.

The view of ports and some other infrastructure sectors has gradually changed as public utilities and providers of public services to network industries that can be organised as commercial activities that provide commodities and can be subject to economic regulation and then perhaps be privatised (Pallis and Rodrigue, 2022; Saragotis and De Langen, 2017).[1] The aim has been to reduce the role of government and its financial responsibility in these sectors (Adler and Liebert, 2014, p.92). While the need for economic regulation of natural monopolies is widely recognised, developing and implementing the appropriate regulation has been more difficult. This has led to the development of several theoretical and applied economic incentive regulation approaches within infrastructure sectors.

The conventional approaches to economic regulation of regulated firms have been based on cost plus and rate of return models. The models were mainly aimed at ensuring cost recovery through regulated tariffs and securing a minimum rate of return for the companies. However, in the post-liberalisation of network industries era, these models lacked sufficient incentives for cost efficiency. As a result, revenue cap and price cap models of regulation have increasingly been adopted by sector regulators. It is noteworthy that in many instances these models are not observed in pure forms but become part of hybrid regulation models. More recently, as the sole focus on cost efficiency has been replace by achieving and balancing multiple outputs such as quality of service and environmental concerns. As a result, forms of output-based regulation models of energy networks have been implemented in the UK and Italy. Figure 1 summarised the main characteristics of these models.

[1] Please, see also The World Bank's so-called *Port Reform Took Kit* (https://ppiaf.org/sites/ppiaf.org/files/documents/toolkits/Portoolkit/Toolkit/module3/port_reform.html)

Figure 1. Evolution of incentive regulation methods



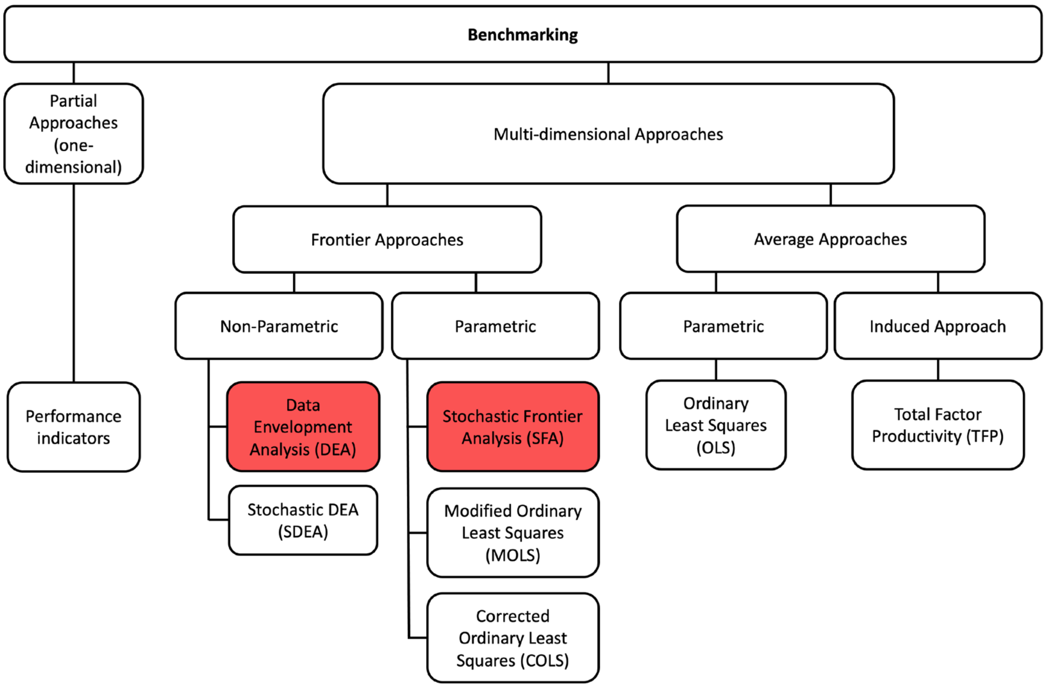
Source: Little (2017)

2.1.1 Benchmarking and regulation

Benchmarking of infrastructure and network industries using efficiency and productivity methods has been widely used in various economic disciplines and by many energy and water regulators (Giannakis et al., 2005; Jamasb and Pollitt, 2003). In particular, since the liberalization of energy industry in the 1990s, sector regulators have used benchmarking a tool that enhances application of economic regulation. The methods are based on identifying an efficient frontier representing best practice in the industry as part of economic regulation of natural monopoly energy networks. Alternatively, yardstick regulation methods – where regulators use benchmarks from comparable sectors to set prices – can, in principle, be used, although the practicalities of this (e.g., data quality) need further research (Reinhold et al., 2010). Figure 2 illustrates an overview of the different benchmarking methods used in academic research and economic regulation of utilities.[2] We review the application of these methods to research and economic regulation separately later in this chapter.

[2] See Jamasb and Pollitt (2001) for a description of the benchmarking methods.

Figure 2. Benchmarking Techniques



Source: Cullmann (2005)

2.2 Airports

Airports are subject to various forms of economic regulation. It can be discussed and is subject to further research as to which of the regulation models provide elements can also be applied to ports as energy hubs. This is examined in the following.

The use of price caps is common in incentive regulation of network industries. Price caps can also be combined with benchmarking and yardstick regulation methods or be applied to single companies based on their own past performance (Tretheway and Waters II, 1998). A price cap has strong incentive properties that makes it a convincing candidate to be considered for the economic regulation of ports. This can also be combined with profit-sharing mechanisms between the company and its customers.

While airports may be subject to economic regulation, they may at the same time be exposed to competitive pressure from other airports, something which is not inconceivable in the port sector. The combination of internal regulation and external competition is uncommon in other infrastructure industries but interesting and requires research and investigation of individual ports or airports. The strength of the relationship between airports and the airlines becomes an important factor (Bush and Starkie, 2014).

Many ports are under public and local ownership. Since the 1990s, many infrastructure industries have been privatized and subsequently subjected to economic regulation or operate in competitive environments. While privatization is not a prerequisite for economic regulation or participation in market competition, economic theory assigns some advantages to this. However, the case of power sector liberalization in Norway shows that effective regulation or market competition can be applied to publicly owned utilities and bring about most advantages of privatization (Littlechild, 2018).

The importance of regulation, irrespective of ownership type, is also evidenced in an efficiency study of European and Australian airports. But it also shows that a monopolistic airport is less efficient than private ones, while competitive public airports are efficient, though have higher charges (Adler and Liebert, 2014). In addition to economic regulation, the governance of airports can also influence the efficiency of airports. A study has shown that while both regulation and governance influence efficiency, regulation tends to be more important than governance (Georges Assaf and Gillen, 2012).

Given the above, and looking at recent changes in economic regulation of Spanish ports, can information be obtained for regulating ports as energy hubs? New Spanish legislation gives ports more freedom over their pricing policy. The degree to which ports can modify their tariffs depends, among other things, on forecasts of traffic, debt levels, objective annual profitability, and reasonable yields on the assets (Tovar and Wall, 2014).

2.3 Other network industries

Regulation of electricity and gas distribution and transmission networks has advanced more than other network industries. Economic regulation of these networks provides relevant insights with regards to economic regulation, investments, cost sharing, access, etc. during the green transition (Rosellón, 2018). The following presents a few of the emerging issues in infrastructure development with relevance for ports as future energy hubs.

For instance, capacity development, investment and access pricing will be important in ports as energy hubs and as regulated infrastructure. Some recent theoretical and applied contributions have addressed these issues and among others have suggested the use of auctions for allocation of output and services from new investments in infrastructure expansions (Khezr and Menezes, 2019; Queensland Competition Authority, 2013).

Port development will be an important feature of future ports as energy hubs. Deller (2011) proposes an analytical model with a control approach to obtain an optimal port expansion strategy, by balancing investment costs for the port and congestion costs for its users (Deker et al., 2011). Related to investments, a common issue increasingly arising from infrastructure investments is that of allocation of costs and benefits (Hogan, 2018). Finally, aspects of economic regulation of railway networks can also be considered in the context of establishing a model of economic regulation for ports as energy hubs, for instance, with regards to privatization or monopoly power abuse on the part of bottleneck carriers and no open rail network access in the United States (Jahanshahi, 1998; Lauriono et al., 2015).

Summary

Governance and regulation of ports is not a very new subject. However, the transition of ports to become green energy hubs will lead to the need to revisit these vital aspects of their governance models and economic regulation of their developments and operation. This section outlined some directions in which these new frameworks may be used in the coming years. Several theoretical concepts and practical models for economic and incentive regulation were briefly discussed here. Lessons of experience from other sectors which have made progress in economic regulation such as the energy networks as well those with resembling features in terms location, cluster of activities, and types of services such as airports will help developing future governance and regulation needs of the ports. Finally, although regulation of ports will be an important matter, the extent to which they are or can potentially operate as competitive entities will be among the important areas to consider going forward. Again, there are cues from the energy and airport sectors that will be helpful in this regard.

3. SOCIAL ACCEPTANCE FOR SUSTAINABLE PORTS AND ECONOMIC METHOD?

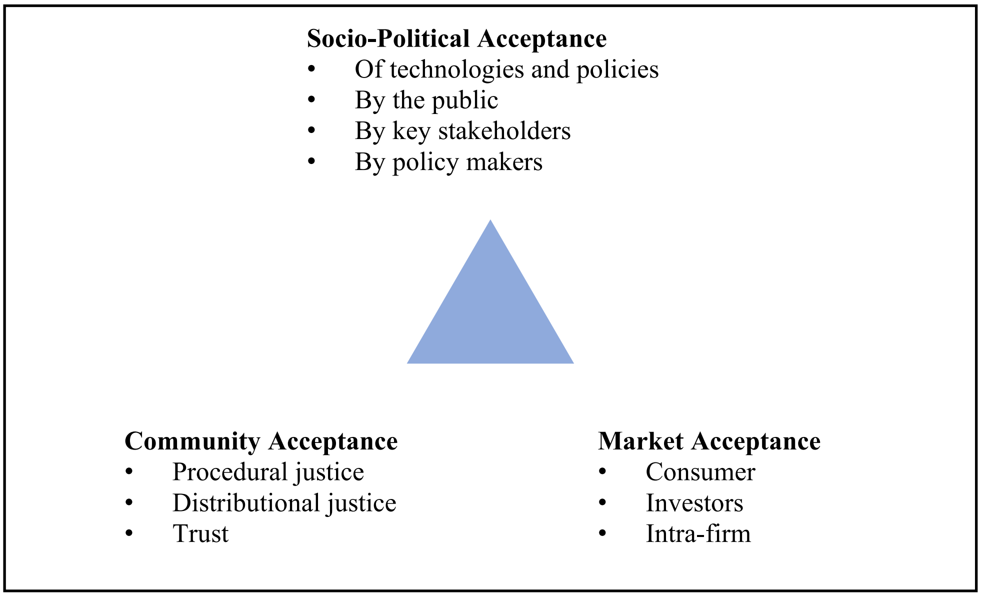
The promotion of renewable energies and infrastructure to combat climate change has become a central task of governments worldwide. However, public acceptance of and opposition to these issues can slow or hinder this process. Particularly, overcoming public resistance and gaining social acceptance at the local level represents an important challenge for the developers of renewable energy projects.

Public perception and acceptance of infrastructure development and new energy technologies is multi-dimensional and spans over different levels, contexts, methods, and disciplines. For example, non-market environmental attributes, social, and economic effects of different activities have local, regional, and national dimensions. The actual and perceived costs, benefits, and risks of these need to be adequately reflected in project planning and consultation process. Research in social acceptance of infrastructure development has shown that communication and trust feature prominently in social acceptance of projects (Gaede & Rowlands, 2018). Trust and communication are closely related to procedures and the process of consultation.

The non-market aspects of infrastructure development need to be integrated in the analytical tools such as social cost-benefit analysis (SCBA). The nature of the subject matter calls for identification of intersections and development of interdisciplinary research not only horizontally across social sciences but also vertically with other sciences and different subdisciplines of engineering disciplines.

Figure 3 shows that economic and social science research has so far mostly covered some narrow aspects of acceptance and socio-political and market acceptance aspects largely remain to be researched. The following presents some insights from selected aspects of single case studies as well as comparative studies and finally a view to how economic approach and research in this area can be developed further.

Figure 3. Triangle of social acceptance of renewable energy innovation



Source: Wüstenhagen et al. (2007)

3.1 Comparative studies of public acceptance

Drawing from research interviews and academic literature, Sovocool and Lakshmi Ratan (2012) conceptualize the conditions that promote investor confidence and the social acceptance of wind and solar sources of electricity. It explores the factors influencing the acceptance of commercial wind turbines in Denmark and India and residential solar panels in Germany and the United States (Batel et al., 2013).

A comparative analysis of public beliefs across three European countries studies the distinction between support and acceptance of high voltage transmission lines in the UK, Norway, and Sweden. The study suggests that public acceptance can be distinct from support and that acceptance has multiple dimensions chiefly in the form of socio-political, market, and community dimensions (Aas et al., 2014). The results also suggested that general acceptance of energy projects is always higher than local acceptance, among other things indicating that the level of trust in the developers of energy infrastructure plays a key role in shaping public responses to them.

A comparative analysis of wind energy in France and Germany explores the factors of social acceptance of renewable energy projects. They identify economic and regulatory factors on the one hand and site-specific and local conditions on the other as key categories of success factors (Jobert et al., 2007). Particularly, they confirm the factors of social acceptance generally identified in the literature (visual impact, ownership, information and participation) but also gives insight into those aspects of social acceptance directly related to the implementation of energy projects (including the local integration of the developer, the creation of a network of support, and access to ownership).

3.2 Single case studies

Wüstenhagen et al. (2007) is one of the earlier examples of the literature on the topic and presents a body of literature that introduces a journal special issue on Social Acceptance of Renewable Energy Innovation. It presents a collection of best papers presented at an international research conference held in February 2006. Gross (2007) studies community perspectives of wind energy in Australia and application of a justice and community fairness framework to increase social acceptance focusing on procedural justice and fairness. His study indicates that the extent to which the outcomes of renewable energy infrastructure developments are perceived fair influences how people perceive the legitimacy of such projects, and that a fairer process of decision-making will increase social acceptance of the outcome.

A comparable study of wind power in Australia points to similar public concern about the wind farms (D'Souza and Yiridoe, 2014). However, a study of hydropower projects in Switzerland shows that ecological concerns rank higher than the fairness aspect of them (Tabi and Wüstenhagen, 2017). A study of wind power development in France uses interview results to develop a set of practical guidelines to be used for increasing the likelihood of public acceptance of projects (Enevoldsen and Sovacool, 2016).

A detailed study of the controversial Bealuy-Denny project a 220 Km-long high voltage transmission line in the north of Scotland discusses how several communities were affected by the development. The project aimed to transport renewable electricity from North of Scotland to the rest of the UK. In addition to the communities affected, the opposition to the project also involved non-governmental environmental organisations (NGOs). In the process, the project became the subject of detailed cost-benefit studies and became the longest running public enquiry in Scotland (Tobiasson et al., 2016).

3.3 New frameworks for future research

Some recent research has explored the determinants of social and public acceptance of energy technologies, for instance, as part of efforts for developing a theoretical basis for a cross-paradigmatic analytic framework useful for facilitating and encouraging joint consideration of the many factors that influence social acceptance (Upham et al., 2015). Tobiasson and Jamasb (2016) propose a Menu of Options approach. The approach has been developed in regulatory economics to exlore and reach socially acceptable solutions for compensation for environmental impact of energy infrastructure development. Williams et al. (2016) survey the acceptance literature that has used the unified theory of acceptance and the use of technology (UTAUT).

On the empirical side, research has aimed to visualize the social acceptance of technologies and fuels using a bibliometric review of the literature (Gaede and Rowlands, 2018). Survey results are frequently used for valuation of non-market goods and attributes in welfare and environmental economics. Contingent valuation survey techniques are frequently used in such studies. For instance, Stigka (2014) conducts a literature review of contingent valuation methods to acceptance of renewable energy technologies.

Summary

It is important to understand the social acceptance of low-carbon technologies and new energy infrastructures such as ports and energy islands. Future research on social acceptance aspects of ports as energy hubs can benefit from research methodologies and design on other infrastructure sectors. A growing body of research is concerned with this subject and approaches the issue in different manners and using different methodologies. Also, the research needs to consider specific technologies such as hydrogen and renewables as well as in the wider context of energy systems and markets. There is limited evidence of such connected knowledge and evidence (Gaede & Rowlands, 2018). The approaches used in this area can guide further research into public acceptance of future port development and investment projects.

4. EFFICIENCY AND PERFORMANCE ANALYSIS OF PORTS

As mentioned earlier, efficiency and productivity analysis methods sectors have proven useful for research, performance analysis, and applied regulation of network and infrastructure. A variety of methods, most prominently the Data Envelopment Analysis (DEA) and Stochastic Frontier Analysis (SFA), are used by scholars and practitioners to measure the productive efficiency as well as spatial and network aspects of ports. Efficiency and productivity analysis measure the performance of firms or sectors relative to the best practice, i.e., efficient frontier, in a given sample of comparable firms, sectors, or countries. A useful feature of these methods is that they accommodate performance analysis using multiple inputs and outputs measured in monetary terms and physical units and often assessed in terms of technological, economic, and environmental factors.

4.1 Economic efficiency

The use of efficiency and productivity techniques has become widespread in economic literature. The techniques mainly originated from applications in the agriculture sector. Since the energy reforms of 1990s and unbundling of natural monopoly networks the techniques have also been used by many electricity, gas, and water regulators as supporting tools for incentive regulation of the networks, in particular the energy distribution networks. The efficiency and productivity analysis techniques used in benchmarking can be parametric and econometrics such as Stochastic Frontier Analysis (SFA) used in economic research but also for policy making purposes (Lovell, 1995). Similarly, the parametric technique Data Envelopment Analysis (DEA) originates from operations research and decision science discipline with many applied research and policy applications such as in seaports (Panayides et al., 2009; Ongzon, 2001).

4.2 Technical efficiency

The efficiency and productivity techniques can be used in several different forms and for different types of analysis. A distance function approach was used on a sample of 14 port terminals observed over the period 2004–2010 to evaluate their efficiency levels and to decompose productivity into technical efficiency, scale efficiency, and technical change (Chang and Tovar, 2014a). Another efficiency study measures dynamic technical efficiency of Spanish ports (Tovar and Wall, 2017). The shadow cost approach is developed in the context of the dynamic duality model of intertemporal decision making to formulate theoretical and econometric models of dynamic efficiency (Rungsuriyawiboon and Stefanou, 2007).

Comparison of parametric and non-parametric techniques can be reassuring and increase confidence in results when used in regulatory or policy making settings. The technical efficiency of the world's largest container ports has been estimated using and comparing both DEA and SFA (Cullinane et al., 2006). Also, another study uses both DEA and SFA methods for measuring the efficiency of 25 major Brazilian port terminals (Wanke et al., 2011). A similar type of study estimates and compares the technical efficiency of the container ports using DEA and SFA methods to analyse the role of infrastructure characteristics on container port efficiency (Hlali, 2018).

A meta-analysis of DEA and SFA studies of the technical efficiency of seaports conducts a comparison of fixed and random-effects regression models (Odeck and Bråthen, 2012). Another study measures how technical progress and scale efficiency gains have improved the total factor productivity of Spanish ports, whereas technical efficiency losses reduced the total factor productivity (Núñez-Sánchez & Coto-Millán, 2012). Another study uses an econometric model to calculate the technical and the allocative efficiency in cargo handling firms in the port of Las Palmas, Spain (Rodríguez-Álvarez et al., 2007).

Another relevant study estimates technical efficiency of Spanish Port Authorities using a directional distance function approach (Tovar and Wall, 2015). In another study of the Spanish ports, the evolution of technical efficiency in port infrastructure service provision in major Spanish port authorities involved in container traffic is estimated (González and Trujillo, 2008). Finally, a comparative study measures technical efficiency of port terminals in Peru and Chile to evaluate the influence of specific contextual variables and finds that, on the whole, Chilean ports are more efficient (Chang and Tovar, 2014b).

4.3 Ownership, structures, and competitiveness

Efficiency and productivity analysis can also be used to study the effect of ownership, structure, and regulation of performance of ports. Using a 'port function matrix' to analyze the administrative and ownership structures of major container ports in Asia, Cullinane et al. (2002) estimate the relative efficiency of these using cross-sectional and panel data versions of the stochastic frontier model (Cullinane et al., 2002). Rodríguez-Álvarez and Tovar (2012) study the effects of regulatory reforms designed so that the Spanish regulatory framework could embrace the forms of port organization and management that would in turn permit the Spanish ports to function competitively and efficiently, and to be suitably positioned within the distribution systems.

Cheon et al. (2010) analyze panel data of port ownership, corporate structure, and port inputs and outputs for 98 major world ports and implementing the Malmquist Productivity Index (MPI) model. Tongzon and Heng (2005) study incorporating the inefficiency effect of port privatization a strategy to gain a competitive advantage. Similarly, Wu and Lin (2008) study national port competitiveness in India and while freight industry is competitive, the transport sector is less competitive.

Summary

Efficiency and productivity analysis methods were mainly developed in the 1960s and 1970s and gradually became mainstream in applied research where comparative analysis of similar entities would be informative such as in the agricultural sector. Liberalisation of network industries followed by economic regulation of natural monopolies led to widespread use of the methods by researchers and sector regulators. Although a number of studies have applied these methods to the port sector, they seem to be lagging behind those of other infrastructure sectors such as energy networks. Moreover, the anticipated role of ports as future green energy hubs will change the conventional economic representation of ports in economic models and their efficiency and productivity analysis. The number and diversity of services in the ports sector and their users will increase in the future. Also, ports will engage in large and new forms of investment some of which have varying degrees of relevance to existing versus traditional and allocation of costs and benefits of investments among these will be needed. Efficiency and productivity analysis methods will play a useful analytical and regulatory role in this changing sector.

5. CONCLUSIONS

The transition of ports to green energy hubs will offer opportunities to extend their economic role into green transition by becoming an integrated part of the green energy infrastructure. This will, however, require revisiting aspects of the ports sector such as governance, supply chains, and operations. This chapter briefly presented some selected economic aspects that are likely to present themselves as important while they have not been part of the recent debate surrounding the future role of ports as green energy hubs.

The anticipated changes in the economic role of the ports will inevitably lead to similar debates as those that followed the regulated activities of the liberalized energy and other network industries. Chief among these will be the need to consider new governance and regulation framework for the ports. The new role of the ports will further highlight the importance of economic efficiency of them. This will in turn lead to debate around the extent to which individual ports are competitive or economic activities and whether they are subject to antitrust or economic regulation. Economic regulation models such as price caps, revenue caps, and especially out-based regulation will be relevant considerations.

We also discuss the analytical techniques for benchmarking the performance of regulated firms against best practice in the sector used by energy and other regulators. While efficiency and productivity techniques have previously been applied to ports these have mainly not been in the context of economic and incentive regulation of these. Using such methods in regulation of ports in their new role may pose methodological and practical challenges.

Finally, the new roles of ports as green energy hubs will require new investments and development of these. While economic return on infrastructure development is often high, increasingly gaining public acceptance of major development projects are challenges by social and local opposition. Economic methods can contribute to reduction of such conflicts of interest through non-market valuation of important project attributes and possibly design of menu of options. These can improve inclusion of public and local valuations in cost-benefit analysis and improve the process of deliberations among the parties concerned.

CHAPTER 4. PORT-CENTRIC SUPPLY CHAINS AS CATALYSTS FOR THE CLEAN ENERGY TRANSITION

Christopher Dirzka

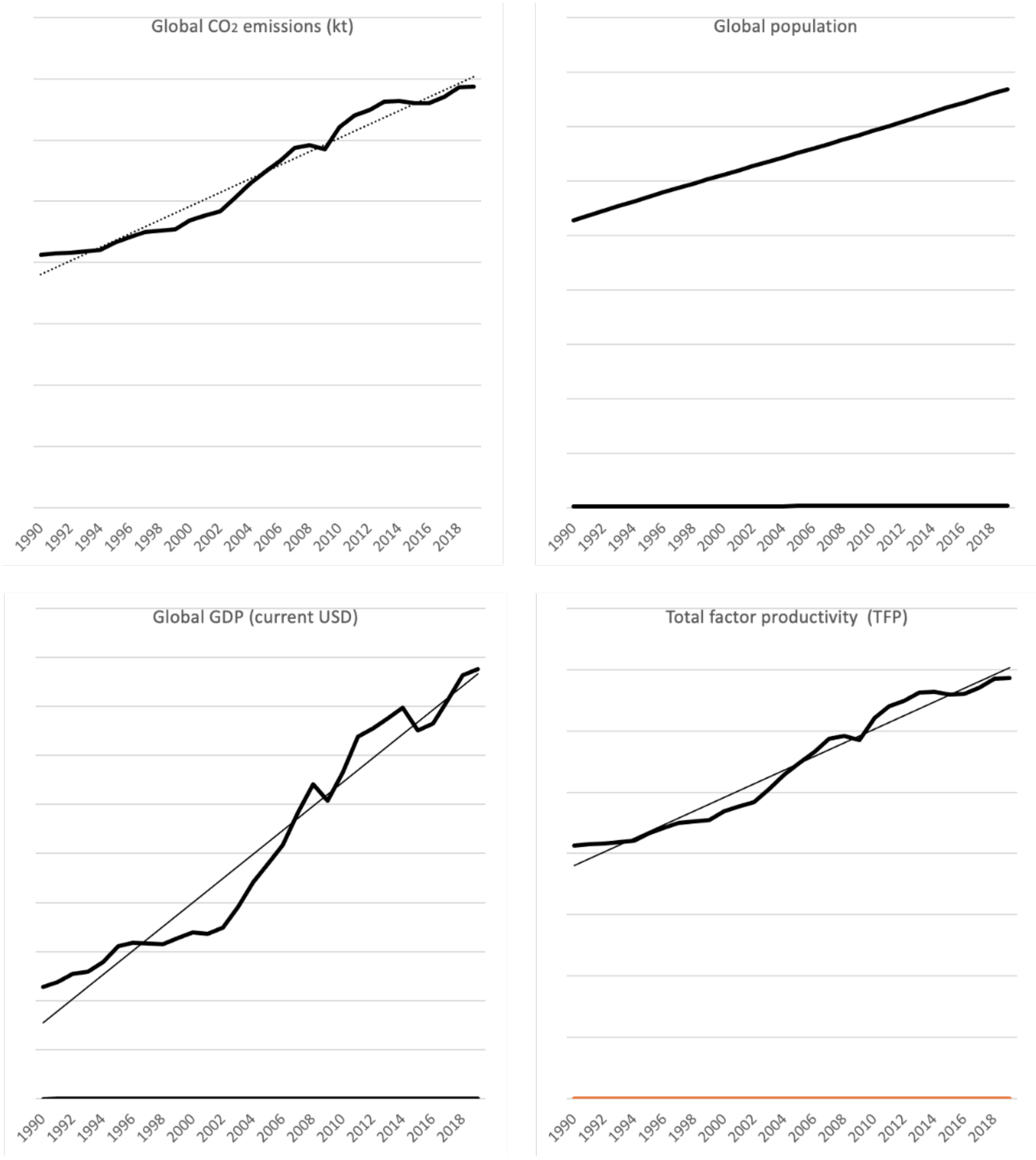
1. INTRODUCTION

In the book, *The Architecture of Complexity*, the Nobel Prize-winning economist Herbert A. Simon (1962) explores the nature and structure of complex systems, which he describes as hierarchical (with smaller sub-systems nested within larger systems) and 'near-decomposable', the latter of which means that interactions within subsystems are stronger than interactions between subsystems. While complexity arises from intricate interactions within and between individual subsystems, near-decomposability suggests that focusing on subsystems makes it easier to understand and manage this complexity. This chapter will adopt this approach to examine the role of ports in the clean energy transition, exploring particularly the interplay between energy and maritime systems and their impact on onshore infrastructure. The ongoing clean energy transition drives this interplay.

The need for the clean energy transition is driven by 'the world problematique', a term coined by the Club of Rome to describe the complex system of ecological, economic, and social challenges faced by humanity. These challenges include population growth, economic stagnation, and environmental degradation. Building on the IPAT concept by Ehrlich and Holdren (1971), which examines the Impact of Population, Affluence, and Technology on energy consumption (and indirectly carbon emissions), the Club of Rome argued that deliberate constraints on exponential growth are essential to avoid a collapse of the world system and to achieve sustainable development while meeting society's basic material needs (Meadows et al., 1972). Responding to this concern, the Brundtland Report, *Our Common Future*, highlighted that the current state of the world system borrows "environmental capital from future generations with no intention or prospect of repaying' (The World Commission on Environment and Development, 1987, p. 14). The report's authors proposed the sustainable development principle, emphasizing that the limits to growth are not artificially imposed but are determined by the earth's capacity to absorb the impacts of the world problematique.

Furthermore, the principle established that these limits should be introduced through political will well in advance, ensuring equitable access to resources and suitable technologies. This political will, understood as a multilateral pursuit, is manifested in the Sustainable Development Goals (SDGs) in 2015. The SDGs encompass economic, social, and environmental dimensions and consist of 17 goals that outline a global agenda for sustainable development towards 2030. Individual goals recognize the importance of fostering a more prosperous, inclusive, and healthier society while conserving natural resources and combating climate change. Supporting the urgent message conveyed by the SDGs, the Sixth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC, 2021) highlighted humanity's significant negative impact on the environment and warned of catastrophic consequences if no action is taken.

Figure 1. Impact, Population, Affluence and Technology (IPAT) concept



Sources: World Bank (2024) for Population and Affluence; Feenstra et al. (2015) and Penn World Table (2021) for Technology/Total Factor Productivity

Beyond ecological degradation, recent macroeconomic and geopolitical events underscore the need for clean energy transition and necessitate a reevaluation of the relationship between energy and maritime systems.

Firstly, the COVID-19 pandemic disrupted the objectives set by the SDGs, causing delays or suspensions in initiatives aimed at supporting global sustainable development. Social equity diminished globally, health systems collapsed, and the economy slowed down. Pandemic risk-mitigation strategies affected every stage of the global value chain (United Nations, 2020). As recovery began, these value chains remained strained due to rebounding global demand and ocean supply chain bottlenecks, raising barriers to market access, particularly for developing nations (UNCTAD, 2021a; 2021b; 2021c). Considering that economic growth and multilateral action underpin the SDGs, the pandemic highlighted how fragile global governance structures are. The question of how to proceed in an environment characterized by short-term pressures and long-term uncertainties challenged societies, i.e., recovery to regain the status quo or reset to invigorate adherence to sustainable development.

Secondly, the energy crisis, driven by high inflationary pressures (partly due to the pandemic) and geopolitical turmoil between Russia and Ukraine, has further emphasized the necessity for a clean energy transition (UNCTAD 2022). High energy prices, exacerbated by dependency on Russian energy and a lack of alternative sources, serve as a significant impetus for adopting cleaner energy solutions.

Naturally, the maritime supply chains that link the global economy and energy markets are severely impacted by regulatory ambitions to mitigate ecological degradation and the prior cited events. These supply chains (SC) haul over 80 percent of the volume of international trade in goods (UNCTAD, 2021c), of which approximately 36 percent are energy products.

The role of these SCs as facilitators of cooperation between energy and maritime systems is crucial for the clean energy transition. They not only facilitate global energy trade but also act as significant energy consumers, primarily relying on fossil fuels and contributing substantially to global anthropogenic emissions (Faber et al., 2020). This dual role has led to increased regulatory scrutiny and an ambition to transition to low- and zero-carbon fuels by 2050. Consequently, this shift will reshape the relationship between energy and maritime systems, particularly necessitating the redesign of onshore infrastructure and processes, including ports and other onshore operations.

The implications of the energy transition on ocean supply chains and their dual role are not yet fully understood. In this context, this chapter examines how shifting global energy and maritime supply chains influence the role and development of ports.

The remainder of this chapter is structured as follows: Section 1.1 introduces the link between energy and maritime systems in the context of the energy transition. This serves to present chapter-relevant supply chain stakeholders while highlighting the state-of-the-art literature on energy transition hubs. Section 2 outlines the background concerning offshore and onshore supply chains, providing insights into the role of ocean supply chains as both utilizers and facilitators of the transition, and their implications for ports. Section 3 discusses instruments to bridge offshore (shipping), nearshore (ports), and onshore (energy) markets. Finally, section 4 concludes by outlining future research avenues.

1.1 Energy Transition within Supply Chains

Given the overall focus on "Ports as Energy Transition Hubs' presented in this report, this section introduces relevant supply chain stakeholders and their relations to the hub, as illustrated in figure 2 by using a spatial segmentation to distinguish roles:

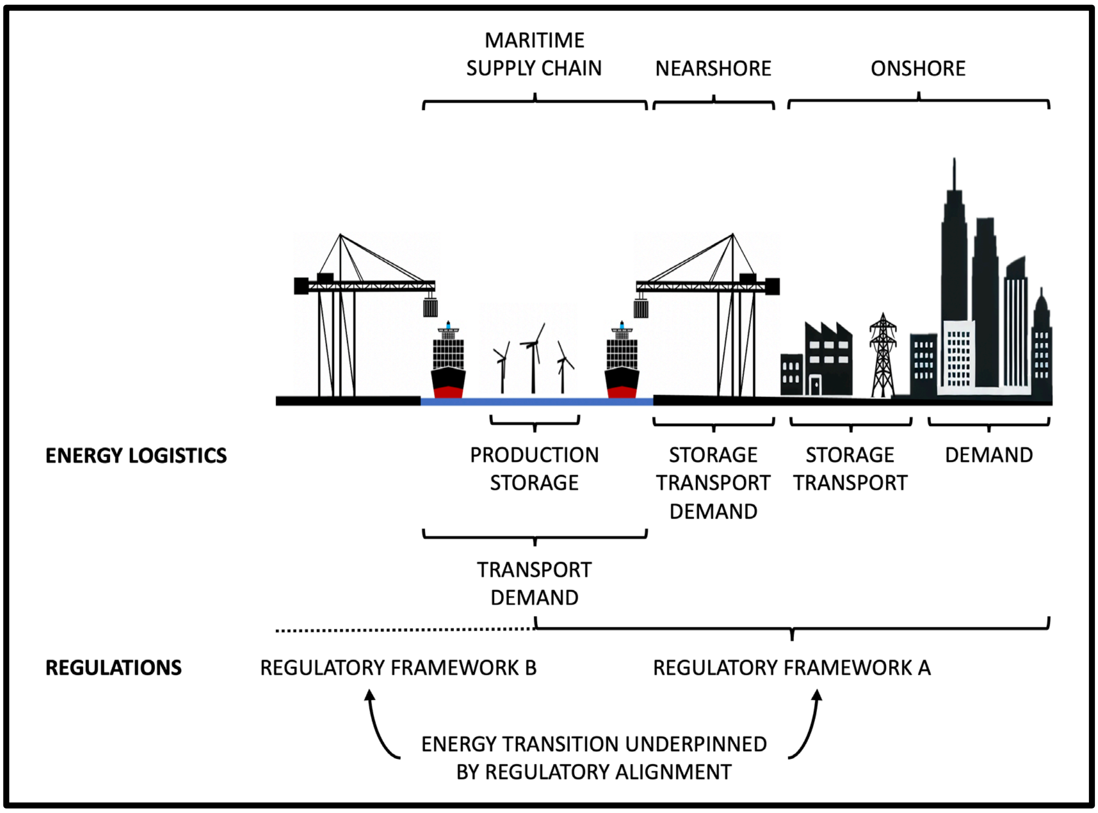
- *Onshore*: Hinterland markets and energy grids, which compete with maritime supply chains for alternative fuels (see section 2.2). This segment includes storage and transport operations.
- *Nearshore*: Ports serving as storage facilities, distributors, and utilizers of energy.
- *Offshore*: Maritime supply chains that facilitate hinterland energy markets and act as energy consumers. Additionally, offshore wind farms are geographically situated within these maritime supply chains. Although shipping provides supply services to these farms, they are linked to onshore energy markets.

Nearshore operations constitute the link between onshore energy systems and maritime supply chains. In this respect, the port as an energy hub is described as 'a unit where multiple energy carriers can be converted, conditioned, and stored. It represents an interface between different energy infrastructures and/or loads' (Geidl et al., 2007, p. 2-3).

In general, energy hubs refer to facilities transitioning from fossil fuel-based operations to more sustainable ones. Ports, in particular, play a crucial role as distributors and storage units, significantly shaping the energy transition (Bjerkan, Ryghaug, and Skjølsvold, 2021) and influencing the dual role of maritime supply chains. Like international shipping, ports are major polluters and have only partially succeeded in reducing their environmental footprint (Poulsen et al., 2018). Consequently, both onshore and offshore structures and operations are subject to regulatory scrutiny, particularly on a national level, given their geographical proximity to urban centers (Sornn-Friese et al., 2021).

National and global regulations targeting maritime supply chains (see section 2.1) aim to reduce fossil fuel usage and promote the adoption of zero- and low-emission alternatives, which impacts hinterland energy markets and port operations.

Figure 2. Transition interplay schematic



Exogenous regulatory pressures driving the clean energy transition are fostering stronger connections between stakeholders (Hentschel, Ketter, and Collins, 2018). Harmonizing regulations across national boundaries and ensuring industry cooperation in complying with such regulations is critical to achieving decarbonization. For instance, ports linked by maritime supply chains can support technical innovations (see section 2.1) and supply low- and zero-carbon fuels. This also applies to stakeholders within the maritime supply chain, who are forming alliances to enable green transport operations. However, the strength of these linkages depends on local regulations, port governance, port size, and the operators associated with the ports (see also chapter 5 of this report).

2. BACKGROUND: OFFSHORE AND ONSHORE SUPPLY CHAINS

2.1 Sustainable maritime supply chains

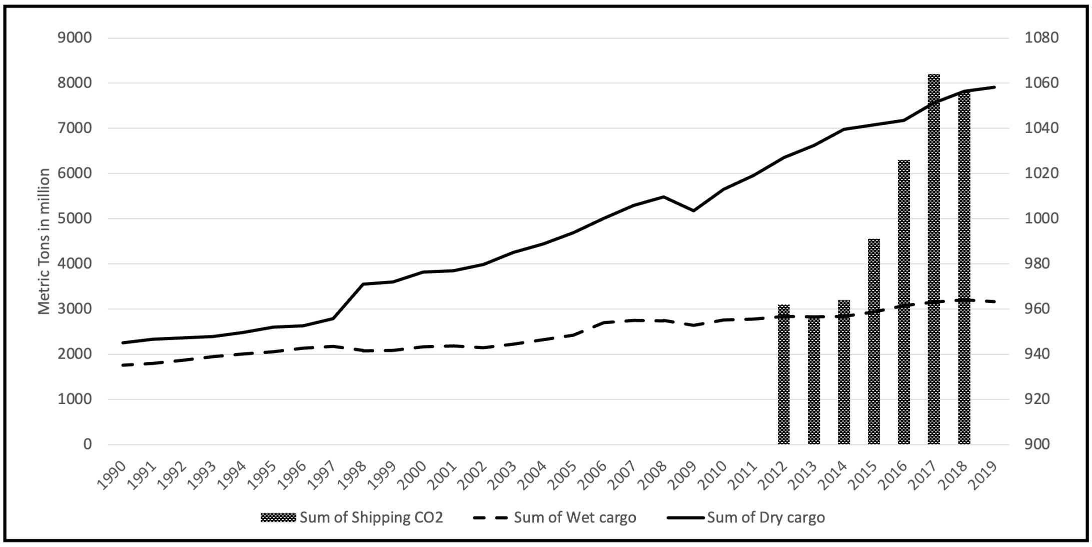
This section outlines the role of maritime supply chains in the energy transition, focusing on their contributions to the global economy, energy consumption, and carbon emissions. It examines the sector from both an energy efficiency perspective (technical and operational) and a regulatory perspective, presenting the push-and-pull factors that shape the relationship between nearshore and onshore infrastructure (ports and energy systems).

In 2018, ocean supply chains contributed almost three percent to global anthropogenic emissions, totaling 1.076 million tons (Faber et al., 2020). This marks a 9.6 percent increase from the 977 million tons emitted in 2012. Under a business-as-usual (BAU) scenario, where forthcoming regulations have no impact on carbon emissions, CO2 emissions in 2050 could be about 50 percent higher than in 2018. This increase is closely tied to the global gross domestic product (GDP) and population growth. For example, during the decade-long globalization surge in the 1990s, the shipping activity to GDP growth multiplier exceeded four. In the 21st century, particularly post-2015, this multiplier remained around one, due to geopolitical and technological factors reducing the appeal of outsourcing or offshoring production (World Bank, 2020).

The roles of maritime supply chains as both utilizers and facilitators are influenced by population, affluence, and technology. Shipping volumes are projected to continue rising, with estimates ranging between seven and 35 Gt/yr by 2050, corresponding to a sector energy demand of nine to 25 Exajoule (EJ). Therefore, integrating energy and maritime systems is crucial to create synergies and produce sufficient alternative fuels to meet this demand (Müller-Casseres et al., 2021).

Guided by scholarly discourse, sector integration should be complemented by industry initiatives and appropriate regulations to enable the energy transition. Such industry initiatives would include operational changes (e.g., voyage adjustment, capacity utilization, weather routing) and the adoption of new technologies (e.g., asset size, propulsion systems, hull design) (Faber et al., 2009; Eide et al., 2011). As an intermediate step in the clean energy transition, the operations management literature has discussed initiatives to lower fossil fuel usage before transitioning to low- and zero-carbon fuels.

Figure 3. Shipping markets and carbon footprint



Source: Comer et al. (2020)

Against this background, changes in operational voyage speed and respective implications on ports were examined. Voyage speed is the main proxy for fuel consumption. The relation is established via three main approaches: The seminal third power relationship proposed by Ronen (1982), approximating fuel consumption using a ship's constant-coefficient and sailing speed. Estimation pointed to a constant that ranges between 2.7-3.3, relating to 3,000-8,000 TEU container ships (Meng, Du, and Wang 2016). Another approach also considers payload conditions, relying on a ship's displacement. Adopting more slender ship designs can lower fuel consumption and impact operations at berth (Lindstad, Asbjørnslett, and Jullumstrø, 2013; Lindstad, Sandaas, and Steen, 2014; Lindstad and Bø, 2018). Finally, incorporating specific fuel consumption (sfc) and engine power (PB) in brake horsepower (BHP) was considered (in lieu of speed over ground) to estimate fuel consumption (Veneti et al. 2017). Case studies indicated that slight speed accelerations translate into almost 50 percent more fuel consumed in tons per nautical mile (Cariou, Parola, and Notteboom, 2019). Given this, slow steaming impacts capacity utilization and industry supply, as well as service networks, i.e., lowering speed changes the demand for onshore fuel storage and demand, requiring adjusting port operations.

Going beyond the approximation of fuel usage and emissions, a nascent and still developing research stream considered other variables that impact consumption. These variables related to operational decisions, and the effectiveness of hull cleaning suggested additional fuel consumption drivers related to meteorological, technical, and operational conditions and ocean currents (Acciaro and McKinnon, 2015; Bal Beşikçi et al., 2016; Meng, Du, and Wang, 2016; Bialystocki and Konovessis, 2016; Adland et al., 2017; Capezza et al., 2019; Dirzka and Acciaro, 2021; Sun, Meng, and Chou, 2021).

As stated in the prior paragraph, lowering fossil fuel usage constitutes an intermediate step towards the clean energy transition. Utilizing low- and zero-carbon fuels and facilitating the respective trades provide the prospect to transition, i.e., operational changes or technologies are not sufficient (Cullinane and Yang, 2022). Fuel types such as biofuels can reduce emissions by 25-84 percent or LNG by 5-30 percent (Bouman et al., 2017). Yet, as indicated by Lagemann et al. (2022), cooperation between the energy and maritime systems is necessary to achieve the clean energy transition, which goes together with re-designing port operations and investments in onshore infrastructure. Besides, a share of the merchant fleet would need to be retrofitted or built with capacities to utilize and transport these new fuel types (Schroer, Panagakos, and Barfod, 2022). Given the significant barriers to adopting alternative fuels, regulatory push-and-pull tools would need to be in place to support the energy transition.

2.2 Introducing the status-quo in the maritime supply chain

The emissions trajectory in shipping, estimated by Annual Efficiency Ratio (AER)[3] and Energy Efficiency Operational Indicator (EEOI)[4] indicates some improvement with 22 and 32 percent in the respective order against 2008 measures under a vessel-based allocation methodology. It shall be critically remarked that improvements are not linear as most gains occurred before 2012, and since 2015 the annual pace has slowed down significantly to 1-2 percent. Economies of scale, specifically in dry bulk and container shipping, can rationalize the initial gains on the asset level and lower operational speeds (i.e., slow steaming), besides technological advancements (Bouman et al., 2017). This also implies that the natural limits related to the ship size and technical restrictions to slow steaming flatten the performance curve. For example, in the containerized shipping sectors with average carbon intensity and average speed in nautical miles diminished by 17.8 and 5.6 percent, while the average asset size in twenty-foot containers (TEU) rose by 32.9 percent in 2018 over 2012 levels (Clarksons Research, 2022). In sum, the maritime supply chains will stay hard-to-abate, and the carbon footprint is destined to grow further.

To counter the trajectory of rising emissions, the International Maritime Organization (IMO) adopted the Initial Strategy at MEPC 72 in 2018. This policy framework was influenced by the ambitions set under the Sustainable Development Goals (SDGs), particularly Goal 13, which focuses on combating climate change, and the Paris Agreement (2015), which aims to limit the global temperature rise this century to below 2°C above pre-industrial levels.

However, it is important to note that neither the SDGs nor the Paris Agreement specifically address the shipping industry. Instead, they delegate the responsibility to the IMO to establish appropriate targets. The core objectives of the Initial Strategy were to reduce carbon intensity by 40 percent by 2030 and 70 percent by 2050, based on 2008 levels, and to reduce total GHG emissions by 50 percent by 2050. Three target ranges were outlined in this framework based on insights on the data collection initiatives[5] and include respective measures to achieve the objectives of the strategy:

- Short-term measures under the timeline 2018–2023 incorporate the Energy Efficiency Design Index (EEDI)[6] and Ship Energy Efficiency Management Plan (SEEMP)[7], in addition to establishing an Existing Fleet Improvement Programme.
- Mid-term measures between 2023 and 2030 cover new operational energy efficiency measures focusing on newbuilds and existing assets. Under this scope, market-based measures (MBMs) were singled out as a candidate to incentive GHG abatement.
- Long-term measures beyond 2030 relate to the pursuit towards a zero-carbon industry.

The ambitions set forth in this policy framework were commendable as they aimed to serve the public good. However, in hindsight, these targets appear to fall short of the Paris Agreement (2015) objectives. UN Secretary-General António Guterres noted at the UN Global Sustainable Transport Conference (UN, 2021) that the progress is “more consistent with warming above three degrees’ and urged the IMO to revise its strategy to achieve zero-emission by 2050. Scholarly discourse supports this statement as IMO targets allow the shipping industry to emit more than double what was budgeted under the Paris Agreement (Bullock, Mason, and Larkin, 2021). The IMO’s revised greenhouse gas (GHG) strategy, adopted at the Marine Environment Protection Committee (MEPC 80) in July 2023, includes significantly enhanced targets and a clearer path towards decarbonization.

The 2023 IMO GHG Strategy sets a new ambition to reach net-zero GHG emissions from international shipping by around 2050. It also introduces specific interim targets for reducing total annual GHG emissions from international shipping towards 2023 and 2040. The updated strategy

[3] Annual Efficiency Ratio (AER) captures carbon intensity by dividing annual carbon dioxide emissions and distance sailed in nautical miles multiplied by ship deadweight (Faber et al., 2020).

[4] Energy Efficiency Operational Indicator (EEOI) considers overall carbon emission divided by revenue tonne-miles unit within a given observation period (Faber et al., 2020).

[5] Data collection system (DCS) by the IMO and Monitoring, Reporting and Verification (MRV) by the EU refer to compulsory schemes designed to collect the information on asset level bunker consumption and operational characteristics.(see IMO MEPC.282(70) in 2016a and EU Reg.2015/757 in 2015).

[6] Energy Efficiency Design Index (EEDI) refers to a mandatory technical measure by the IMO, which applies to newbuilds and sets forward minimum energy efficiency levels per capacity mile (please see MEPC.203(62) adopted in 2011)

[7] Ship Energy Efficiency Management Plan (SEEMP) is an operational measure to improve energy efficiency with a focus on costefficiency. Operators can utilize the SEEMP to track performance (see MEPC.203(62) adopted in ibid.).

aligns more closely with the Paris Agreement's objectives, incorporating a mix of technical and economic measures aimed at reducing the carbon intensity of marine fuels and implementing GHG emissions pricing mechanisms

The 2023 strategy sets more ambitious targets for reducing emissions, aiming for at least a 20 percent reduction by 2030 and at least a 70 percent reduction by 2040, compared to 2008 levels. These targets indicate significant reductions in shipping emissions, requiring rigorous scrutiny of the industry's ability to meet these goals. Market-based mechanisms (MBMs) such as the Emissions Trading Scheme (ETS) and carbon levies are crucial for internalizing the external costs of emissions. The EU has decided to include shipping in its ETS starting from 2024, covering emissions from voyages within the European Economic Area (EEA) and at berths linked to the European market. This integration is part of the EU's Fit for 55 package, which aims to reduce GHG emissions by at least 55 percent by 2030 compared to 1990 levels. Additionally, a proposed carbon levy within the IMO suggests starting at 100 USD per ton of CO2 by 2025, gradually increasing over time. The IMF has indicated that a carbon price of at least 75 USD per ton of CO2 is necessary by 2030 to meet the 2°C target set by the Paris Agreement.

Given the industry's heavy reliance on fossil fuels and the substantial operational costs associated with energy (Fransoo and Lee, 2013), implementing additional surcharges through MBMs could exert significant pressure. Internalizing carbon costs might initially burden the industry and impact trade networks, potentially driving closer collaboration between energy markets and the maritime sector, but also creating competitive disadvantages for some ports (Gu, Wallace, and Wang, 2019; Lagouvardou and Psaraftis, 2022).

In closing, maritime supply chains undergo internal changes and are pushed and pulled by regulators. While implications on energy markets and port operations might differ, a more integrated view of the whole chain is imperative. Subsequently, the scholarly discourse regarding the implications on onshore operations of these changes in maritime supply chains is reviewed.

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2.3 Implications on Onshore Infrastructure

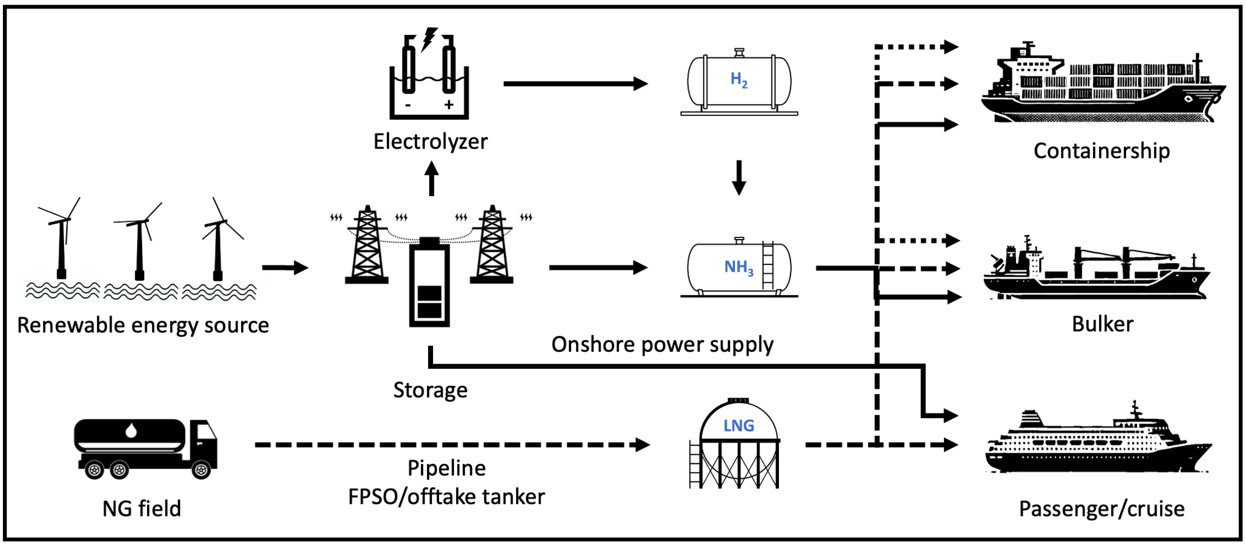
In line with the previous discussion on respective developments, the following paragraphs explore the implications for ports. Although this chapter focuses on the ocean supply chain perspective, it is important to note that these implications are bi-directional. This means that both the ability to transport alternative fuels and the demand for them, as well as the ports' capacity to handle these fuels, are interconnected.

Ports, which have traditionally functioned as standalone nodes within the ocean supply chain network, are evolving into value-driven ecosystems (Robinson, 2002) that operate within interdependent clusters (Langen, 2015) (please see section 3 below). This transformation includes sustainable onshore operations such as onsite assembly (Renews, 2022), alternative fuel storage and production facilities, and connections to offshore energy hubs. Depending on the role ports assume – whether as landlords, operators, or regulatory authorities (Acciaro, Ghiara, and Cusano, 2014; Poulsen et al., 2018) – their governance approaches may vary. Consequently, ports could implement technologies and offer guidance in collaboration with offshore operations.

Just as exogenous pressures (see section 2.1) influence ocean supply chains, governmental interventions can impact sustainability practices at ports. For instance, governments might provide incentives to establish innovative and high-risk facilities capable of storing alternative fuels like LNG (Commission, 2022). Additionally, direct demands from ocean supply chain stakeholders may prompt adjustments in port operations. While the academic discourse on these bidirectional implications remains ambiguous, the effects on both technical and social dimensions are clearly complex. Observations suggest that changes are incremental, and further insights are needed to drive disruptive innovations.

Figure 4 illustrates the connection between hinterland energy markets, alternative fuels, and maritime supply chains

Figure 4. Onshore-to-offshore transition



Source: Adopted from Damman and Steen (2021)

The most immediate implication of the linkage shown in figure 4 is the reduction of vessel emissions at berth, achieved through both technical and operational changes within transport operations and the use of alternative fuels (Du et al., 2011; Lindstad and Bø, 2018). Given the close geographical proximity between ports and urban areas, emissions of SOx, NOx, and PM significantly affect the health of the local population.

Cold Ironing or Onshore Power Supply: This process allows ships, particularly cruise ships and passenger vessels at berth, to connect to the electric grid, avoiding the need to run auxiliary engines. Depending on the energy mix of the onshore grid and the share of renewable energy, this process can significantly reduce emissions (Ballini and Bozzo, 2015; Innes and Monios, 2018; Zis, 2019).

Liquefied Natural Gas (LNG): LNG offers a way to reduce emissions for both ships and ports, though it is not a zero-emission fuel. When compared to onshore power supply, LNG offers similar performance but requires less infrastructure investment. In shipping research, LNG is considered a reliable fuel choice, especially when compared to other options (Gkonis and Psaraftis, 2009; Ursavas, Zhu, and Savelsbergh, 2020; Yin and Lam, 2022; Lagemann et al., 2022). However, limited supply and availability of LNG remain significant constraints.

Liquefied Hydrogen/Ammonia: As zero-emission fuels from a tank-to-wake perspective, hydrogen and ammonia are seen as viable energy carriers. However, if the electricity used for electrolysis is not sourced from renewables, well-to-tank emissions can occur (Bach et al., 2020; Prussi et al., 2021; Pomaska and Acciaro, 2022). According to Lagemann et al. (2022), hydrogen currently has the highest opportunity cost when used in shipping. While hydrogen's technical maturity and implementation are still underdeveloped, ammonia, produced by converting hydrogen, appears to be a more advantageous fuel choice, though slightly less favorable than LNG.

The implications of alternative fuels, particularly hydrogen and ammonia, on ports and hinterland energy systems are not yet fully understood.

3. BRIDGING OFFSHORE AND ONSHORE SUPPLY CHAINS

Green shipping corridors serve as a bridge between offshore (shipping), near-shore (ports), and onshore (energy) market stakeholders, as illustrated in figure 2 and the detailed processes in figure 4. These corridors are defined as specific trade routes between major port hubs where zero-emission solutions are actively supported and demonstrated (McKinsey, 2021; World Economic Forum, 2022). To meet the goals set by the UN's Sustainable Development Goals (SDGs) and the 2023 IMO GHG Strategy, local and limited regulations are insufficient. Green corridors act as integrative instruments, harmonizing regulations across national boundaries and helping to overcome significant cost gaps (compared to the status quo) and challenging market dynamics such as the principal-agent problem and the chicken-and-egg dilemma.

While the concept of green corridors is well-established in transportation research, particularly in hinterland transport (e.g., Panagakos, Psaraftis, and Holte, 2015), its application to maritime supply chains is a relatively new area of study and policy application. In this context, the idea of integrative instruments to support the clean energy transition is outlined in a business case, with section 3.1 highlighting a critical challenge that must be addressed.

Business Case: Operational scale is the primary driver for narrowing the cost gap and overcoming adverse market dynamics. Green shipping corridors can create an environment that supports low-carbon, economically efficient co-modality. As harmonized ecosystems, these corridors could leverage targeted regulations, financial incentives, and a closely connected stakeholder network to achieve scale and scope. However, establishing green shipping corridors requires significant resources, extensive value-chain cooperation, stable regulations, and forward-thinking decision-making regarding operational processes. These aspects are crucial because ships have an operational lifespan around 25 years, meaning the installed propulsion technology determines future deployment options.

A potential business case would depend on the impact (e.g., large-scale decarbonization) and the feasibility of implementation (e.g., technology readiness, investment levels, and community acceptance) and would be based on the following assumptions:

- Zero-emission fuel supply drives customer demand, necessitating initial onshore investments and subsequent offshore asset adjustments.
- Operational costs are directly linked to increased customer demand, narrowing the gap between the status quo and zero-emission fuels.
- Initial investments (CAPEX) under economies of scale lead to higher market supply and lower operational costs (OPEX).
- The impact of initial investments (CAPEX) on decarbonization is positively correlated, meaning larger investments result in greater decarbonization impact.
- The level of value-chain cooperation and regulatory support influences the amount of investment required; stronger internal factors reduce the necessary investments (feasibility-impact relationship).
- The degree of value-chain cooperation and regulatory support is inversely related to the complexity of subprojects during the implementation stages.
- Global oil market dynamics (or overall economic health) can either strengthen or weaken the business case, with narrower spreads increasing investment opportunities.

The first fully established green shipping corridor could serve as a model for establishing others, acting as a spearhead for further development. It would demonstrate to regulators and industry stakeholders the feasibility of narrowing the current competitiveness gap. Regulatory support might include mechanisms like Emission Trading Schemes (ETS), expedited permits (enhancing feasibility), loan guarantees, and CAPEX subsidies. Along with piloting technologies and organizational structures, the first green shipping corridor requires substantial investments and high levels of cooperation across the supply and demand chains. Previous collaborations between the shipping industry and fuel producers indicate general feasibility and impact. Direct investment could act as a catalyst, with guaranteed multi-year off-take commitment contracts to de-risk investments and/or ‘contracts for difference’ (CfD) being considered. Notably, CfDs would involve the taxpayer assuming some financial risk.

Once green shipping corridors mature globally (i.e., when sufficient integration of energy and maritime systems is achieved), regulators can transition to supporting competitive interactions. Aggregated supply would enable economically viable operational costs per unit produced, while technological advancements and process optimization would reduce the required capital investment. Linking green shipping corridor subprojects to adjacent routes could further leverage resources by aggregating demand.

The concept of green shipping corridors, initially enacted at the 2019 UN Climate Action Summit as a key approach to reducing the global greenhouse gas emissions attributed to the shipping industry, involves creating specific maritime routes where zero-emission or low-emission vessels operate, supported by collaborations among governments, ports, shipping companies, NGOs, and technology providers.

Ports play a crucial role by upgrading infrastructure such as the installation of onshore power supply (OPS) at ports (e.g., Rotterdam and Hamburg). Allowing ships to reduce emissions while at berth, developing LNG bunkering facilities, and supporting research on ammonia as a zero-emission fuel. Success factors are believed to include strong public-private partnerships, regulatory support, and port infrastructure, while overcoming challenges such as high costs and regulatory harmonization.

3.1 Research challenges

As mentioned in the previous section, *green shipping corridors are capital-intensive and carry high risks*. The scholarly discourse needs to explore ways to recoup initial investments, which is crucial for successfully integrating energy and maritime systems. The following paragraphs outline a potential research path:

By applying the learning curve theory, this challenge can be addressed. This theory, integral to corporate strategic planning, provides policymakers with insights into the cost-effectiveness of new technologies over time. Learning curves offer stakeholders insight into how costs may decrease over the operational lifespan of a project (Zwaan and Rabl, 2003; Nemet, 2006). Seminal quantitative studies have shown that production costs tend to decrease in a semi-consistent manner with each doubling of production, often following the 80-20 rule, where unit costs drop by 20% as output doubles. More recent estimates suggest that production unit costs can decrease by 25-30% with each doubling of accumulated production, although market competition may reduce this effect to around 5-10%. This indicates that, despite internal learning gains, much of the acquired knowledge is disseminated throughout the market. The key insight from the learning curve is that frequent operations lead to improved output and reduced costs over time. Numerous studies across various industries have validated this relationship, operationalizing the curves using cumulative production factors and response cost changes to capture learning and technological improvements.

When applied to green corridors, learning curves can offer a strategy to close the competitiveness gap between green shipping corridors and fossil fuel-based trade routes. Insights from other green energy technologies and innovative infrastructure projects, such as photovoltaics (Hong, Chung, and Woo, 2015), can help identify catalysts that influence costs. Understanding customer needs for specific fuel types and emerging preferences will also shape the project's impact and feasibility. Future research could examine how R&D investments and direct policy interventions can accelerate technological progress and cost reduction.

4. CONCLUDING REMARKS

The external pressures driving the clean energy transition have a significant impact on stakeholders throughout the global supply chain. This transition requires extensive collaboration among regulators, hinterland markets, ports, and the shipping sector. This chapter introduced the dual role of shipping in the transition – both as a user and a facilitator – and discussed its implications for ports. It also outlined the concept of green corridors as a tool to support sectoral integration and highlighted the primary challenges in establishing these corridors, offering a path for further research.

This chapter explored various emerging areas of knowledge within the broad topic of energy and maritime supply chain integration:

As a potential research direction, scholars might investigate who should take the lead in selecting suitable fuel types, considering the advantages and disadvantages of being a first mover in the value chain—an issue often referred to as the "chicken-and-egg" problem (Mäkitie, 2021). This includes further exploration of untested technologies and processes, as well as the development of long-term cost curves to create clear business cases for the transition (e.g., cost curves for electrolyzers). Additionally, research should identify which targeted regulatory frameworks (e.g., carbon levies and subsidies) would most effectively support progress (Lagemann et al., 2022). This involves determining whether a single fuel type should be standardized or whether a blend of fuels would better facilitate the transition and identifying mechanisms to reduce competition for fuels with other sectors.

Given the maritime sector’s high sunk costs, it is important for scholars to study how legacy capacity issues can be addressed and how to align operations and investments with policy goals (Schroer, Panagakos, and Barfod, 2022). Collaboration across sectors is crucial, so opportunities for partnerships—such as R&D initiatives involving ocean transport firms, terminal operators, and regulators—should be explored (Poulsen et al., 2018; Bjerkan et al., 2021). These collaborations should help to de-risk investments in alternative fuel production, storage, and transportation technologies. Additionally, research should examine the spatial implications of fuel production and usage, assessing potential changes in supply chain networks, particularly for least developed countries (LDCs) and small island developing states (SIDS).

CHAPTER 5. CONTENT, STRUCTURE AND GOVERNANCE OF TRANSACTIONS: A BUSINESS MODEL

Henrik Sornn-Friese

1. INTRODUCTION

At the outset of the 'Ports as Energy Transition Hubs' project presented in this report, we identified port governance as a key theme and challenge for advancing the role of ports in the energy transition. Port governance refers to the system of rules, policies and processes that determine how a port is managed and operated, and effective governance is needed because port operations and development are capital-intensive, use scarce (public) land, generate externalities (e.g., dust, emissions, noise), and involve many decision-makers and stakeholders, including the port authority, terminal operators, rail operators, trucking companies, logistics providers, manufacturing companies, waste companies, and port-cities (Nursey-Bray, 2016; Fobbe and Hilletofth, 2021; Pallis, 2022).

Different models of port governance can, given the legal framework within which a given port operates, include public ownership, private ownership, and public-private partnerships, and each individual model adopted has its distinct way of making decisions about investments, development, operations, and other critical aspects of port management. The model adopted has important implications for individual ports and for the country in which they are located (Ferrari and Musso, 2011). Among other issues, a port's governance model can significantly affect its efficiency, competitiveness, and ability to respond to changes in markets and technology. On a higher level, the port governance model can impact a country's trade and economy, as well as broader societal issues. Well managed ports can serve as engines of economic growth, facilitating trade and creating jobs, while poorly managed ports may become bottlenecks that hinder economic growth and development.

Port governance is also an important analytical lens in maritime and port research (Zhang et al., 2018). The maritime and port research field is multidisciplinary and studies all aspects of maritime transport and port operations, including but not limited to maritime transport economics, port operations and management, shipping and trade logistics, port infrastructure and development, and environmental impacts and sustainability. Using port governance as an analytical lens means focusing on how different governance structures, policies and management practices and processes affect various outcomes in ports and the maritime industry.

1.1 From port governance to port business models

This chapter explores port governance issues as they pertain to the role of ports in facilitating the clean energy transition, aiming to identify central areas or knowledge gaps in need of further research and development. In our endeavor to uncover the intricacies of port governance and the role of ports in fostering the clean energy transition, the research team engaged a diverse array of stakeholders across the maritime and energy value chains (please see chapter 1 for an overview of the stakeholders involved). Our original inquiry on port governance was framed around the four basic questions raised by Veira et al. (2014): 'who governs', 'what is governed?', 'how is it governed?', and 'for what purpose?', thus aiming to provide a comprehensive understanding of the key governance issues within ports in the context of the present study and to identify central knowledge gaps.

However, it became evident that, while indeed foundational, these questions did not fully resonate with the pressing concerns and opportunities identified by those commercially and strategically involved in the field. Rather than problematizing governance structures, the questions raised to us by stakeholders were concerned more with identifying what kinds of port businesses should be developed and what should guide the strategic efforts of the port management entities to embed themselves in a new clean energy ecology of somehow interdependent organizations and institutions. While the governance model of a port is crucially important in the clean energy transition, understanding the business model of a port is critical for identifying new opportunities, attracting investment, and facilitating innovation and collaboration in the renewable energy sector.

Firstly, the energy transition requires ports to adapt to changing market conditions, as the demand for traditional fossil fuels declines and the demand for renewable energy sources increases. This shift requires ports to adopt new business models that are focused on facilitating the development, deployment, and distribution of renewable energy technologies. Secondly, the energy transition is likely to result in the emergence of new players in the port industry, such as renewable energy companies, that require different business models than traditional shipping and logistics companies. Understanding these new business requirements is essential for port operators to identify new opportunities and partnerships in the renewable energy sector. Thirdly, the port's business model will impact the level of investment in renewable energy infrastructure and technologies. A port that has a business model that prioritizes environmental sustainability and the transition to renewable energy is more likely to attract investment in these areas. Finally, the port's business model is likely to enable the level of innovation and collaboration in the renewable energy sector. A port that encourages innovation and collaboration among stakeholders is more likely to facilitate the development of new technologies, resources and capabilities, and strategies that can accelerate the energy transition.

Our dialogue with stakeholders was in this regard instrumental in steering our exploration towards more nuanced and commercially relevant research questions, focusing on the decision-making processes around renewable energy, green fuels, pricing strategies, collaborative partnerships, attraction of new types of port tenants, and service adaptation to changing customer segments. Thus, in line with the exploratory nature of the present study, and because of extensive stakeholder dialogue, the original narrow focus on port governance was reframed as broader knowledge gaps concerning how the clean energy transition can affect the business model particularly of ports (including, e.g., the development of new services, the cost structure of port operations, key partners, customer relationships, and revenue streams) and how port business models can be changed to accommodate the clean energy transition (business model innovation).

This begs research aiming to better understand the nature of the opportunity that the clean energy transition presents to ports, how ports can adapt to exploit the opportunity and create value, and how ports can appropriate some of the value created for themselves and for the value chains in which they are embedded. In theoretical-conceptual terms, this implies a shift in the understanding of port governance, moving from a traditional view with a focus on physical assets and operational efficiency as the main value proposition for ports, to a more dynamic and stakeholder-inclusive perspective with a broader focus on stakeholder value creation and the value capture by the port.

The remainder of this chapter follows in two main sections. Section 2 ('Port governance, port authority renaissance, and business model change') discusses the evolving role of ports, transitioning from traditional port authorities to more commercially focused port development companies. Ports are seen both as critical physical infrastructure for trade and industry, and as complex organizations driving economic development. This dual perspective highlights the importance of ports in the clean energy transition, with their infrastructure facilitating the trade and production of renewable energy technologies. Ports also serve as logistical hubs and manufacturing sites for renewable energy components. Furthermore, modern port governance emphasizes strategic, value-driven management, fostering partnerships and innovation to enhance sustainability and efficiency. This shift necessitates innovative business models that integrate advanced logistics, renewable energy infrastructure, and stakeholder engagement to create and capture value in the clean energy transition. Section 3 ('Current knowledge gaps') identifies existing knowledge gaps in understanding the emerging role of ports as energy transition hubs, focusing on three key areas. These gaps were identified through stakeholder dialogue and secondary sources, employing the framework laid out in section 2 with emphasis on the content, structure, and governance of transactions.

Offshore wind developers creating O&M hubs in ports

In 2019, offshore wind developer Orsted opened its ‘East Coast Hub’ in the British Port of Grimsby, thur greatly expanding the company’s existing offshore-related activities in the port. It is today the world’s largest offshore wind O&M centre, serving as base for Orsted’s six offshore wind parks in British waters (Westermost Rough, Lincs, Race Bank, Gunfleet Sands, Hornsea I, and Hornsea II) and providing more than 350 high-value jobs, mostly employing local workers from the Humber region.

2. PORT GOVERNANCE, PORT AUTHORITY RENAISSANCE, AND BUSINESS MODEL CHANGE

In the context of the present study, it is useful to think of ports in a narrow sense as physical locations and in a broad sense as complex organizations overseen by a central management entity, traditionally referred to as the port authority and more recently as a 'port development company' (the latter notion seeking to capture the changing role of ports with a stronger commercial focus and mindset). The perspective of ports as physical locations is what informs most policy debates around ports as critical infrastructure, perceived as assets that are vital to a nation's economy, functioning and safety and must be protected to maintain societal functions and citizen well-being. The perspective of ports as complex organizations would enrich policy discussions by considering the holistic nature of ports as intricate systems driving economic development and trade facilitation. Both the location aspects and the organizational dynamics are necessary constituents of port governance and business model innovation.

2.1 Ports as locations

Ports as physical locations for trade and industry, providing key infrastructure (e.g., quays, berths, docks, utility networks, waterways, rail, and road) and superstructure (e.g., office buildings, terminals, handling equipment, warehouses, storage areas, workshops, plants), could play a critical role in the clean energy transition.

Table 1 outlines some of the critical roles that ports play in the global clean energy transition and industrial activities. Ports are essential for the trade of clean energy products, enabling efficient import and export of renewable energy components, green fuels, and captured CO2. They serve as logistical hubs for offshore wind operations and manufacturing sites for large renewable energy components, contributing significantly to local economies and job creation.

Table 1: Examples of key roles that ports may play in the clean energy transition

Role	Description
Clean energy products trade	Ports are essential in the global supply chain for clean energy components and technologies (e.g., wind turbines and towers, solar panels, biomass reactors, conversion technologies, or batteries and other storage systems). They facilitate the import and export of renewable energy products, green fuels, captured CO2, and renewable energy system components (e.g., wind turbines, solar panels, biomass reactors, batteries). Ports' strategic locations and infrastructure support efficient movement of these large and advanced components, essential for the clean energy transition.
Renewable energy manufacturing and logistics	Ports may serve as logistical hubs for the operation and maintenance (O&M) of offshore wind parks and may attract significant investments from offshore wind developers, who may become major port tenants and finance the building of O&M facilities that will create high-value jobs and contribute to the economic development in port regions. Ports may also serve as marshalling areas for renewable energy installations and locations for manufacturing renewable energy components, which are often large and difficult to transport by land. Ports offer direct access to shipping routes and often also have land areas suitable for setting up large-scale manufacturing facilities for renewable energy components.
Port business ecosystems	Ports host maritime activities like shipbuilding, marine equipment supply, maritime services, and fisheries. They also accommodate non-maritime industries such as chemical plants, power plants, steel plants, car assembly, and food production. This creates opportunities for circular economy practices, waste-to-energy, and industrial symbiosis by facilitating recycling and material reuse.
Renewable energy generation and green Fuel Production	Ports are becoming renewable energy producers by hosting solar farms, wind turbines, and green fuel production facilities (e.g., PtX plants for hydrogen or synthetic fuels). This integration enhances energy efficiency, reduces carbon emissions, and supports cleaner energy systems.
Bunkering infrastructure	Ports are ideal locations for new fueling and bunkering infrastructure, including electric vehicle charging stations and green fuel distribution for ships and other mobile units. These facilities support the frequent refueling needs during port stays, contributing to the overall sustainability and efficiency of transport and industrial operations.

Ports are not merely points of transit; they are geographical clusters, or 'port business ecosystems' (de Langen et al., 2020; de Langen, 2023) hosting a variety of maritime and non-maritime industrial activities. Most medium-sized to large ports host a range of maritime industrial activities such as shipbuilding and repair, marine equipment supply, different types of maritime services, and often-times fisheries and other 'blue economy' industries. Some commercial ports may also serve as naval bases, although they are typically governed by strict regulations and a clear separation of operations. Non-maritime activities that are often clustered in ports include chemical plants, power plants, steel plants, car assembly plants, paper mills, food production companies, and companies producing construction materials, such as, cement, bricks, and tiles (Rodrigue and Notteboom, 2022). This provides for ample opportunities for ports to implement circular economy practices, waste-to-energy, and industrial symbiosis by facilitating recycling and reuse of materials and energy (De Langen and Sornn-Friese, 2019).

Furthermore, some ports are becoming renewable energy producers, integrating solar farms, wind turbines, and green fuel production facilities, thus reducing carbon emissions, enhancing energy efficiency, and transitioning towards cleaner energy systems. By embracing electrification and renewable energy generation, ports can significantly reduce their carbon footprint, improve sustainability, and become key players in the global effort to combat climate change (DNV, 2020).

Ports can also directly host facilities for green fuel production, such as, power-to-X (PtX) plants, which convert electricity into fuels like hydrogen or synthetic fuels (see also chapter 2 of this report), aiding in reducing carbon emissions from transport and industrial activities. For example, Denmark's Port of Aalborg is engaged in the development of supply facilities based on green fuels for the transport sector. Among other things, the Aalborg port authority is currently establishing a test area within the port perimeter, where Denmark's first large-scale PtX plant will produce 75,000 metric tons of e-methanol annually from early 2025 (Forefront Aalborg, 2022). Port of Rotterdam is similarly developing a network of hydrogen filling stations and installing hydrogen electrolyzers to produce green hydrogen for local consumption and export.

Finally, a port is an appropriate site for new fueling and bunkering infrastructure, such as, charging stations for electric vehicles or distribution of green fuels to ships and other mobile units, which require frequent refueling during their stay at ports.

In this narrow sense of focus on ports as infrastructure, a port's facilities and physical capacities can be understood as contributing directly to the clean energy transition, while serving national or local strategic interests and economic development.

2.2 Ports as complex organizations and elements in value driven chains

In the broader sense, the notion of a port would include the port managing entity (i.e., port authority or port development company) that manages it. Viewing ports not just as physical locations that provide critical infrastructure to an economy, but rather as complex organization, is to recognize that they are dynamic entities involving various stakeholders and occupying multifaceted roles beyond mere infrastructure. Acknowledging ports as complex organizations highlights the importance of stakeholder engagement, strategic decision-making, and operational efficiency within and, potentially more important, beyond ports. Such an understanding emphasizes the need for effective management, coordination, and adaptation to changing economic circumstances and global trade dynamics.

Port authorities are typically government or municipality-owned entities tasked with administering and regulating port operations. They often possess extensive governance powers, allowing them to ensure smooth functioning and growth of the port. Recent discussions in the port management literature introduce the notion of 'port development companies' (PDCs), marking a shift in perspective from traditional port authority roles and responsibilities towards more commercially oriented, flexible, and competitive models of managing and developing port infrastructure and services (De Langen and Van der Lugt, 2017; Van der Lugt, 2017; De Langen and Saragiotis, 2018). The notion aims to encompass port management entities that adopt market-driven strategies and seek to maximize revenue through diversified services. It can refer to both privately owned entities and traditional port authorities that have adopted or expanded their roles to encompass activities typically associated with port development companies.

Port managing bodies would indeed have a key role to play in the clean energy transition, as they can enact policies to reduce emissions within and beyond the port perimeter, invest in renewable energy infrastructure, or incentivize the use of cleaner technologies. They could also collaborate with municipal, national, and international government bodies, private enterprises, and other ports to facilitate the transition to more sustainable forms of energy. Thus, whereas ports as locations provide the necessary infrastructure, port managing bodies provide the governance, regulations, policies, and decision-making processes that guide and develop activities within and beyond the port (including often the investments needed to enable and accelerate transitions).

Port governance involves decisions regarding a multitude of tasks and activities within the areas of port policy formation, public authority functions, technical management of port land, market and prizing, management of concession agreements, and emerging issues (Pallis, 2022). The importance of port governance is significant, especially considering the ability of ports to contribute to a smooth clean energy transition. For example, port governance plays a crucial role in driving wider societal transitions by creating collaborative platforms, regulatory incentives, and partnerships (Lind et al., 2023). Port governance is also essential for ensuring that ports are developed sustainably and that environmental standards are upgraded to support renewable energy and green fuel value chains.

Renaissance port management: Robinson (2002) has suggested that the understanding of port governance should change from a conception of a port as simply a geographical place that efficiently handles ships and cargo (within an efficient administrative and policy framework) to an elaborate conception of ports as complex organizations that are embedded in value-based chain constellations and create value by working together with key stakeholders. Such constellations can be regional, as for example in the case of cross-border renewable energy clusters (e.g., the 'North Sea Hydrogen Valley'), or extend across oceans (e.g., the transpacific 'green shipping corridor' between Los Angeles and Shanghai). In such a view, ports are conceptualized as delivering value to shippers and other third-party service providers in the value-driven chain. How the individual port (or perhaps several ports in unusual collaboration) positions itself in the value-driven chain becomes a key question.

Particularly, ports 'will segment their customers in terms of a value proposition; and will capture value for themselves and for the chain in which they are embedded in so doing' (p. 252). This includes working with commercial stakeholders, such as, manufacturers and exporters that may not even be physically located in a port but who nevertheless rely on its services. As also discussed in chapter 6 of this report, such 'distant' stakeholders tend to focus on the economic benefits that the use of a particular can offer, such as low transport costs and high-quality infrastructure, while geographically closer stakeholders may pose different requirements to a port (e.g., how it handles social and environmental issues).

As ports search for new ways to create value, they must restructure their business models and processes to become more embedded in value-based chain structures. The notion of a 'renaissance port authority' (Verhoeven, 2010) emphasizes the emerging roles of the port managing entity in facilitating change, and even taking on entrepreneurial tasks beyond its traditional jurisdiction.

By fostering partnerships not only with entities within their physical boundaries but also with external stakeholders reliant on port services (e.g., manufacturers and exporters), port managing entities can significantly enhance their strategic value, contributing to more efficient and sustainable transportation and logistics networks.

Ports as locations for renewable energy components manufacturing and assembly

With the growing focus on offshore renewable energy, some ports become strategic locations for the manufacturing, assembly, and maintenance of offshore wind turbines and other marine-based renewable energy infrastructure.

Siemens has made significant investments in turbine manufacturing facilities in ports. In 2014, Siemens invested £310 million in an offshore wind turbine blade manufacturing, assembly, and servicing facility in the British Green Port Hull, which has since been upgraded with a further £186 million investment to produce increasingly larger blades. These investments were undertaken in collaboration with Associated British Ports (ABP) and have created more than 1,300 new local jobs and transformed the port into a world-scale hub for offshore wind.

In 2015, Siemens began building a £200 million manufacturing facility for wind turbines nacelles in the German of Port of Cuxhaven, at the maritime crossroads between the North and the Baltic Seas. The plant began production in 2017 and created around 1,000 new high-value jobs.

Offshore wind manufacturing developments are also underway in U.S. ports. In California, the Humboldt Bay area is being prepared for the construction of wind farms and the manufacturing of wind turbine components. In Port of Long Beach, the proposed ‘Pier Wind’ will be a massive facility for the manufacturing and assembly of offshore wind turbines, including 1.6 million square meters of newly built land. On the U.S. East coast, the Kitty Hawk Offshore project will spur major investments in Port of Virginia’s Hampton Roads terminals and in ports along the southern North Carolina coast.

In Taiwan, the state-owned electricity company Taipower joined forces with the Taiwan International Ports Corporation (TIPC) to develop offshore wind manufacturing, assembly, and O&M facilities in the Port of Taichung. They will be hubs for several offshore wind farms in support of the nation’s ambitious offshore wind plans.

2.3 Business model defined

The evolving view of a renaissance port management, which emphasizes the deep embedding of ports within value-based chain structures, parallels the business model (innovation) agenda in the general management literature (see, e.g., Foss and Saebi, 2017; 2018) towards recognizing and leveraging the intricate web of value creation. In the context of ports, renaissance management entails a transformative shift from traditional, operationally focused entities to proactive, strategic participants in broader value chains. Similarly, the general management literature has increasingly focused on the importance of innovative business models that encapsulate not just the core business activities but also the active role of companies in creating, delivering, and capturing value through extensive networks and stakeholder engagement.

A business model (BM) can be viewed as an activity system, the design of which is based on three primary elements; namely the content, the structure, and the governance of transactions that a company has designed to create value by capitalizing on unique business opportunities (Zott and Amit, 2010). In broad terms, content refers to what activities are performed, structure deals with how these activities are linked and sequenced, and governance determines who performs the activities and where and under which sanctions and rewards systems they are performed.

- The *content of transactions* design element refers to the specifics of what is being traded (e.g., physical products, services, or information) and encompasses the tangible and intangible assets a company must have to effectively facilitate such exchange. This includes not only the goods and services but also intellectual property, proprietary technology, or specialized knowledge.
- The *structure of transactions* delineates the network of entities participating in the exchange and defines their roles and relationships. Particularly, value creating activities can be performed both within and outside the boundaries of the focal company and include interactions with partners, suppliers, and customers, thereby emphasizing the networked nature of business models. This includes the organizational framework, detailing whether the transactions are bilateral or involve a complex network of multiple parties. Moreover, the structure element describes how these relationships are organized, which could range from loosely to tightly coupled systems (see, e.g., Orton and Weick, 1990), and involve different organizational configurations (Mintzberg, 1993; 2023).
- *Governance* pertains to the mechanisms and systems that regulate the conduct and terms of the transactions. While 'governance of transactions' should be understood as something broader than 'corporate governance', the two are closely interlinked. The governance of transaction involves the legal and contractual frameworks that dictate the terms of engagement between the parties (e.g., service agreements, land lease agreements, concession contracts, joint venture agreements) as well as the informal norms and standards that guide behavior, alongside formal policies and regulations that enforce compliance. It also covers decision-making processes, control measures, dispute resolution mechanisms, and how risks and rewards are shared among the parties. A company's board of directors is intricately linked to the governance of transactions: The tasks associated with corporate governance (e.g., resource management, risk control, and maintaining external relationships) are fundamentally aligned with those required to manage and evolve the business model. The board's role is seen as custodial, ensuring that the business model is continuously adapted to meet strategic goals and stakeholder expectations (Page and Spira, 2016).

While a BM has been defined in many different ways, there is general agreement that it denotes a company's core logic for creating and capturing value (Nickerson et al., 2007): The BM specifies a company's fundamental value proposition(s), the market segments it addresses, the structure of the value chain required for realizing the value proposition, and the mechanisms of value capture that the company deploys, including its competitive strategy (Chesbrough and Rosenbloom, 2002; Teece, 2010; Foss and Saebi, 2015).

A value proposition describes a company's portfolio of products and services, and how it creates unique value to customers. For example, a port's value proposition to potential customers in the clean energy transition could include factors such as providing reliable access to renewable energy and green fuels, offering incentives for adopting renewable energy technologies, and developing specialized facilities and services for renewable energy customers. Customer value can stem from the unique features, benefits, or experiences that differentiate the company's products or services from competitors' offerings. Value creation is about more than just the final product or service, however, and encompasses everything from the initial idea to the delivery and beyond, including the relationships built with customers and the broader societal impact.

Achtenhagen et al. (2013) emphasize the importance of viewing value creation through the lens of the company's value chain, which consists of a series of activities that it performs to bring a product or service from conception to market and support. This includes the company's resources and capabilities, its value chain activities, its strategic positioning in the market, how it focuses on the customer (i.e., companies create value by understanding and meeting customer needs, preferences, and expectations more effectively than competitors), and how it engages in continuous innovation.

Value capture (sometimes referred to as value appropriation), on the other hand, is the process by which companies convert their value propositions into revenues (Clauss, 2017). For example, a port can generate revenue from clean energy customers through a variety of mechanisms, such as leasing land and infrastructure for renewable energy projects, charging fees for access to clean fuels and services, and earning a share of the revenue generated by clean energy operations on port property. The value capture process relates directly to a company's ability to generate profit and ensure its long-term viability. A systematic outline of value capture would include understanding of revenue streams (i.e., how income is derived through direct sales, licensing agreements, fees, advertising, and so on), pricing mechanisms (i.e., how the right price is determined), and the company's cost structure (i.e., the composition of the fixed and variable costs incurred to operate its business). Zott and Amit (2010) posit that, although closely related, business models and revenue models should be seen as analytically distinct, with the former aimed at total value creation for all parties involved and laying the foundation for the narrower value capture by defining the overall 'size of the value pie' (p. 218).

2.4 A business model innovation approach

Following from the above, business model innovation (BMI) means changing the logic between how value is created and how it is appropriated (Snihur et al., 2021). A BMI approach can be used to identify challenges and opportunities for ports to create value as facilitators of the clean energy transition. In this context, ports must create value for their stakeholders by providing advanced logistical services and renewable energy infrastructure and technology, and capture part of the created value for themselves. This implies that ports must develop compelling value propositions that bring value to the relevant stakeholders and generate cash flows and profits, and this may entail strategic initiatives beyond the traditional landlord governance functions of port authorities (Van der Lugt et al., 2015; Pallis and Notteboom, 2022).

BMI is not an easy and straightforward task for ports. While defining the value proposition of a port in the context of the clean energy transition must as a minimum entail decarbonizing the port's own activities (i.e., scope I and II emissions), it also involves the more fundamental question about what type of company the port aims to become (given the unique challenges and opportunities dictated by local circumstances).[8] Should the port managing body decide to continue operating the port as a traditional hub for the transshipment of cargo and focus mainly on providing renewable energy and green fuel options for shipping and trucking companies? Should that choice potentially include port user incentives to decarbonize shipping emissions outside of the port jurisdiction (i.e., scope III emissions)? Should the port alternatively choose to become a storage or manufacturing location for companies in circular and renewable industries? Or would it be better to develop into a location for the production and distribution of renewable energy, say from offshore wind, and potentially also provide land for hydrogen production, ammonia synthesis, methanol production, and green fuel storage?

Each of such choices depends on a profoundly different BM. For example, Jurong Port in Singapore continues to operate as a multi-purpose cargo port and operator of one of the world's largest bunkering terminals but has amended its value proposition with a port-centric sustainability strategy to significantly reduce the port's own carbon footprint and integrate sustainability practices into the very fabric of its operations. This choice includes setting specific emissions reduction targets, aiming to achieve 62% carbon emissions reduction by 2030 from 2005 levels[9] and investing in solar photovoltaic (PV) panels on all rooftops to offset the energy consumption of port buildings.

A different business model has been developed by the Port of Amsterdam, aiming to develop specific areas of the port as an industrial cluster for circular and renewable industries. This choice includes reserving vacant land for specific activities and investing in tailored port infrastructure, and over a relatively short period this strategic choice has changed the port authority's revenue stream so that land revenues are now more important that port dues (De Langen et al., 2020). A similar approach was chosen by the Nantes Saint-Nazaire Port, the fourth largest

[8] For recent inventories of innovative solutions to decarbonizing ports, please see DNV GL (2020) and EIT InnoEnergy (2022).

[9] For more information, please visit www.jp.com.sg/about-us/sustainability/.

port in France and a significant industrial hub and multimodal logistical center in the Loire estuary region. Over the past decade, the French port has shifted its focus towards renewable energy and ecological transition and in so doing has diversified its operations to include new sectors (particularly offshore green hydrogen) and supporting innovative solutions, expanded its infrastructure and equipment, and transformed its business model by developing real estate and storage capability.[10]

3. CURRENT KNOWLEDGE GAPS

The following sections employ the above conceptual framework on the three categories of business model design (content, structure, and governance of transactions) and the accompanying revenue model. The framework serves as a foundation to delineate existing knowledge gaps concerning ports as hubs for the clean energy transition, identified through our analysis of media coverage, public discourse, and continuous stakeholder dialogue.

3.1 Content of transactions

As some ports globally transform towards becoming clean energy transition hubs, they have new opportunities to innovate and diversify their offerings, aligning with renewable energy targets and green fuel adoption goals and meeting the changing needs of their customers and other key stakeholders. The clean energy transition calls for a reevaluation of the roles that ports play. This transformation, underpinned by a business model approach with an emphasis on the content of transactions, involves several critical research avenues.

Initially, there is a need to redefine the identity and functionality of port managing entities to better align with the emerging roles of ports in the clean energy transition. Such redefinition will increase our understanding of ports' capacities to act as hubs for renewable energy and alternative marine fuel production, storage, and distribution, calling for an in-depth analysis of the potential, requirements, and broader implications of these roles. Furthermore, exploring the possibilities for ports to serve as energy nodes that link renewable energy and green fuel supply systems, both onshore and offshore, with non-maritime energy consumers is vital. This exploration should identify the potential and requirements for ports to effectively bridge these energy systems, thereby extending their impact beyond traditional maritime boundaries. In tandem, pinpointing new industries that could flourish within ports as energy transition hubs is essential, as these industries could drive the decarbonization of international shipping (including innovation, sustainability, and economic growth).

How should port managing entities innovate their offerings (products, services, and information) to align with the emerging roles of ports as clean energy transition hubs, and what impact does such innovation in the content of transactions have on facilitating the integration of renewable energy systems, green fuels, and new industries within maritime and broader energy ecosystems?

The clean energy transition for ports involves a multifaceted approach to increasing energy efficiency, promoting renewable energy and green fuel use, and reducing environmental impact. The increasing adoption of Onshore Power Supply (OPS) as an addition to the product portfolio of especially European ports is a significant step towards this transition, allowing ships to connect to the local electricity grid instead of using their engines while docked and thereby reducing GHG emissions, especially if the electricity used is based on renewable energy. It also reduces local air pollution thus leading to significant health benefits for populations living close to ports (FEFORT, 2022).

Additionally, the creation of a repository of proven port processes that enhance productivity, reduce waste, and improve environmental performance could serve as a valuable resource for ports worldwide. Such a repository would facilitate knowledge sharing and the adoption of best practices across the maritime industry. Lastly, crafting comprehensive guidelines on technical, organizational, and personnel training solutions is crucial for minimizing energy use and emissions from ports, thereby significantly improving their environmental footprint.

Each of the above services can be provided as standalone new services or they can be offered in some form of combination. As standalone services they would cater to specific needs, e.g., within the renewable energy and green fuels sector. For example, a port might develop a dedicated facility for the storage of green hydrogen only, serving as a critical node in the hydrogen supply chain. Similarly, it could offer specialized berthing services for vessels carrying wind turbine components, leveraging its unique capabilities and infrastructure to serve the OW energy industry. Such new standalone services would allow ports to target niche markets within the broader renewable energy sector and thus position themselves as key players in specific areas of the clean energy transition.

[10] For more information, please visit www.nantes.port.fr/en/port-professionals/cargo/energy-sector/new-energy-sources.

Combining services, on the other hand, would involve creating integrated solutions that cater to multiple aspects of renewable energy and green fuel markets simultaneously. Such an approach would target the interconnectedness of the clean energy supply chain and seek to offer a more comprehensive service package. Indeed, in their continuous search for new ways to create value and their corresponding efforts to restructure their business models and processes, transportation service providers have gradually shifted from their traditional focus on individual service strategies to a focus on service bundle strategies and creating 'bundle value' (Panou et al., 2015), i.e., customers perceive greater value because they receive a comprehensive solution that meets multiple needs simultaneously. Specifically, service bundling can be a strategic choice for companies to create added value and differentiate from their competitors, thus impacting their long-term business strategy. Applying the notion of service bundling strategies to the port business ecosystem and the strategies of the port managing entity, De Langen (2023) distinguishes between integrator service bundles and ecosystem service bundles.

3.2 Structure of transactions

The networked nature of business models refers to the interconnected and interdependent relationships between a company and its various external parties. When striving to adapt the business model of a port, it is key that port management collaborates with key stakeholders across the relevant value chain (see, e.g., Lu et al., 2016). Identifying knowledge gaps concerning the structure of transactions is pertinent in the context of ports transforming into clean energy transition hubs. Interdependencies determine how different activities relate and impact one another. For port managing entities, the activities surrounding the transition to clean energy hubs involve multiple stakeholders, such as, shipping companies, energy companies, regulatory bodies, technology providers, logistics companies, and various shipping intermediaries. The success of one activity (like green fuel bunkering) can influence the effectiveness of another (e.g., renewable energy infrastructure development).

How can port managing entities redefine their value propositions and operational models to accommodate emerging customer segments and integrate the key resources needed, while developing their stakeholder relationships and optimizing port operations and strategic goals (including, e.g., logistics and supply chain management, cargo handling and throughput, trade facilitation, and commercial development) as energy transition hubs?

Developing compelling value propositions as clean energy (transition) hubs requires ports to identify new customer segments, develop key resources (e.g., renewable energy infrastructure, technology, and talent) and activities, build strong relationships with their customers and other key stakeholders, and develop their marketing and distribution channels to properly reach their customers.

The transition of ports into clean energy transition hubs necessitates a paradigm shift from their traditional focus on customary maritime customers and tenants, such as shipping companies and commodity traders, to a broader and more diversified approach. If not developed, the traditional focus of port management entities on infrastructure and efficiency in cargo-handling can significantly impact their role as enablers of the clean energy transition. In the context of a rapidly evolving energy landscape, ports are required to extend their reach and adapt to the needs of emergent sectors that are central to renewable energy and green fuel systems. Ports, therefore, must investigate and engage with emerging sectors that contribute to the clean energy transition, but which may have been peripheral or are entirely new to their operational models in the past (e.g., companies specializing in renewable energy equipment manufacturing, biofuel production, hydrogen production and distribution, energy storage, and carbon capture and storage). These sectors bring with them unique requirements for infrastructure, services, and regulatory compliance, which are distinct from traditional port operations (Damman and Steen, 2021).

For instance, renewable energy equipment manufacturers may require alternative landing infrastructure, large storage areas, and specialized handling equipment for the assembly and transportation of renewable energy technologies and components (e.g., wind turbines). Biofuel production companies might necessitate facilities for the safe handling and storage of biofuels, as well as logistics services tailored to the peculiarities of biofuel distribution. Hydrogen production and distribution is an emerging sector that requires ports to handle high-pressure containers and invest in specialized pipelines and storage facilities that can safely store and transport hydrogen. Energy storage companies, which are critical for managing the intermittent nature of renewable energy sources, may seek spaces for large-scale battery storage systems and connections to energy grids. Carbon capture and storage (CCS) technology will require ports to facilitate the transport and storage of captured carbon, possibly in liquid form, necessitating a new set of infrastructure and expertise.

However, there is a fundamental gap of understanding the unique needs and contributions of these new customer segments and broader supply chain dynamics and becoming value-adding partners in broader value chains is a stretch for many ports. Once ports develop a thorough understanding of the specific needs and requirements of their tenants and other customers, they can make more informed decisions about how to allocate their limited resources (Anderson et al., 2006). Becoming customer-centric is however a difficult challenge, particularly as port authorities traditionally have regarded port infrastructure as their main value proposition and perceived of the port as simply a 'temporary parking space for goods coming in and going out' (Baker, 2019). Traditionally, therefore ports have tended to focus on optimizing their internal processes to increase economic efficiency[11]. Important challenges for port management involve becoming more conscious of the customer base that is dependent of the port and include the questions of how to better respond to specialized needs and requirements of port users and tenants and how to integrate further into multiple and increasingly complex supply chains.

Understanding the specific needs of these emergent sectors implies that port managing entities must engage in thorough market and technology research, forge new partnerships, and often make substantial investments in their infrastructure. This may involve collaborating with energy and technology experts to design port facilities that can accommodate the unique requirements of these sectors, revamping port operations to handle new types of cargo and provide value-added services, developing the business ecosystem within port areas dedicated to the clean energy transition to enable innovation and synergies, tailoring regulations and safety protocols to ensure the safe handling and storage of new forms of energy and their carriers, re-skilling and up-skilling the port workforce to prepare them for the demands of these emerging industries, and more.

3.3 Governance of transactions

Governance can have a significant impact on an organization's ability to carry out business model innovation. The question of how a particular port governance model limits or enables the ability of a port to regulate the conduct and terms of transactions between relevant parties and to engage in business model innovation with the aim to better facilitate the clean energy transition is thus key. Port governance models can vary widely – from centralized government control to autonomous, corporatized entities (and everything in between). Each model has its own set of advantages and disadvantages, and its success can be influenced by the economic, social, political, and environmental context in which it operates. Over the past half a century or so, port reform has changed the governance structures of port management worldwide, from primarily state-owned and -controlled forms of governance in most countries to various degrees of private enterprise involvement and corporatization of the port management body (Brooks and Pallis, 2012).

The landlord port governance model is today the most common model of allocating public versus private sector responsibilities in the provision of port services, with more than 80% of ports around the world being managed under this model (Notteboom and Haralambides, 2020). In this model, ownership of the port land remains with the port authority, which is typically a state-owned enterprise, while the infrastructure is leased to private operators, who then typically provide and maintain their own superstructure, employ their own cargo-handling equipment, and hire the needed port labor. As a landlord, the port authority remains responsible for the long-term development of the port area and the maintenance of basic port infrastructure.

The landlord model has the advantages that the long-term national, regional, and local interests as well as the connections and synergies with the city, region, and other sectors are secured through public ownership and operation by the port authority. At the same time, the outsourcing of port operations and various services to

[11] The focus on port and terminal productivity and efficiency is also evident in the academic literature on port business and port economics, which has tended to primarily emphasize port operations, throughput, and economic impacts of port operations (see, e.g., chapters 30-32 in Grammenos, 2010).

private entities ensures that the relevant actors each focus on what they do best when the best or the cheapest wins the contract. The vertical separation of port authority and port service provision under the landlord model allows for competition between different service suppliers in a port (Van Reeven, 2010), secures appropriate investments in superstructure, and raises efficiency in port operations (Brooks and Cullinane, 2006). Indeed, the landlord model has proven effective in raising the technical efficiency of terminal operations (Cano-Leiva et al., 2023). In this way, the ports ensure both public support and participate in the long-term economic development of a city or wider region economy, just as they contribute to ensuring the competition of private companies in connection with services in and around the port (Struensee & Co. and Blue Consulting, 2017).

At the same time, however, the landlord model implies some level of competition and potentially counterproductive conflict between the port management entity and the port tenants. Port management entities and port tenants thus often have complex relationships characterized by both cooperation and competition. In some ports, for example, the port management entity may itself, or through a port-owned subsidiary, own specific superstructure and cargo-handling equipment and operate certain maritime service (e.g., towage, dredging, logistics and warehousing, pilotage services, or terminal operations) in direct competition with private companies or favor certain private service providers over others. There may also be more general conflicts over access to and use of the port land area as well as competition in terms of securing funding, resources, or even government support for infrastructure projects and technological upgrade in ports. The extent and nature of such competition can vary widely depending on the structure of the port, the regulatory environment, and the specific roles and responsibilities defined by the government.

Brooks (2006) argued that no ideal model of port governance is intrinsically superior to others and that the effectiveness of port governance depends on various factors (e.g., local conditions, the specific needs of port stakeholders, and the broader objectives that the port aims to achieve). Indeed, given the uniqueness of every port in the European Union (EU), it is logical that not every port has the need nor the ability to adapt to changing circumstances in the same manner, although all ports have an increased focus on and are taking at least some actions towards sustainability. Especially larger ports, urban ports, and more industrialized ports are moving beyond the traditional landlord function and becoming increasingly 'entrepreneurial' and 'proactive' with regards to the energy transition and digitalization (Vonck et al., 2021). This perspective underscores the importance of flexibility, adaptability, and a tailored approach to port governance that considers the specific requirements of any given port, including its role in the national and global supply chain, the stakeholders it serves, and its long-term strategic goals, rather than the adoption of a one-size-fits-all model.

How do various port governance structures, including the landlord model, affect the efficiency and scalability of clean energy initiatives within ports, and in what ways can ports innovate their governance structures and mechanisms within existing regulatory frameworks to enhance their role as facilitators of the clean energy transition?

This calls for a more context-sensitive research agenda on port governance, recognizing the need to identify the right fit for the specific context and challenges of each individual port with a focus on identifying, analyzing, and fostering governance models that enable port managing entities to effectively contribute to the clean energy transition. Such a research agenda calls for best practice case studies of ports that have successfully transitioned into clean energy transition hubs as well as comparative studies of different port governance models. Identification of the specific factors within different port governance models that facilitate or hinder the adoption and innovation of clean energy practices and technologies within ports and by port authorities would be of research interest.

Corporate governance constitutes a separate but key area for management research in the context of the clean energy transition. Indeed, the corporate governance structures of ports, particularly the composition of their Boards of Directors, can significantly influence their ability to effectively support and lead in the clean energy transition. Unlike in the corporate world, where board members are typically selected for their expertise and experience in a particular industry, port boards often include politically appointed members or elected officials (Knatz, 2022). These individuals may bring valuable insights from the public sector, but they frequently lack specific knowledge of port operations, logistics, or the unique challenges associated with the transition to renewable energy and green fuels. This disconnect can create significant challenges in aligning the board's strategic direction with the operational needs of the port, especially when navigating the complex and rapidly evolving demands of the clean energy sector.

How can port authorities effectively navigate the complexities of governance when board members, often appointed based on political considerations rather than sector-specific expertise, may lack the necessary understanding of port operations and the strategic imperatives of the clean energy transition? What strategies can port directors employ to bridge this knowledge gap, ensure informed decision-making, and align the board's priorities with the long-term goals of supporting and facilitating the clean energy transition?

During our stakeholder discussions on port governance, further concerns were articulated. A central concern discussed was the question to what extent it should be the role and responsibility of port management entities to enable the energy transition, or if this task should rather be shared with or delegated to other entities? This question may challenge the traditional patterns of port involvement in value-based chain structures, especially within the context of the clean energy transition. It prompts further critical examination of existing legal frameworks (e.g., at national and municipal levels), which underpin the landlord model of port governance and may, in turn, limit the capacities of ports to actively engage in and facilitate the clean energy transition.

This concern highlights the need to study the legal and institutional constraints that delineate the operational scope of ports (within and across regions), potentially limiting their ability to innovate their business models and adapt their governance to accommodate the demands of clean energy, green fuels, and broader sustainability initiatives. Institutional inflexibilities (e.g., rigidity of legal frameworks) can impede ports from redefining their transactional governance to enhance efficiency, foster collaboration, and pursue sustainability goals more effectively. Consequently, there is an imperative to reassess and possibly reform institutional restrictions, enabling a more flexible and dynamic governance model that would better allow ports to not only navigate the challenges associated with the clean energy transition but also to seize new opportunities for assuming and sharing entrepreneurial leadership in the clean energy transition. Addressing these legal and regulatory challenges is crucial for developing a port business model that is resilient, adaptable, and capable of contributing significantly to the global environmental agenda.

2.1 Revenue model

Participants from diverse sectors within the maritime and energy value chains, who were engaged in our stakeholder workshops, demonstrated a profound interest in understanding the financial ramifications of the clean energy transition on the operational and revenue frameworks of ports, particularly as investments in clean energy projects is long-term and highly uncertain. There was a pronounced call for academic research to critically examine the current status quo, with a specific focus on delineating how the ongoing shift towards sustainable energy sources is influencing the revenue generation mechanisms of ports.

Taking stock of the present: How is the ongoing energy transition already impacting the revenue generation of ports?

The return on investment (ROI) for clean energy projects are likely to be highly uncertain and long-term, and ports may not only face difficulties in securing financing from investors who seek quicker returns but must also operate within a highly complex regulatory environment with potentially unstable and changing policy frameworks, which makes long-term strategic planning challenging. However, while ports might have to bear substantial upfront costs when investing in clean energy technologies and infrastructure (including retrofitting existing technologies and infrastructure), the long-term economic benefits for ports as clean energy transition hubs may also be considerable. Ultimately, ports could expect significant cost savings from reduced energy costs through the generation and use of renewable energy as well as lower operational costs by adopting more efficient technologies.

Beyond potential long-term cost savings, the clean energy transition also provides opportunities for ports to generate new types of revenue streams, significantly broadening their economic base and potentially reducing financial risks through a hedged product portfolio. In broad outline, the revenue model of ports traditionally revolves around port charges for basic cargo handling and ship services, additional value-added service fees, concession fees and land lease income, and public-private partnership models.

Cargo tariffs are fees charged for the handling and storing of goods within the port area. They can vary depending on the type, volume, and storage duration of the cargo. Port charges for ships are dues charged for using the port's navigational, docking, and berthing services and will depend on the size and type of ship and the port turnaround time. Land leases contribute to port revenues through the renting out of port-owned property for commercial, industrial, or logistical operations, providing a steady income over longer periods. Value-added services are charged separately and may cover various port-related services in shipping operations, such as, customs-clearing (e.g., documentation handling, inspections, and payment of duties and taxes), security services (e.g., surveillance and monitoring, cargo inspections, emergency response), drydocks for ship repair and maintenance, supply services beyond traditional cargo handling and storage, environmental services (e.g., waste reception and processing, ballast water treatment), or services aimed at reducing shipping emissions and increasing energy efficiency (e.g., carbon credit trading). Ports can also charge environmental fees to promote sustainable practices (Lam and Notteboom, 2014).

The traditional revenue models for ports may be challenges by the unique requirements that come with the clean energy transition, and ports must therefore innovate their revenue models to stay competitive and relevant. Offshore wind projects, for instance, require large areas in ports for short-term leases and typically involve only a few turbine installation vessels, which make infrequent port calls. This is very different from the typical high-volume, high-frequency operations associated with conventional port activities, such as, container shipping and ro-ro traffic. Denmark's Port Esbjerg provides an illustration of how a new port revenue stream from offshore wind installations can lead to innovative revenue models and allow the port to capture a portion of the new value created as an offshore wind marshalling and offshore installation port. Identifying these unique requirements led Port Esbjerg to creatively shift its revenue model towards a pay-per-use model, focusing on offering flexible, project-based access to its infrastructure and services without necessitating significant upfront capital investment from its clients. This model facilitates wind turbine manufacturers and wind farm developers in conducting their operations more efficiently and cost-effectively. By providing storage areas, pre-assembly sites, and tailored logistic solutions on a pay-per-use basis, the port has managed to ensure that its customers only pay for the exact services and infrastructure they use, when they use them (PES Wind, 2022; Sornn-Friese, 2023).

How can ports innovate their revenue models to capture a larger portion of the value created in the ecosystem of the clean energy transition and sustainable maritime operations?

CHAPTER 6. SOCIAL DIMENSIONS OF THE DEVELOPMENT OF PORTS AS ENERGY TRANSITION HUBS

Petar Rosenov Sofev, Kirils Kondratenko, Boris Tsachkov, and Aleksandar Petrov Petkov

1. INTRODUCTION

The energy transition at sea and on land will lead to the adoption and handling of new green fuels at ports and various developments that will enable ports to become energy transition hubs. And while the adoption of this will have a direct and measurable positive effect on the climate and in most cases the local environment, their public acceptance and other social implications need to be not only acknowledged but also well understood and managed in an effective, just, and sustainable way.

Some port management bodies have taken on an active role as community managers (Chlomoudis et al., 2003), including for the energy transition. The focus of this community building and facilitation is normally on the organizational level (e.g., firms within the port area, local municipality, various civic organizations, and member associations such as docker unions). Ports have traditionally focused on stakeholders within the port area, including the port tenants that are their customers. However, with the green transition, the importance of engaging with stakeholders beyond the port area is growing, as closer cooperation will be required.

The main aim of this chapter is to identify the most important concepts and discussions in the literature and identify potential gaps that require further investigation. It draws insights from related industries (e.g., social acceptance of large infrastructure projects) to highlight the importance of investigating and understanding the needs of different stakeholders, their interactions and influence on the energy transition and the increasingly important role of ports.

1.1 Port stakeholders, stakeholder groups, and their interaction

Ports comprise nodes within large transportation networks, making them natural hubs for related businesses, thus ports can affect and be affected by a variety of stakeholders ranging from the private to the public sector and local communities (e.g., the port city) (Fobbe and Hilletofth, 2021). Naturally, different stakeholders influence the port in different ways and have different, sometimes conflicting goals and interests (De Langen, 2006). The success of a port may be heavily attributed to how the port management body manages its own relationship with stakeholders, and the relationship between individual and groups of stakeholders (see also chapter 5 of this report). Often, the difference between and complexity of the stakeholder mix raises the issue of conflicts of interest between them, which can subsequently lead to issues about future port developments (Langenus and Dooms, 2018). According to De Langen (2006), port development raises five most common conflicts of interest between various stakeholders:

- Environmental protection versus port development
- Urban development versus port development
- Labor conditions versus port development
- Resident interests (safety, quality of life) versus port development
- Overall economic development versus port development

Potential conflicts between stakeholders underscore the need for fair and efficient port management, which allows the port to effectively balance the value it generates among its various stakeholders. While identifying and distinguishing between stakeholders is important, it is even more crucial to understand the differences in the port's relationships with these stakeholders to adequately address their needs and expectations.

From the port's perspective, the primary factor that defines the needs and values of different stakeholders is the varying impact the port has on them – essentially, the balance of benefits and potential negative effects. Typically, the impact of the port is directly related to a stakeholder's geographical proximity to it. For instance, large international shipping companies benefit from the added value provided by the port but are often less affected by the negative externalities, such as environmental, light, and noise pollution. In contrast, local communities living near the port are continuously exposed to these negative effects unless the port takes sufficient measures to mitigate them.

Stakeholders farther from the port tend to focus more on economic benefits, such as low transport costs and high-quality infrastructure, and are less concerned with social and environmental issues. These 'distant' stakeholders, such as transport firms and end users of port services, often demand ongoing port development. On the other hand, stakeholders within the immediate vicinity of the port, such as local communities, prioritize social and environmental concerns (de Langen, 2006). Port city residents and environmental groups often find themselves in conflict with port development due to concerns over potential traffic congestion, reduced quality of life, and other negative externalities.

Additionally, as a port transitions from a local logistics hub to an international economic center, there may be 'benefit spillovers,' where the additional benefits generated by port operations are 'leaked to' other actors along the value chain. These actors, often powerful foreign entities, may use their influence to steer the port towards maximizing shareholder value. Meanwhile, the negative externalities, such as environmental degradation and noise pollution, remain concentrated in the local community, exacerbating concerns and conflicts over further port development (Notteboom and Winkelmans, 2003).

NGOs and local civil society groups are mostly interested in ports reducing their negative externalities (e.g., air emissions and overall environmental impact) and ensuring the safety of the port workers and residents (De Langen, 2006). A major concern is the air pollution from the port area, which could be coming from heavy industrial activities, machinery at the port, tugboats, or vessels maneuvering or at berth using their auxiliary diesel engines (Sorte et al., 2020). Some NGOs focus on the ports' impact on the whole supply chain and consider that ports have a major role in society to mitigate climate change and accelerate the adoption of green fuels, whilst also reducing the local environmental impact by providing onshore power supply (Transport and Environment, 2022).

An important stakeholder group is port workers. According to de Langen (2006), port workers are mainly driven by their needs for job security, high wages, and career development opportunities. Career development opportunities are especially relevant considering the green transition as port workers will need to acquire new skills to serve emerging industries at the port such as offshore wind. Some ports (e.g., Port Esbjerg) work with the trade unions to establish training programs for the dock workers . Similarly, Port of Felixstowe views employee training as an opportunity to maintain a higher level and wider range of services offered. The relationship with trade unions in this regard is seen as a prospect for sustained positive change of the port's operational and business performance (FEPORT, 2018). Clemence Cheng, CEO of Hutchison Ports, the company that owns Port of Felixstowe, has noted that through 'thorough training of highly skilled and customer-focused staff, [the port is] able to provide a service that is not only efficient and speedy, but also dedicated and individual' (Port of Felixstowe, 2012).

Ports must continually maintain their competitive edge by reducing the labor intensity of their operations, which often leads to gradual dismissals and layoffs, thereby shrinking the local workforce employed by the port. This trend, particularly noticeable in developed countries, weakens the clear and measurable positive relationship between the port and the local community by reducing the port's role in job creation. As a result, the port's public image among city residents may shift from being seen as a driver of economic development to a source of negative externalities (Parola and Maugeri, 2013).

To illustrate, the proposed framework (table 1) provides a combined overview of common internal and external port stakeholders and argues that the geographical proximity of a stakeholder to the port expands their needs to include values outside of the economic dimension, namely social and environmental. This is based on the above arguments that suggest that the exposure to negative externalities and diminishing local employment provided by the port challenges the conventional image of a port as an economic development hub and stresses the importance of a wider range of responsibilities.

Table 1. Geographic proximity of port stakeholders

Stakeholders and stakeholder groups

Non-Governmental Organizations

Transport firms

End users of port

National and supranational government and regulators

Academic and research institutions

Press and Media

Port shareholders

Suppliers

Local and Regional government and regulators

Local community

Local environmental groups

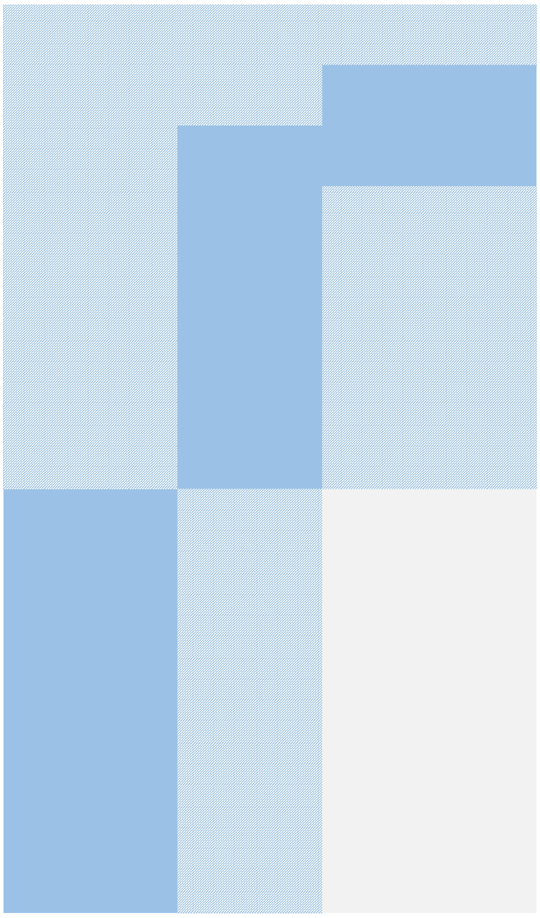
Employees within the port area

Port management

PA board members

Port related manufacturing industries

Geographical proximity to Port



Immediate *Close* *Distant*

Source: Inspired by Dooms (2019); De Langen (2006); Langenus and Dooms (2018).

Additionally, the needs of stakeholders are highly dependent upon how fair the distribution of benefits and value associated with the port's operation is both perceived and measured in actual terms. The benefit and value distribution may be direct or indirect, as well as stratified into economic, social, and environmental dimensions. Direct economic benefits are mainly reaped by port customers, whereas the local community would normally only receive a fraction of the economic benefit which would settle in the port community through locals employed in the port or the local businesses located in the immediate vicinity of the port, as well as hinterland industries adjacent to the community's area.

Table 2. Direct and Indirect value types

Value type	Direct	Indirect
Economic	• Value-added creation through port operation • Employment creation	• Fair distribution of benefits • Cluster development
Social	• Community-related events • Waterfront area redevelopment	• Investments in education and training • Establishing community consultative groups
Environmental	• Strategic land use, such as buffer zones and wildlife corridors • Restoration and compensation of lost environmental assets	• Environmental monitoring and transparent reporting • Global stakeholder networks and partnerships aiming to share sustainable best-practices

Source: Based on Notteboom and Winkelmans (2003)

The needs of local businesses and communities are closely tied to the balance between the benefits provided by the port and the negative externalities it generates. If the port management body can reduce the environmental impact of the port's activities while enhancing its own role as an active community builder, the needs of the community are more likely to be met. A key factor in achieving this is the fair distribution of benefits, which should acknowledge and address the concerns of stakeholders. Failing to do so could lead to stakeholder dissatisfaction, resulting in negative consequences for the port, such as public protests that might prompt actions from authorities, ultimately harming the port's competitiveness.

Recognizing the importance of creating social value, the port can contribute to community support both directly and indirectly. Direct contributions often involve sponsorships and organizing events or projects for community members. However, indirect contributions tend to create more long-term value for society. These include investments in education and training, which help the community grow and develop over time (Notteboom and Winkelmans, 2003). Ensuring the fair distribution of value and benefits is crucial for the sustainable development of the port and its stakeholders. Establishing mutually supportive and synergistic relationships can give the port a competitive advantage in the long term by fostering a cooperative community, a well-educated workforce, and efficient, loyal value chain networks.

To mitigate its negative impact on society and the environment, a port must actively pursue new sustainable measures. While some ports focus primarily on reducing their carbon footprint, others address broader sustainability issues, such as preserving natural heritage, supporting indigenous peoples, and protecting aquatic life. These efforts contribute to sustainability on different levels, with some addressing global challenges and others focusing on regional issues. De Martino (2021) categorizes these initiatives according to the specific sustainability challenges they address:

- Climate and energy (e.g., Port of Rotterdam—Zero Emission Services; The Northwest Ports Clean Air Strategy)
- Community outreach and port city dialogue:
    - Social dimension (e.g., Hamburg Port Authority—homeport) and
    - Environmental dimension (e.g., Port of Açu—Protecting Sea Turtles)
- Health, safety, and security (e.g., Port of Antwerp—Wearable device program)
- Governance and ethics (e.g., Ports Australia—Port Sustainability Strategy Development Guide).

Research suggests that some measures, such as tackling employment and air quality issues, are much more prominent in the port's sustainability practices, whereas some practices based on the specific conditions of the local environment are unique (Acciaro, 2015).

2. THE PORT-CITY RELATIONSHIP

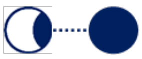
Ports and cities have historically shared a symbiotic relationship. Ports have often been the driving force behind the development of port cities—urban areas that originated and initially grew because of port activities. For instance, some of the largest cities in the United States, such as New York, Detroit, Boston, and Los Angeles, began as settlements centered around port activities and eventually grew into major cities. Although today, port activities contribute relatively little to their overall economic power (Fujita and Mori, 1996).

This relationship between ports and cities is evolving, especially in the context of the green transition. The shift toward alternative energy and green fuels for shipping and the broader economy, along with the potential for ports to become energy transition hubs, is creating a new level of cooperation and interdependence. For example, as energy transition hubs, ports could become even more integral to urban transport systems by providing refueling services for hydrogen-powered city buses, passenger and commercial vehicles, and regional trains. Additionally, ports can supply cities with district heating by utilizing waste heat from various industrial activities, such as Power-to-X (PtX) and ammonia production, as demonstrated by Port Esbjerg (European Energy, 2022).

Academic interest in the port-city interface took off in the 1980s. Hayuth (1982) defined the so-called port-urban interface as a dynamic and evolving relationship between a port and its surrounding urban area, describing it as a vacant space at the geographical frontier between port-owned land and urban zones. Over time, the interface has evolved to include various dimensions such as economic factors, social aspects, political considerations, technological advancements, and environmental impacts.

This naturally leads to varying interpretations depending on the perspective and dimensions considered. For instance, some stakeholders may focus primarily on the economic and geographical aspects of the port-city interface, while others, including the port and the city itself, may adopt a broader perspective (Daamen, 2007). Traditionally, the relationship between a port and a city has often been viewed as a source of tension between their development goals. Van den Berghe and Daamen (2020) suggest that this conflict arises from the tendency to see the port and the city as two distinct entities, separated by a clear boundary. In some cases, particularly with container terminals, this separation is reinforced by security measures that prevent local residents from entering or passing through the port, which can lead to a sense of social alienation from the port.

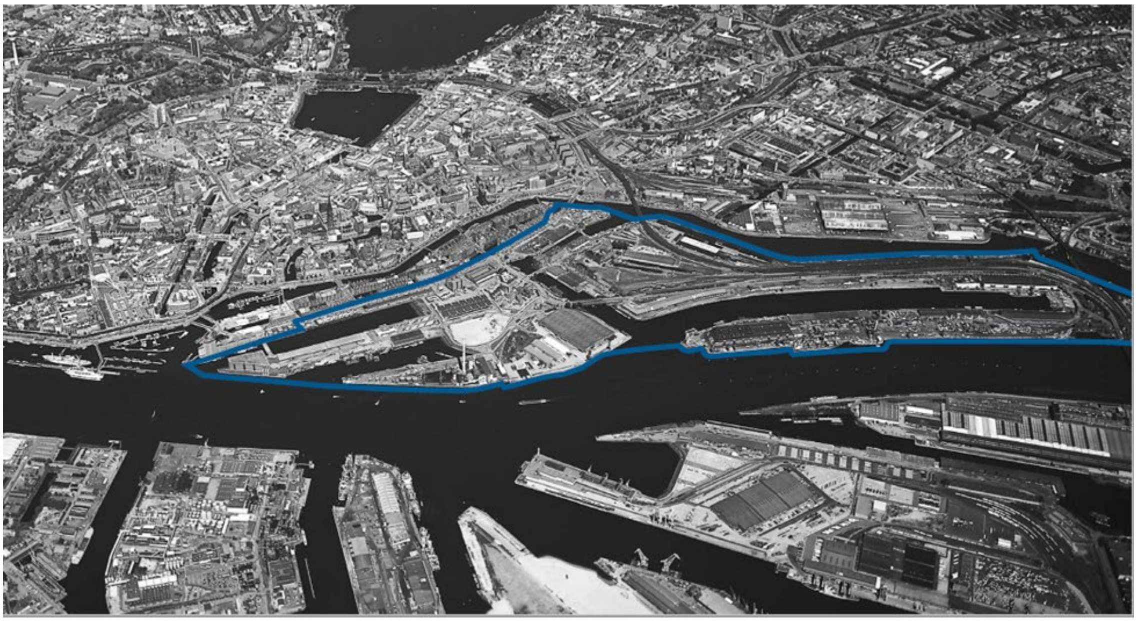
Table 3. Stages in the evolution of the port-city relationship

STAGE	SYMBOL ○ City ● Port	PERIOD	CHARACTERISTICS
I Primitive port/city		Ancient/medieval to 19th century	Close spatial and functional association between city and port.
II Expanding port/city		19th - early 20th century	Rapid commercial/industrial growth forces port to develop beyond city confines, with linear quays and break-bulk industries.
III Modern industrial port/city		mid-20th century	Industrial growth (especially oil refining) and introduction of containers/ro-ro require separation/space.
IV Retreat from the waterfront		1960s - 1980s	Changes in maritime technology induce growth of separate maritime industrial development areas.
V Redevelopment of the waterfront		1970s - 1990s	Large-scale modern port consumes large areas of land/water space; urban renewal of original core.
VI Renewal of port/city links		1980s - 2000+	Globalization and intermodalism transform port roles: port-city associations renewed; urban redevelopment enhances port-city integration.

Source: Hoyle (2000)

Ports increasingly face competition for waterfront space from other users, including commercial, recreational, and residential interests. The redevelopment of the London Docklands, which began in the 1970s and continues today, is one of the most well-known examples of transforming underutilized port land into a high-density urban area (Bell et al., 2021). Another example is the port city of Hamburg, which illustrates the later stages of the port-city interface as outlined in table 3. Here, the successful redevelopment of former port land into the HafenCity area is creating a premier mixed-use urban space, leading to enhanced integration between the port and the city. When fully developed, HafenCity will house more than 15,000 residents (HafenCity, n.d.), as shown in Figure 1. The successful transformation of former port land into vibrant urban areas stands as a leading example of the evolving port-city relationship.

Figure 1. Aerial view of HafenCity (highlighted with blue) in Hamburg, Germany



Source: Adopted from HafenCity (2006)

The closer spatial integration of the port and the city presents challenges for the energy transition because it 1) generally makes it more difficult for ports to obtain the necessary approvals for development projects, such as assessing the risks and safety of handling alternative fuels like LNG, hydrogen, and ammonia, and 2) increases the number of stakeholders with whom the port must co-exist and collaborate (Fan et al., 2021).

Furthermore, the fixed locations and physical boundaries of ports pose some challenges to their role in becoming energy transition hubs. For example, a port that wants to serve the offshore-wind industry will increasingly require more port space . However, in some cases, port expansion is physically limited by the urban areas (social dimension) on one side of the port and protected marine ecosystems (environmental dimension) on the other. Such is the case of the world's biggest offshore wind port, Port Esbjerg (Niras, 2020). Importantly, most port developments need to address several social and environmental factors. Traditionally the trade-off between port activities and developments and environmental impacts have been a major concern for society and have put a strain on the port-city relationship (De Langen, 2006).

2.1 Port-citizen relationship

It could be argued that ports are rarely well understood by the public and generally have a bad image of unclean and sometimes dangerous areas of the city. In many cases, citizens could be unaware of the economic and social benefits the port brings to the local community and rather focus on the negative externalities they directly experience such as air, noise, and light pollution. To mitigate this, ports today are increasingly aware of the public interest and try to ensure any new developments not only bring economic benefits (which are generally taken as a given) but are also in line with social and environmental issues (Notteboom et al., 2021). Furthermore, port management bodies are often viewed by the public as the main point of contact for complaints about negative externalities, such as noise pollution, occurring within the port area. This is the case even when the port management body may not be directly responsible for these issues, which might instead stem from activities carried out by one or more port tenants (Verhoeven, 2010).

However, ports can implement different strategies to improve their public image (Notteboom et al., 2021).

Organizing Port Days (inviting the public to the port area and hosting different activities for all ages) is a good way to improve a port's image. Port representatives can participate in different public meetings and highlight the benefits a port brings to the community. A port that adopts a green port management strategy and attracts green investment is also likely to improve its image. The increasing ambitions to participate in the green transition by, for example, becoming a leading offshore wind port could lead to gaining public support for ports and port developments, as citizens may feel pride in the port and the port city coming into the spotlight. The Esbjerg Declaration signed by Germany, Belgium, The Netherlands, and Denmark to develop 150GW of offshore wind by 2050 in May 2022 at Port Esbjerg and the subsequent positive publicity in local media, is a particularly good example (Martini, 2022).

3. BALANCING BENEFITS AND DRAWBACKS FOR THE LOCAL COMMUNITY

Ports and cities have historically developed as mutually beneficial and interdependent entities, and a synergic and dynamic relationship has followed the two throughout history. The geographical proximity of the port to the city is far from being the sole reason for their close relationship. The port-city relationship is shaped by a multiplicity of intertwined formal and informal networks and relationships that are based on values not limited to the economic domain. Concepts like the port-city interface as seen in table 3 include relationships within economic, social, political, technological, and environmental dimensions.

In practice, this means that even though a port may be as an independent business entity, it is still to the largest degree a part of local, regional, and global socio-technical systems. Nevertheless, despite the irrevocable importance of mutual development, there has been a noticeable rise in perceived alienation between the port and the port city community. While there is a multitude of causes, which not only differ from one case to another but also dynamically evolve over time for each case, there are some key drivers of port-city estrangement (see, e.g., Savoldi, 2024).

In the past, ports provided a tangible benefit to the community by creating a significant amount of direct and indirect employment. However, in many industrial and post-industrial economies today, there is a growing disconnect between the city and the port. This gap has emerged because ports no longer generate as many jobs as they once did, due to changes in cargo handling practices. As modern ports employ fewer workers, more people perceive the port as operating at the expense of the local community rather than for its benefit (Parola and Maugeri, 2013).

Particularly, the competition for a scarce resource – land – further intensifies the rivalry between the port and the city. Urbanization leads to cities growing in population and size, while ports face increasing pressure to expand as global economies grow. This is particularly relevant for ports that require more space, such as those specializing in offshore wind turbine installation, transshipment, and maintenance.

Additionally, industrial and port areas have become secluded and physically separated from the city by fences, customs outposts, and other barriers, depriving the city of access to and visibility of port activities. As a result, the local community, which is geographically bound to the area, is the only stakeholder that continuously experiences the port's negative externalities. Such dynamics shape the expectations of the port city community, who look to the port to deliver economic, environmental, and social benefits, as well as to create and distribute value.

The energy transition at sea and on land will lead to the adoption and handling of new green fuels at ports and various technologies that will allow for ports to become energy transition hubs. While the adoption of this will have a direct and measurable positive effect on the climate and in most cases the local environment, their public acceptance and other social implications need to be not only acknowledged but also well understood and managed in an effective way. Though some benefits and value can be material, objective and measurable, perceived values and benefits play perhaps as important a role. The degree to which the community can positively affirm the net-beneficial consequences of such developments is the key determinant of the direction that the transition would flow into, and as research and practice shows, the sentiments of the community can be hard to grasp and rather indecisive.

Two key factors were found to significantly influence public perception of the benefits associated with the development of renewable energy infrastructure: procedural justice and distributional justice. Procedural justice involves ensuring that the public is actively engaged at every stage of the project, typically through public consultations, hearings, and information campaigns. Many emphasize the importance of a transparent decision-making process that involves the community in a meaningful way to achieve a sense of procedural justice (Aaen et al., 2016). To meet citizens' expectations for procedural justice, developers should allow the public to voice concerns about issues like health impacts, property values, tourism, and the local environment, and should take genuine steps to address these concerns (Batel, 2020).

A transparent process, free from misinformation and public mistreatment, is crucial for fostering social acceptance (Segreto et al., 2020).

Distributional justice refers to the fair distribution of costs and benefits among individual stakeholders and groups (e.g., Segreto et al., 2020; Batel, 2020). Since the local community is often the primary stakeholder directly affected by the negative externalities of port operations (e.g., air emissions, light and noise pollution, and increased traffic congestion), the community tends to have the highest expectations for distributional justice. To meet these expectations, the port management body or the infrastructure developer must carefully assess the specific conditions and needs of the community.

Issues such as a lack of procedural justice or lack of distributional justice do not emerge spontaneously. Firstly to qualify for such resistance, the project developer should be seen as 'foreign' to the local community. For example, a project where the community is not necessarily a beneficiary is likely to be met with some resistance, whereas local grassroot initiatives are more likely to catch on. Some research highlights the need in democratizing the processes related to the energy transition, suggesting that the involvement of the community indirectly acts as a guarantee of both a certain level of public acceptance and a general positive and proactive attitude towards future green initiatives.

The material or measurable benefit and value may be stratified into economic, social, and environmental dimensions and can be shared directly or indirectly (Notteboom and Winkelmans, 2003). Value creation is a dynamic process and the value demanded is closely related to the process of development of a community. Acting in the role of a community manager, a port should therefore provide the full array of value and benefits to the community to maintain and promote their synergistic mutual development.

Furthermore, by increasing the involvement of the port within the community, it can also count on increased dedication of the community to promote the wellbeing and development of the port itself, as the fact of their symbiotic relationship surfaces and becomes directly visible to either party. Currently, many ports are becoming increasingly aware that economic value creation is not only seen as granted, but also insufficient in the eyes of the city community, and therefore strive to develop with social and environmental concerns in mind (Notteboom et al., 2021).

3.1 Cooperative ownership and public acceptance

Żuk and Żuk (2022) suggest that democratizing the clean energy transition by involving civil society more directly in green energy projects – such as through cooperative ownership – could accelerate the transition. Developing energy infrastructure under cooperative ownership models can provide access to non-market social resources (e.g., trust), which can lead to greater acceptance of these projects (Magnani and Osti, 2016). Community participation in green projects encourages critical voices that challenge traditional perspectives and promote the concept of 'energy democracy' (Żuk and Żuk, 2022). Community-owned energy generation is seen as a key element in democratizing decision-making processes related to societal transformations (Seyfang et al., 2010).

Polycentric governance of energy infrastructure (i.e., a decentralized and multi-level approach to managing and regulating energy systems) is believed to facilitate the coevolution of physical infrastructure and socio-economic institutions and actors (Goldthau, 2014).The modern concept of community renewable energy (CRE) projects spans from energy infrastructure owned by green cooperatives to co-ownership of green energy projects between local communities, enterprises, and the government (Magnani and Osti, 2016).

This raises the question of whether such ownership models could potentially be applicable and beneficial in the development of green energy projects in ports. However, there is apparently a lack of studies examining cooperative ownership models in relation to green energy infrastructure in ports specifically. However, involving the public in socio-technical changes aims to integrate different perspectives and secure public acceptance for energy projects (Scherhaufer et al., 2021) and is believed to raise awareness regarding energy issues and promote more sustainable energy consumption (Magnani and Osti, 2016). We can thus suggest that this could also apply strongly for any energy transition projects in ports.

4. GAINING PUBLIC ACCEPTANCE FOR INFRASTRUCTURE AND PORT DEVELOPMENT PROJECTS

A widely recognized concept that explains challenges in social acceptance is the "Not In My Back Yard" (NIMBY) phenomenon. As defined by Pol et al. (2006), NIMBY refers to the social rejection of facilities, infrastructure, or services that are necessary but carry negative associations. This concept describes situations where individuals may support an idea in principle but oppose its implementation if it occurs close to them – figuratively speaking, in their own backyard. In the context of energy infrastructure, NIMBY illustrates how a community that generally understands the need for new infrastructure and supports energy initiatives can still resist the development of such projects within their local area (Komendantova and Battaglini, 2016).Another way to think of the NIMBY effect is that the introduction of a new object into the local environment may create a dissonance in the perception of the locals who have an alternative vision of what their environment should be like. Subsequently:

> *"NIMBY is the motivation of residents who want to protect their turf ... [, alternatively, these are the] protectionist attitudes of an oppositional tactics adopted by community groups facing an unwelcome development in their neighborhood' (Dear, 1992, p. 288).*

These explanations unfold the inherent difficulty of tackling the issue of social acceptance, which is the difference between values of individuals that constitute a society. Practice shows that citizens exposed to the same project development, may interpret and respond to it differently, and either engage in a conflict or not (Aaen et al., 2016). Therefore, some scholars claim that the concept of NIMBY is overly simplistic and inaccurate, since it argues in favor of a generalized response to the same factor, yet many academic articles that investigate the social acceptance of energy infrastructure still reference the NIMBY concept (Carley et al., 2020). Certain strong arguments in favor of alternative approaches claim that NIMBY only covers opposition that stems from selfishness, ignorance, or irrationality (Batel, 2020).

Some types of opposition, alternative to NIMBY, may be classified as 'qualified resistance' which implies an approval of a proximate placement of infrastructure but demands some additional conditions that must be met (Batel, 2020). The debate about whether the NIMBY approach is adequate revolves around the fact that NIMBY implies the opposition of geographical proximity to an object, whereas some studies develop frameworks where new theories are applied and combined to understand the individual values and sensemaking that shape the acceptance or opposition (see, e.g., Aaen et al., 2016; Komendantova and Battaglini, 2016).

To address many of the potential concerns, conflicts, and solutions as possible, we will discuss the implications relating to the general concept of social acceptance alongside the NIMBY effect. Researchers studying social acceptance and the NIMBY effect in the context of renewable energy infrastructure generally agree on several key factors that trigger opposition. Maassen (2019) identifies the following contributing factors:

- Noise and other perceptible disturbances
- Landscape impact
- Damage to flora and fauna
- Health issues
- Lack of community involvement in the decision-making process
- Lack of financial benefits for locals
- Negative impact on local properties

However, the significance of these factors varies depending on the type of infrastructure, the affected population, political context, and other variables, making universal conclusions difficult. Despite this, this research has identified trends and gaps in the literature, which will be presented in the following sections.

Many scholars emphasize the importance of procedural justice and a transparent decision-making process that allows citizens to actively participate in projects that directly affect their lives and surroundings (Aaen et al., 2016). Traditional public engagement methods, such as plenum meetings with one-way communication, may give developers a superficial understanding of public concerns. Instead, addressing issues that matter to individual citizens may be more effective. Providing detailed plans, maps, and opportunities for direct dialogue between developers and the public is perceived by locals and stakeholders as a success factor (Komendantova and Battaglini, 2016).

Even if substantial public involvement proves challenging for developers, minor community involvement can still improve public perception and acceptance. Concerns and distrust often stem from a lack of knowledge; therefore, fair, transparent, and honest information sharing, along with opportunities for feedback, can build trust between the community and the developer (Segreto et al., 2020).

To satisfy citizens' need for perceived procedural justice, developers should allow the public to address and mitigate their concerns regarding health implications, property value impact, tourism, and environmental concerns (Batel, 2020). The need for transparency and public consultation is driven by concerns about potential negative visual and health impacts. Transparent information dissemination and community participation not only contribute to social acceptance but also help establish lasting mutual trust between developers and the community. Therefore, a transparent process free from misinformation and mistreatment of the public is crucial for gaining social acceptance (Segreto et al., 2020).

Additionally, some studies indicate that citizens want clear and transparent information about why their location was chosen and what are (were) the alternative options (Komendantova and Battaglini, 2016). Although there is general consensus among researchers in terms of the importance of informational campaigns on the social acceptance of an energy infrastructure project, there are indications that social acceptance may be politically compromised prior to the beginning of the campaign. For example, Komendantova and Battaglini (2016) observed in their study of transmission lines in Germany that public opinion was shaped by politically opposed entities before the developer initiated public consultations. This suggests that timely action is crucial in shaping public opinion.

Additionally, evidence suggests that citizens' political self-identification affects the level of acceptance of various energy types, suggesting that ideological conservatives are more inclined towards fossil fuels and nuclear energy, whereas ideological liberals are more likely to favor wind energy (Carley et al., 2020). Similar tendencies have been observed in other studies, where conservative and centre-progressive voters were found to be less supportive renewable energy adoption (Segreto et al., 2020b). Different countries and regions may have different political atmospheres, which may influence the trust and willingness to adopt renewable energy, as well as their tolerance for the costs endured by the community from the development of a project (Segreto et al., 2020).

Demographic composition and geographical characteristics of society also plays a role infrastructure acceptance. Higher levels of education and younger age generally correlate higher social acceptance (Segreto et al., 2020). However, younger citizens may be less likely to participate in informational events and may strongly oppose new infrastructure if they believe it is unnecessary (Komendantova and Battaglini, 2016). One study suggests that knowledge about an energy type increases support in 95% of cases but increases opposition in 5% (Carley et al., 2020).

In developing countries with unstable power supplies, citizens are more likely to accept renewable energy and associated infrastructure if it promises a more stable and affordable energy supply (Irfan et al., 2021). Some argue that citizens accustomed to industrial landscapes are more likely to accept new technological installations than those familiar with natural landscapes (Petrova, 2016, as cited in Maassen, 2019). Additionally, younger demographics, more accustomed to technological surroundings, may be less likely to view installations like wind turbines as negative landscape factors (Segreto et al., 2020b). These findings highlight the importance of demographic analysis in site selection for energy infrastructure projects, though local behavioral trends shaped by economic, cultural, and political environments must also be considered.

One of the other components of securing social acceptance is distributional justice, which requires a fair distribution of both the benefits and the costs for a given energy infrastructure project (Segreto et al., 2020; Batel, 2020). The formula for distributional justice is not set in stone and is highly dependent upon local subjective perception of justice, however, it follows some general patterns that may provide insight into ways to tackle this issue. The primary variable that constitutes perceived justice is fairness in the distribution of costs and benefits, which may be expressed both in economic (financial) and environmental terms. Studies show that communities that express genuine concern about their local environment are less likely to be motivated by financial support, nevertheless, depending on the circumstances, support in the face of lower energy rates and local employment creation may be highly advantageous (Segreto et al., 2020). Those citizens who identify themselves as having stronger place attachment are likely to be more cautious and hesitant regarding energy infrastructure development, however, this factor is found to have no significant influence on the respondent's choice to support or oppose a project (Bidwell, 2013).

Instead, it may be a deciding factor when it comes to the developer's potential approaches to distributional justice. Investigation of wind energy acceptance in Romania concluded that over 40% of respondents would view expert reports regarding the environmental impact of wind turbines as a motivating factor that would improve their acceptance, whereas only 27% would be motivated by financial benefits (Maassen, 2019). This reflects the trend within the respondent's attitude, which suggests that genuine concern for natural and health damages and potential disturbances outweighs the prospective financial stimulation.

Nevertheless, a study of social acceptance of wind energy in Michigan concluded that the primary factor that contributes to the acceptance of renewable energy infrastructure is the anticipated economic impact, further elaborating that the greater the economic benefit - the lower is the perceived negative impact on the landscape (Bidwell, 2013). Here the difference may lie in different meanings of said benefits, but regional preferences are likely to play a significant role.

In some cases, direct financial benefits may be seen as a way to bribe the public, which may in turn decrease the actual social acceptance, in such cases it is found that creating (even limited) employment for the locals may significantly increase their support (Segreto et al., 2020).

Table 4. Drivers of social acceptance

Prominent Driver	Sub-Category	Notes
Trust	Information exchange	Developers should share transparent and comprehensive informations
	Public involvement	Opportunities should be created for residents to be involved in the development process
	Procedural justice	Fairness should be guaranteed in resolving disputes
Distributional justice	Fair distribution	Costs and benefits should be fairly distributed between residents and developers
	Compensation	Direct or indirect financial compensation may be a good incentive
Siting issues	Physical characteristics	Residents may have issues with potential environmental or health impacts depending on the physical characteristics of the REP
	Emotional factors	Attachment to specific places may be a factor
Socio-demographic factors	Political atmosphere or community characteristics	Effects vary by country and are still not easy to predict

Source: Segreto et al. (2020)

Table 4 gives a comprehensive overview of prominent drivers of social acceptance and some of the potential means that developers may use to comply with society's demands. The following sections apply these driving factors of social acceptance on contemporary examples of energy infrastructure projects that are met with social resistance due to issues with social acceptance, including the NIMBY effect.

While many issues of social acceptance can be linked to the NIMBY effect, some forms of opposition to renewable energy infrastructure are not related to proximity but rather to disruptions in lifestyle and other impacts on well-being. A prime example is the installation of offshore wind farms in waters used for commercial fishing. In these cases, concerns about visual impact are minimal, but the indirect effects on communities can be significant. Such conflicts are occurring globally, particularly in the East Atlantic and North Sea regions, where the proximity of wind farms leads to the spatial exclusion of fishing areas (EU MSP, 2021).

Additionally, offshore wind farms can obstruct the navigation routes of fishing vessels. Although some operators attempt to compensate fishers, the compensation is often viewed as inadequate. For example, in France, a subsidy of 16,301 Euros per megawatt of installed wind capacity is distributed across the entire fishing industry, which is considered insufficient given the social costs involved (Ambec and Crampes, 2021). In August 2021, French fishers filed a complaint against the Saint Brieuc wind farm, citing hydraulic fluid leaks from the installation vessel that threatened scallop populations. The national court rejected the appeal, which fishers saw as evidence of favoritism and a lack of concern (Ambec and Crampes, 2021). This perceived lack of distributional justice, even if based on irrational fears, can create significant challenges for offshore wind farm developers, as many of these conflicts remain unresolved due to a lack of regulatory solutions.

Some projects, like the Baltic Pipe in Denmark, faced public opposition due to environmental concerns, despite their strategic importance. The Baltic Pipe project is a (currently finished) natural gas pipeline project that connects Poland and Norway. The main wave of the protests was spurred in 2020, where the opposition was driven by environmentalists who argued that Denmark's role in the project was inconsistent with the country's energy transition goal (Dogra, 2021). However, given the current energy supply crisis, particularly concerning natural gas, public opinion might now be more supportive of such projects. This highlights the importance of understanding how national and global political agendas influence public perception and suggests that the results of studying social attitudes can vary significantly depending on the political context.

Our above review of existing literature on the port-city interface has revealed several gaps and areas where further investigation is needed. One major gap is the lack of studies comparing public acceptance of similar projects across different countries. This absence of comparative research limits the reproducibility of findings and reduces their practical value for project developers. This gap may be due to the relatively low scale of renewable energy infrastructure deployment and the rapidly changing political environments that can influence public acceptance in a short time.

Additionally, there is a significant lack of literature that explores social acceptance in the context of both ports and renewable infrastructure together. This gap hinders our understanding of the potential social challenges associated with ports as energy transition hubs. However, it is reasonable to expect that more research in this area will emerge as more projects are initiated.

Moreover, the reviewed literature seldom addresses why certain factors influencing social acceptance are overlooked by developers. By focusing solely on societal perspectives, current studies provide little insight into why developers might avoid certain practices, despite the risks involved. The existing literature tends to concentrate on the same set of variables, often neglecting factors such as income and public support for renewable energy and related infrastructure. This suggests a need for future research to incorporate a broader range of variables, which could lead to a deeper understanding of relevant trends.

During one of mPATH workshops, an important questions was asked by a representative of a large green energy developer:

“What is society’s best interest?’

Defining the best interest of (a) society is a complex question, which could be very subjective and abstract. It is important to explore its various spectra to understand what truly makes a society and could enable smooth and beneficial governance and transition to green energy. For the purpose of this report, we can suggest the following definition:

“Society’s best interest could be defined as a just and fair distribution of resources and responsibilities, balancing present and future needs’

5. CONCLUSION

The development of ports as energy transition hubs presents a complex and multifaceted challenge that requires a deep understanding of the social dimensions involved. The transition to new green fuels at ports necessitates a comprehensive approach that considers not only the technological and economic aspects but also the social and environmental implications. As highlighted in this report, the concept of the port-city interface plays a crucial role in shaping the relationship between ports and their surrounding urban areas, encompassing economic, social, political, technological, and environmental dimensions. Furthermore, the literature review conducted in this chapter revealed significant gaps in the understanding of social acceptance in relation to both ports and renewable infrastructure. The current body of literature lacks comprehensive investigations into the social dimensions of ports' role as potential energy transition hubs, indicating a need for further research in this area. Additionally, the limited focus on certain variables, such as income and general public support for renewable energy and related infrastructure, underscores the necessity for a more inclusive approach to studying social acceptance in the context of port development.

Moreover, the role of port management bodies as community managers is paramount in addressing the social implications of the energy transition. Effective community engagement, transparent communication, and proactive measures to mitigate potential social drawbacks are essential for building strong and mutually beneficial relationships between ports and their surrounding communities. As the energy transition continues to unfold, it is imperative for stakeholders to consider society's best interest, defined here as a just and fair distribution of resources and responsibilities, balancing present and future needs. This holistic approach will be instrumental in guiding the governance and transition to green energy, ensuring that the social dimensions of port development as energy transition hubs are carefully managed and integrated into the overall transition strategy.

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