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Renewable Energy, Resilience, Digitalization, and Industrial Policies in Seaborne Transport

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Abstract: This paper delves into sustainability and energy policies influencing the governance and dynamics of global maritime trade. Resilience and sustainability are also discussed, along with the obstacles encountered and strategies to overcome them. The analysis underscores the importance of developing long-term strategies and participatory processes, focusing on government involvement in promoting structural changes towards a more sustainable seaborne transport system. Part of our research is also dedicated to outlining the different factors influencing this industry among different continents, highlighting the need for increasingly unified governance frameworks internationally. By incorporating resilience theory and new technologies, with a high potential in terms of GHG emission reduction, governments and firms can better engage stakeholders, ensure business resilience, and address climate change risks. This study concludes that ports have significant power in driving structural change, and modernization across various areas—such as digitalization, energy policies, safety, green fuels, environmental sustainability, and effective coordination—is essential for their continued development.

Keywords: trade flows; ports; renewable energy; territorial structural change; energy policies; industrial policy; transport; digitalization; energy efficiency; sustainability; green fuels; innovative technologies

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1. Introduction

Recent events such as US–China trade tensions, the COVID-19 pandemic, as well as the war in Ukraine have contributed to international economic uncertainty, impacting ports worldwide. To understand the potential for port development, it is crucial to assess critical trends shaping the industry. This paper aims to identify the factors fueling the growth of seaborne transportation. By exploring the relationship between port governance, renewable energy policies, digitalization, and industrial strategies, this research aims to highlight the emerging trends of maritime transport, particularly as the global economy becomes increasingly interconnected and leans towards sustainability. The first major tendency is related to the uncertainties surrounding future trade growth. As stated by the International Maritime Organization (IMO), the demand for cargo transportation is expected to grow globally by three to seven times by 2050. However, the OECD's International Transport Forum updated these projections in 2021, predicting a more modest two-fold increase by 2050 [1]. Nevertheless, it is undeniable that the transport sector is becoming a high-technology industry, which is fundamental to our economy, with 1.3 million public and private enterprises employing 10.2 million people and providing goods and services in the EU. Effectively, it has been observed that between 1995 and 2019, the volume of transported goods increased by 41%, while passenger transport rose by 33%. These data were recorded

before the COVID-19 pandemic, which caused a temporary decline (European Commission of Mobility and Transport). Notably, the transport industry has experienced significant transformations, making research and innovation vital for its continued progress. At the European level, consideration has occurred, particularly in aviation and maritime transport. Additionally, the internal market has fostered competitive international road haulage and expanded rail operations [2]; therefore, thanks to these data, which explain quantity and complexity of trade flows, it is now possible to understand the importance of developing and improving modern ports. Other significant trends regard the uncertainty over the effects of government policies or company decisions towards reshoring and nearshoring, the increasing protectionist measures announced by some major global economies, the production and use of biofuels, and the diffusion of electric vehicles. Amidst these emerging trends, it is worth noting that while international trade in goods and services displays a certain degree of resilience, it is the exchange of information—digitally ordered and delivered goods and services—that is increasing at a faster rate [3]. All these trends can have tremendous impacts on the role of ports, which partly explains the increasing emphasis on their development portrayed in the academic literature over the past decades. Numerous studies have explored Port Community Systems (PCSs), software platforms that connect multiple actors in port environments to enhance commercial exchange [4]. Research has also examined port competitiveness within supply chains [5], focusing on productivity and efficiency [6], as well as on the environmental and sustainable impacts of ports. Therefore, maritime transport is often considered a sustainable mode of transportation in relation to emissions per kilometer, although its environmental impacts are still significant [7].

Earlier reviews, such as those proposed by Robinson [8] and Notteboom and Winkelmans [9], provided in-depth analyses of port efficiency, primarily from an economic perspective. However, these studies lacked a broader, more holistic approach that incorporates crucial factors like industrial policy, as this paper intends to do.

This study seeks to fill this gap by evaluating how industrial and energy policies, investment strategies, and government regulations, such as sustainable policies, influence port development, productivity, and competitiveness. Additionally, this study will examine the broader role of ports as hubs that integrate global trade, promote industrial policy, and support economic growth through cross-border manufacturing and distribution. The goal is to provide insights into how ports can enhance their roles within global value chains, capturing value for themselves and the wider supply chain. In this scenario, Notteboom and Winkelmans [9] analyzed factors such as trade policies, government regulations, investment incentives, and strategic planning to understand how policy decisions influence port efficiency and competitiveness.

Port development is inherently tied to the expansion of infrastructural ecosystems. More specifically, in order to accelerate port development, it is essential to create “smart” infrastructural ecosystems, where efficiency, adaptability, innovation, and customer satisfaction are enhanced by lower carbon footprints. The aim of this idea is to reduce GHG emissions by taking precedence over trade levels, growth trends, or profit generation [10]. Therefore, it is possible to notice that ports play a crucial role in facilitating international trade and boosting national economies, as well as driving the implementation of new energy policies and structural adjustments. In certain cases, ports evolve alongside the cities they serve, forming “port cities” such as Rotterdam and Antwerp.

Today, as reported by the United Nations Development Program, 55% of the global population resides in urban areas, while 40% live within one hundred kilometers of the coast, placing them close to water-related hazards [11]. However, ports serve as critical hubs for integrating various cultures and economic knowledge within global value chains. They add benefits to shippers and third-party actors, supporting cross-border manufacturing

and distribution. Ports segment clients based on value propositions; consequently, they gain value for themselves and the supply chain they engage with [8].

In spite of this, the growing complexity of global trade networks also exposes ports to various risks, including those from unpredictable events, such as the COVID-19 pandemic; these events can lead to temporary port closures and significantly affect port governance. In particular, the pandemic highlighted the vulnerability of maritime connections [12], underlining the crucial role of ports. Therefore, it is necessary to understand their socioeconomic impact as essential structures within the global interchange system.

In addition, a key trend in modern port development is the growing emphasis on environmental sustainability and the development of new energy policies. The increase in port traffic poses a significant threat to the ecosystem, necessitating strategies that prioritize environmental protection and GHG emission reduction while balancing social and economic goals. Implementing a "green marketing" plan that integrates these goals is crucial for sustainable port expansion [7]. Alkhatib et al. [13] describe "green marketing" as a management strategy designed to meet consumer and business demands in an environmentally friendly and financially viable way. Consequentially, a port can market itself as a "green port" by integrating sustainability into its plans, operations, and organizational framework [14]. Given that port authorities possess significant capacity to enable environmental enhancements, new government policies are needed to achieve a cultural shift among the private and public parties involved. Moreover, strategies and energy policies that promoting environmental change among residents, leverage technology, and support international trade are necessary for a port to be recognized as green [15]. The adoption of "smart ports"—which maximize energy efficiency and reduce GHG emissions through digitization and intelligent systems—is central to this effort [7].

Moreover, due to growing public health issues, port authorities have more frequently engaged with ecological responses. The maritime industry, which contributes 2.1% of greenhouse gas emissions, with oil tankers alone accounting for roughly 28% of emissions from international maritime transit, faces significant environmental challenges [16]. Technological advancements and green technologies aimed at reducing fuel consumption, adopting cleaner energy sources such as liquefied natural gas and synthetic fuels, and introducing electric motors are among the strategies designed to level the environmental impact of shipping [17]; to that extent, studies on global value chains (GVC) demonstrated that effective environmental upgrading can be achieved by concentrating efforts on the entire chain, including the shipping sector [18].

Another significant aspect involves the impact of digitalization and automation on trade. For instance, The COVID-19 pandemic functioned as a catalyst for accelerating digitization of various port operations and enhancing communication within the port community and allowing business activities to continue during the crisis [12]. The digitalization of several production processes in logistics and transport, achieved sustainably and effectively, becomes a vehicle for significant structural changes, allowing for the substitution of specific skills (like manual or technical operations) with foreign ones, which may be more efficient [19].

Moreover, this study's in-depth analysis of the structural adjustments required in port governance provides a forward-looking perspective. By advocating for sustainable practices and technological innovation, it offers practical, evidence-based recommendations to guide port authorities in adapting to environmental and economic challenges. This paper also examines the structural adjustments necessary for port operations in the context of environmental sustainability, technological innovation, and the ecological challenges facing ports.

Therefore, to achieve these objectives, the analysis focused on articles that concurrently discussed port activity, structural change, energy, and industrial policies. The findings aim to identify emerging trends and gaps in the current research landscape. By analyzing these trends, the paper seeks to uncover how industrial policies are shaping the structural changes within port governance, particularly through the lenses of technology, sustainability, and resilience.

2. Ports as Drivers for Economic Growth and Structural Change

Ports are not merely logistical hubs; they are critical drivers of economic development, which encompasses the expansion of industries, creation of jobs, increase in incomes, and enhancement of infrastructure, all of that contributing to a higher standard of living. Ports have a prominent position in this process by reducing production and transportation costs, thereby boosting output, employment, and income [20]. Different scientific articles express interest in the responsibility of ports as key actors both in structural evolution and trade politics, as well as the framework of economic development. The identified trends highlight how ports are increasingly being recognized not only for their logistical functions but also for their broader impact on regional and national economies. Effectively, ports are recognized as essential components of economic systems that can shape industrial strategies and influence global trade dynamics.

The following section examines the interconnected roles of ports, industrial policy, and economic development, highlighting how strategic investments and well-designed policies related to port infrastructure can drive significant economic transformations.

In response to collective needs, many countries are increasingly developing industrial policies aimed at fostering the evolution of their industrial economies. These policies can be read as attempts to guide or manage structural changes [21–24]. The resurgence of industrial policies designed to stimulate profound changes reflects the current context of industrialization, characterized by intense interdependence, rapid technological advancements [25–28], and ongoing economic crises [29]. These factors necessitate the adoption of well-designed and innovative policies [30–36].

Industrial policies, according to Ferrannini et al. [37], play a pivotal role in addressing pressing social and economic challenges such as poverty, unemployment, and lack of human development. In other words, these policies are essential components of recovery strategies. Hakan Kaya [38] emphasizes that renewable energy investments should be prioritized to mitigate environmental degradation while addressing employment challenges, advancing what Di Tommaso et al. [24] describe as "socially sustainable" structural change—a transformation that preserves social equity, collective interests, and well-being.

Leading economists, including Justin Lin [39], Dani Rodrik [40], and Joseph Stiglitz [35], have recently advocated for industrial policy despite concerns raised by critics like Pack and Saggi [41]. Proponents argue that government intervention is essential to address market failures and social risks, while critics caution against potential missteps by governments. In this context, Ninni et al. [42] highlight a range of industrial policy tools that could help mitigate global instability and sustain structural transformation processes.

Historically, high-income nations such as the US and various OECD and EU countries have pursued industrial strategies focused on enhancing productivity and competitiveness, often at the expense of social objectives [37]. However, evolving global conditions demand a recalibration of industrial policy to balance productivity gains with broader social and environmental priorities.

In this framework, it is worth recalling that port logistics are essential for economic growth and serve as a key indicator of local economy health. Ports provide both direct and indirect value to the economy, especially prominent port clusters like those in Le

Havre and Rotterdam, which in 2007 contributed roughly 21% and 10% of the GDP of their respective districts [43,44]. This raises significant questions regarding the role of public ports in driving structural changes in the region and the industrial policy that is required to facilitate these transformations.

The implementation of port network strategies involves a range of methods, from loose coordination between ports to complex partnerships with other transport hub authorities. Recent studies confirmed that effective collaboration among these organizations benefits not just the direct stakeholders, but also the overall logistical efficacy of the port network. Given that ports and other infrastructures are essential to a nation's economy, they need to strive for more ambitious objectives with the aid and engagement of the State [45]. However, despite their significant logistical capacities, communication between the port authorities of nearby cargo terminals remains crucial, as it influences the broader organization of port administration management [46,47].

So, instead of being analyzed solely as technical infrastructures, ports should be considered components of a complex system where interactions, synergies, and conflicts are necessary to make decisions and formulate policies [48,49]. Furthermore, it is possible to identify intriguing realities of port cities where symbiotic processes have been activated by expanding the scope of the study to the territorial domain. Numerous studies conducted at macroeconomic level have demonstrated that the link between ports and cities leads to substantial economic growth [50–53]. Countries with maritime outlets seem to have 80% higher trade volumes and more growth prospects, according to Girard and Di Palma [54]. Moreover, ports play a vital role in paving the way for new business markets and promoting economic benefits typically distributed unevenly across business sectors and geographic areas. However, the facilitation of such activities usually entails a few subjects or actors who are involved beyond a local level [54].

To meet the demands of modern global trade, port facilities require substantial modernization, involving investments of hundreds of billions of dollars globally. Historically, European governments have invested in major port infrastructure projects; however, recent funding cuts are challenging even for the largest ports, making it difficult to remain competitive [55]. To address these challenges and ensure that ports remain competitive and profitable, it is crucial to foster resilient port competition through the adoption of innovative strategies and adaptive capacities. Additionally, it is essential to analyze how port governance can drive structural changes. The demand for reforms in technology, infrastructure, and environmental policies becomes evident in the quest to enhance resilience as a central feature of maritime facilities [56]. The strategic significance of ports is further underscored by developments in the Arabian Peninsula, located near the Suez Canal and major Asia-Europe routes. Regarding this, Saudi Arabia has launched a National Maritime Strategy as part of its broader National Transport and Logistics Strategy, aiming to strengthen the maritime sector and enhance its global competitiveness. This initiative focuses on developing port infrastructure, improving shipping and marine services, expanding the shipbuilding and repair industry, fostering maritime tourism, and promoting the sustainable growth of fishing and aquaculture activities. By implementing this strategy, Saudi Arabia seeks to leverage its strategic geographic position to facilitate international trade and contribute to the diversification of its economy [57]. Moreover, the Jeddah Islamic Port, built in 1976, has played a key role in the city's urban expansion, which has been influenced by government investments in infrastructure and fluctuations in land prices. Through continuous investments in capacity expansion and modernization, the port not only handles over 65% of maritime traffic entering Saudi Arabia but has also driven significant structural changes in the local economy. Its growth has stimulated the development of key sectors such as logistics, trade, and industry, transforming Jeddah into a strategic hub

for international commerce and accelerating the city's urbanization process [58]. Examples of this kind of industrial policy are also exemplified by China and Singapore, which have planned large investments to increase the ability of their ports and consider maritime trade as a component of their larger strategies for international development. Similarly, Africa is undergoing significant port industry transformations despite ongoing political unrest and economic challenges. On the subject, in the past fifteen years, various regions of Africa have experienced a significant influx of investments in ports, both from public and private entities. Recent estimates indicate that between 2004 and 2019, the total investment in port infrastructure surpassed $50 billion, an amount approximately thirteen times higher than that invested between 1990 and 2004. This trend highlights not only a substantial increase in investment but also growing competition among African nations in the fields of logistics and international trade [59,60]. Therefore, it is evident how governments have understood the economic importance of ports, so the investment decisions applied could be considered wise and appropriate.

3. Policies for Technological Innovation Within Port Logistics, to Improve Efficiency and Sustainability

First and foremost, logistics is one of the sectors involved in the innovation process, which is gradually moving toward sustainability, new energy policies, and technological innovations, especially in port cities. Technology has the power to promote sustainability by including green policies into production systems. It has been argued that technological advancement has the potential to balance economic and environmental gains, benefiting all stakeholders while reducing negative impacts on the planet [61]. By adopting sustainable practices in the use of innovative technologies, firms can not only register operational efficiencies and cost savings but also help the greater good by decreasing their carbon footprint, supporting social development, and influencing economic growth [62]. On the downside, innovation can cause unintended consequences, particularly as technologies gain more widespread use and as unanticipated impacts emerge. For instance, local policies adopted in many jurisdictions to introduce biofuels have affected global food prices [63]. Moreover, some major risks associated with technological improvements towards higher efficiency are related to the possible substitution of jobs with negative consequences on social sustainability and cohesion. If we keep exploring new modern technology, various studies have highlighted the opportunities of artificial intelligence (AI) for our society. For instance, AI solutions can help reduce pollution, waste, or carbon footprints; however, there are some risks associated with it [64].

Theoretically, these initiatives provide an in-depth understanding of the areas, objectives, and supportive factors that port cities must work with to encourage a responsible and green measures transition. These can increase stakeholder awareness and involvement, improving the efficiency of economic, environmental, social, and technological flows. The shift towards smart and sustainable logistics in ports aims to handle the growing volume of imports and exports, along with associated GHG emissions, in a digitally advanced and resilient way, with the goal of minimizing vulnerability and reducing environmental impacts on urban areas [65]. Several port cities have partnered with tech companies to implement these innovations. In addition, digital technologies have a pivotal role in the increase in the logistics industry. The digital revolution, started in the 1980s, is transforming the global supply chain, known as "Logistics 4.0". This evolution is driven by the growing use of computerization, AI, and cybernetics in production processes: it is no longer possible to separate digital trends from sustainability ones. The topic regarding the current energy crisis, geopolitical conflict, climate change, and limited natural resources influence the production of new technology and innovative instruments [66]. In this context, new business

models are expected to emerge in port cities, made possible by advancements in digital technologies. Indeed, experts estimate a new expansion of a global cargo control system in a space akin to the Internet, called the Physical Internet (PI). Thanks to PI, products would be transported impeccably on an intermodal cheaper complex. This will be due to advanced data management technologies.

One of the key accelerators of this vision, which is centered on innovative development, is the blockchain—a system designed to document an increasing variety of product or item properties. The supply chain must be prepared, and adequate aid is required within ports. These ecosystems provide unmatched opportunities to enhance coordination and optimize performance by seamlessly facilitating the flow of information, increasing visibility, and empowering decision-making abilities and strategic advancements. However, the involvement of multiple parties and the complexity of processes introduce a greater risk of vulnerabilities in marine shipments. Technological development has a crucial position in promoting international trade development: numerous innovative organizational, technological, cultural, and policy-related initiatives are found in the maritime port sector, simultaneously linked to multiple dimensions [67]. Innovations in ship-to-shore interfaces, hull and engine design, and integrated systems-based bridge management are just a few examples of how these improvements are taking shape. [68–71]. One of the main reasons for this growth is the proliferation of ships designed to transport thousands of increasingly uniform containers and their operation in ports. As a result, industrial policymakers have made the required preparations to reduce uncertainty regarding the direction of technology.

De La Peña Zarzuelo et al. [72] emphasize the transformative impact of emerging technologies in reshaping port operations and terminals. Their work highlights key projects that integrate digital solutions across the entire port ecosystem, ranging from urban areas and the port hinterland to the global supply chain and port authorities. The maritime industry examined the topic of digitalization, alternative fuels, and initiatives to change their business. The panel also underlined the urgent need for regulations and the relevance of introducing a level playing field in Europe to test and implement new technologies [73].; emphasizing that cybersecurity has become a valid solution to prevent bad events. Smart ports are becoming more connected, with various devices, agents, and activities working together, which is favored by the introduction of new technologies, such as the Internet, modern computers, and new software [72]. Innovative technologies such as drones represent novel technologies that can influence the maritime industry thoroughly: they are currently in use in ports, terminals, port limits, at sea, and other industry subdomains [65]. Key technological advancements include artificial intelligence and advanced software solutions such as [74] GPS tracking systems, which can localize every movement in the ocean [75] and drones, used to obtain information and capturing images [76]. Furthermore, real-time consumption and emissions monitoring stations contributed to register a decrease in emissions equal to 23% [77]. Additionally, other fixed and mobile digital devices such as vessels, bridges, antennas, port cranes, and warehouses improve efficiency and connectivity across the port ecosystem.

Therefore, information and communication technologies allow greater control of inbound and outbound flows, improving the circularity of goods and reinforcing customs security between countries [65].

Moreover, ensuring cybersecurity and professionally training a crew with the IT and nautical skills required to manage long-term sea voyages remotely are critical to consider. IoT (Internet of Things) and blockchain, two cutting-edge Industry 4.0 technologies, are of particular interest to seaports [78–80]. According to Yang et al. [81], the use of interconnections and sensors are the two main pillars of the IoT. These developments have enhanced the accuracy and dependability of devices that are helpful to collect temperature or geolo-

cation data, as well as interconnection via ICT networks. By enhancing data gathering, transmission, and consumption, object-applied technology helps seaports expand their present logistics activities, such as truck allocation or stacking, and establish new ones, like container tracking [82,83]. Yet, due to the numerous risks involved in shipping, which make it hard to plan predefined routes, there are concerns that autonomous ships will lose control and cause environmental disasters as well as severe economic harm.

The classification of ports has evolved alongside technological advancements, with fifth- and sixth-generation ports (e.g., Rotterdam, Shanghai, Singapore, and Hamburg) being the most prevalent today. Stakeholders expect these ports to provide higher-quality, more efficient handling services. Megaships, now a key part of logistics, rely on these ports to function as hubs without operational limitations. However, blockchain technology can be useful in collecting event data, since it facilitates collaboration, transparency, and interdependence among logistics processes in supply chains [84,85]. De La Peña Zarzuelo et al. [72], Wang et al. [86], and Henríquez et al. [87] have reported improved decision-making processes, power operating costs, traceability, security, and transparency, among other benefits from the application of blockchain technology in ports. Consequently, a multitude of functionalities, use cases, and business models are made possible by these two components [88].

Building on these advancements in supply chain logistics, the maritime industry is also being transformed by the development of autonomous ships. To that extent, although fully autonomous vessels are not yet operational, advancements suggest that such ships may eventually be remotely controlled from land. Level 4 autonomous ships—designed primarily for short-sea shipping and minimal human intervention—are being developed as part of the AUTOSHIP project [89]. Current debates focus on their true autonomy—which refers to high automation, potential impacts on maritime law, and the roles of crew members. These advancements promise to lower crew costs, reducing human error with positive implications for both economic efficiency and environmental sustainability, significantly influencing maritime operations. [89]. According to many authors, several accidents are caused by human mistakes: consequently, autonomy will reduce this matter. However, the complete absence of onboard crew raises significant legal and logistical issues, leaving the timeline for full implementation uncertain.

As already stated, digitalization has many benefits, but it also presents a risk of cyber-attacks, which could completely halt supply and service chains in international maritime trade [90]. Ahmad et al. [91] suggest that future research could focus on integrating neural networks to enhance machine learning and improve digital security. Furthermore, the maritime transport industry's persistent reliance on considerable human labor constitutes a critical vulnerability [71]. Despite technological developments, progress in reducing emissions remains limited: refueling tankers and barges would require the construction of new terminals, which presents significant logistical and social acceptance challenges. Nevertheless, research can help operators and port authorities work toward substantial cost savings and emission reductions by focusing on the use of hydrogen in land and water-borne transportation, the use of batteries for traction and support, the use and conversion of renewable energy, and consumption monitoring. A remarkable demonstration of this is the IMO Research Fund, created to support technology research but was unfortunately discontinued in June 2022.

Moreover, the implementation of sustainable and alternative energy technologies has recently influenced port operations, improving business performance. Among these technologies, LNG (Liquefied Natural Gas) has emerged as a critical transitional fuel in the maritime sector, gaining interest due to its potential to reduce emissions compared to traditional fuels. Despite the challenges, investments in these technologies continue, as

outlined in the objectives of the European Support Organization [92], being them crucial to improving ports' standing and relationships with cities. However, to facilitate the construction or adaptation of the infrastructure required to implement the use of LNG, financial incentive policies and cooperative development policies among the various stakeholders are required. Port authorities should also promote an awareness campaign to sensibilize the stakeholders on the topics [93].

Furthermore, the adoption of sustainable and renewable energy technologies has helped reduce dependence on non-renewable energy sources, like fossil fuels, while expanding the use of alternative ones such as ammonia, methanol, and hydrogen, which can be divided from fossil fuels, biomass or produced through electrolysis combined with carbon capture and storage (CCS) or direct air capture (DAC), referred to as e-fuels. Both biofuels and e-fuels have the potential to lower GHG emissions compared to traditional fossil fuels [94].

Environmental risk assessment and predictive models, enabled by digital innovations, support a conscious port business model. These technological advancements facilitate cost forecasting for sustainable operations, engage stakeholders in strategic decision-making, and help track policy effectiveness and port resilience [95]. Several positive effects have resulted from these changes: using conventional waste as an energy source has solved many problems associated with its disposal, resource flows and transformations have increased positive externalities, and pollution has been reduced [96]. Furthermore, reusing byproducts has decreased reliance on raw materials and finite resources [97]. The term "Smart Port," which lacks a precise definition but refers to technology management, digitization, the potential for more efficient operations, the integration of ports with cities, and the use of green energy, offers a contemporary perspective on the classification and development of ports and maritime transport. Thus, according to Karaś [98], to be defined as a "Smart Port", some social, economic, and technological innovations integrations are needed. Two perfect examples of "smart ports" are in Europe: the port of Hamburg and the Port of Rotterdam.

Consequentially, it is important to understand that adopting environmentally maritime logistics may greatly boost the benefits of sustainability, such as electrification, hybridization, and the use of alternative fuels [99]. To that extent, it is fundamental to evaluate the performance of the ships and the ports simultaneously to ensure a decrease in emissions from the port itself [100]. Research is being conducted on a device called Onshore Power Supply (OPS), or cold ironing, to reduce air pollution in port areas. By connecting to the quay's energy, ships must be ready to connect to this technology, which intends to enable vessels to cut pollution while in port. This technology obviously requires specialized installations in ports, which often struggle with associated costs, since most ships are not configured to receive shore power [101].

This is a crucial challenge for the development of European ports, most of which are urban. As a result, the port's social acceptability is significantly impacted by the problem of emissions and noise pollution. According to data from the Port System Environmental Energy Document (DEASP), all ports are equipped with the Cold Ironing process; all dockside activities are powered by electricity, depots have solar panels installed, ports and cities are connected by hinge areas, and sensor digitization is being developed through the Port Community System. Despite starting from a technologically outdated position in both LNG and cold ironing, the project, linked to the PNRR and supported by funding and research initiatives, is expected to overcome these difficulties and challenges.

Building on these technological foundations, the following part delves into how these innovations aim at improving climate change adaptability.

4. Building Resilience for Environmental Sustainability

Climate change is a crucial issue, particularly in relation to resilience, which can create opportunities for environmental sustainability and green technologies. It is undeniable that social and economic challenges will be significantly influenced by climate change. To that extent, building the adaptive capacities of coastal communities is key to addressing urgent issues like rising sea levels and extreme weather, as these communities appear particularly vulnerable to these changes [102]. In fact, when catastrophic circumstances occur more frequently and with higher intensity, the danger of transportation service interruption or delays increases [103]. Furthermore, this may be a significant problem as the port sector is vulnerable to cost-cutting [72]. A multitude of environmental difficulties are presented by the port-maritime setting, such as the mounting pressure from diverse coastal activities that result in disputes and the deterioration of both natural and man-made habitats. In addition to these environmental concerns, the dynamics of supply chains and port competition exhibit complex, nonlinear behaviors, which can further destabilize the system. Profits and costs in the transportation sector are influenced not only by the volume of goods being transshipped or transported inland but also by various technological and market factors, including fuel prices, energy consumption, handling costs, and transport services. These variables make the system highly susceptible to external shocks, such as catastrophic events or economic crises, which can disrupt port operations, undermine efficiency, and have negative repercussions on transportation [104].

As we can observe in Figure 1, for example, despite a high density of ships being globally recorded along coastlines between 2012 and 2022, a noticeable decrease was also observed along routes from the equator to the poles, primarily due to extreme navigational conditions, including sea ice, monsoons, and the distance of these routes from major economic hubs [93,105].

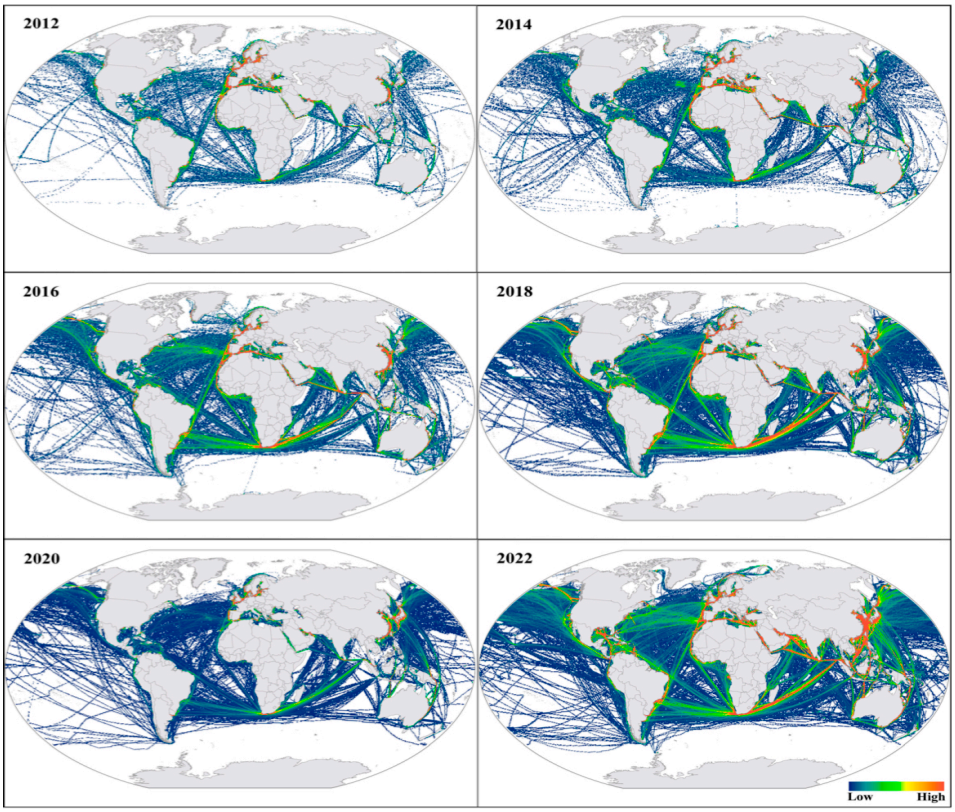

Figure 1. Global density of marine traffic, 2012–2022, by Xue Wang, Debian Du, and Yan Peng.

Global maritime traffic showed an overall fluctuating upward trend between 2012 and 2022, with key turning points: two major phases of decline were observed, from 2014 to 2015 and from 2019 to 2020, due to COVID-19 crisis [105]. Ship emissions pollution degrades air quality, exacerbating the global warming problem and harming human health. Approximately 3% of global greenhouse gas emissions are derived from the shipping industry, so the two phases of decline, described above, might be considered a benefit for sustainability, as air pollution is decreased [106].

Pollution derived from invasive species and declining marine biodiversity further underscore the vulnerability of the ecosystem. It is imperative to develop resources and innovative technologies to better understand how these changes will affect port communities more easily. The first tactic employed is the adoption of regulations that enhance the body's ability to adapt to and recover from occurrences such as rising GHG emissions. The second strategy is mitigation, which lowers harmful emissions, with the goal of contrasting climate change [102].

The climate effects of maritime emissions are also a major concern since ships carry 80% of the world's cargo, and ports are becoming increasingly important to the global economy. To manage the issues of social, environmental, and economic transformation, the city/territory system requires a new eco-friendly model, based on mutualistic and circularization frameworks. Through the density of the relationships it generates, symbiosis serves as a tool to strengthen and multiply ties at all levels, enhancing the system's potential for regeneration and rendering it more durable, efficient, and dissipative.

Progress has indeed been made in this context. As shown in Figure 2a, 15 chokepoints have been identified as fundamental due to their strategic position, located along key sea lanes, where they establish vital connections among major sea expanses. They also contribute to the strategic importance of the areas where they are situated and have a substantial impact on the sustainability and progression of global marine transport. Chokepoints with high volumes of maritime traffic gain strategic significance due to their greater ability to regulate vessel movement. To assess their relative importance, as illustrated in Figure 2b, yearly average maritime traffic data for each chokepoint were utilized to categorize the fifteen strategic chokepoints into five distinct classes [105].

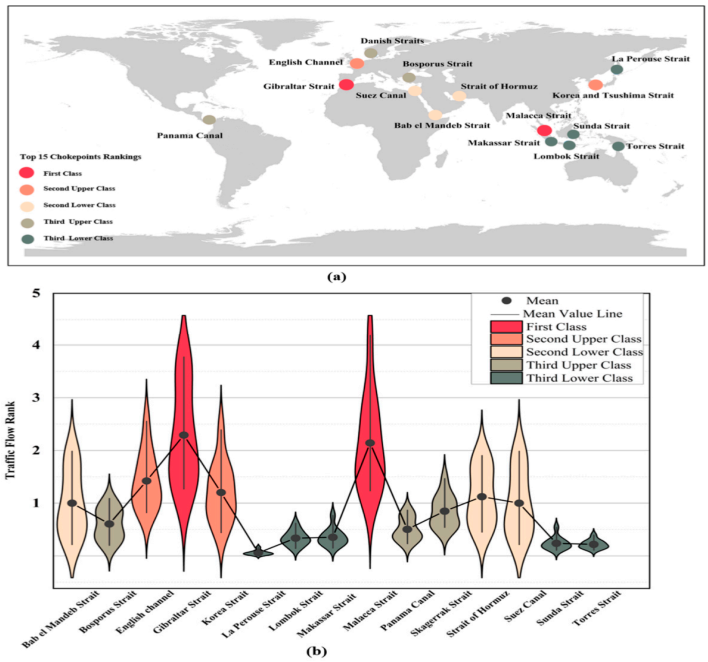

Figure 2. (**a**) Diagram of the 15 strategic chokepoints. (**b**) Ranking of strategic chokepoints by maritime traffic.

Given the high degree of concentration of flows around such areas, they become the natural candidates for large-scale and potentially internationally cooperative initiatives aimed at finding solutions that can both guarantee resilience and increased sustainability of trade flows. Moreover, chokepoints are crucial for global energy trade as they serve as key transit routes for oil, natural gas, and LNG. Major chokepoints handle significant volumes of energy exports, making them vital for global supply. Any disruption in these points can lead to price volatility and affect energy security worldwide. Their geopolitical significance further underlines their importance in maintaining stable energy markets [107]. In fact, these chokepoints play a crucial role as maritime transshipment hubs strategically positioned along key sea lanes, contributing to their strategic importance, and having a profound impact on the sustainability and progression of global maritime transport [105]. Understanding the long-term value of these straits is essential for creating policies that ensure stable and sustainable maritime trade, supporting global economic resilience in times of change [105]. If efficient and sustainable management of the transport of these flows through chokepoints is critical, the nodes in this system are the ports, which are fundamental. In the logistics chain, ports serve not only as connections to external maritime routes but also as essential hubs that link to larger terrestrial regions, facilitating the transition from sea to land transport, making them pivotal in the movement of goods. Therefore, it is crucial for port authorities and their stakeholders to take the lead in advocating for change. By implementing low-cost, clean energy-powered, zero-emission freight and passenger ships, ports can control energy use and emissions, reducing hazardous pollutants from machinery, ships, and other transportation vehicles. In response to these challenges, the naval sector faces an increasing number of national, international, and local regulations aimed at reducing environmental impact. Consequently, multiple ports are encouraging fleet and truck operators to transition to less polluting vehicles, sometimes providing financial incentives to support this shift [108]. Many ports must enhance energy efficiency due to stricter modern environmental regulations. So, nowadays the port industry is increasing the adoption of renewable energy and alternative fuels [109].

The main focus is the relationship between port management and environmental sustainability, emphasizing that improved port management can enhance the sustainability of maritime operations [110]. A key element in this context is Annex VI of the MARPOL convention, which provides a regulatory framework aimed at gradually reducing SOx (Sulfur Oxides) and NOx (Nitrogen Oxides) emissions from ships. These two gases, in fact, are major contributors to air pollution. Therefore, in order to contrast these emissions, onshore power supply systems would be useful in this context as they allow ships to shut down their engines while berthed and use electricity from national grids. Additionally, following the approval of strict regulations at the MARPOL convention, companies are being urged to consider LNG (liquefied natural gas) as a ship fuel because of its cost-effective and eco-friendly characteristics.

Another important aspect for ocean governance, the blue and green economy, and sustainable development is the control of underwater pollution; to that extent, the ports and the maritime sector have emerged as major players in this respect. Working together, ports—especially the ones located in the North Sea, Baltic Sea, and Mediterranean—can produce policies and procedures meant to reduce pollution in and around port areas. One of these programs, the National Port Master Plan (or UWNMP7), aims to guarantee that pollution and CO_2 emissions are managed using inexpensive and safe instruments [111]. According to Becker et al. [112], the latter would make it possible to recognize environmental threats and, consequently, implement plans to manage and track the port's stability, improving the evaluation of port operations. Environmental Policies, or EPs, are beneficial since they increase the port cluster's added value and reduce social costs. In alignment with

this approach, European ports are increasingly adopting principles of Industrial Ecology. IE examines the interconnections between environmental, economic, and societal systems, promoting technological solutions that balance environmental responsibility with economic growth. The framework also recognizes the role of socioeconomic factors in fostering environmental sustainability.

For instance, in Marseille, IE has been leveraged to attract new businesses and bolster local energy production. An additional example is Rotterdam, where the oldest IE initiatives have been actuated. Several research programs have been implemented here: one that identified fifteen synergy opportunities and concentrated on material and energy flows; another that produced the strategic plan "Vision 2010", for the ROM Rijnmond region; and the last one, "Port Vision 2030", which aims to reduce greenhouse gas emitted levels and reuse carbon dioxide emissions within the port industrial zone and eventually aiding the transition to eco-friendly industry. This allows for the optimization of the energy supplied to Rotterdam's residential buildings as well [113].

To reach the goal of a complete analysis, it is important to address the concept of resilience—originally defined as the ability of an organism system to restore equilibrium after an unsettling or disruptive event. This definition has since evolved to encompass the ability of any system or person to adjust and return to a stable state, even if that state differs from the initial equilibrium state. There are still differences in the resilience literature because each scenario can be used to explain a different nuance of the same phenomenon [114]. According to the UNO in its Report on the World Conference on Disaster Risk Reduction in Hyogo, resilience is defined as "the ability of a system, community, or society potentially exposed to hazards to adapt, resist, or change to achieve and maintain an acceptable level of functioning and structure". This ability depends on how well the social structure can reorganize itself to enhance risk-reduction tactics and draw lessons from past tragedies for enhanced safety in the future. The term "operational resilience" is then used by the UNO to assess a system's ability to adapt to both shifting conditions and abrupt, significant changes [102]. According to Messner et al. [115], resilience can be leveraged to promote business perseverance, boost stakeholder engagement through the adoption of new technologies and situational adaptation, and mitigate the risks posed by climate change, thus aiding in the achievement of goals in this field.

Continuing to explore resilience strategies, another important aspect that must be analyzed is the connection between ports and the urban environment. This relationship presents a complex challenge, as urbanization can hinder port efficiency while making urban environments more susceptible to the physical impact of port operations. However, port cities often show a reluctance to adopt a definitive position on climate change. In truth, sectoral activities only make up a tiny percentage of the potential and essential instruments for climate change adaptation strategies due to a lack of support for their implementation at all levels. The distinct rhythms and intensities of port operations, facilities, and coastal communities present additional challenges to balancing between federal regulations, coastal cities, and seaports. Although there are many opportunities and strategies available to support the entire port system in becoming climate-resilient, ports are generally reluctant to expect climate-related actions due to their expensive and overburdened infrastructure. For example, in Brazil, issues with costly financing and overly developed infrastructure make it difficult to implement environmental protection laws. Considering the cyclical nature of ecological processes, new legislation should reassess the city's structure. If these new laws are introduced, port areas will become more efficient through new development routes that benefit from economic viability and advance harmoniously with ecological processes. Specifically, several steps would be appropriate to the shift to a green economy [116].

PGOs and other national policies can adopt Nature Based Solutions to achieve Sustainable Development Goal 13, which focuses on combating climate change by using the UN 2030 Agenda as a guide. Area and Master Plans, on the other hand, promote port adaptation, which calls for establishing expansion trends to reduce and alter port infrastructure. Master Plans can be updated by setting up strategies for adapting to climate change, while Area Plans are the only ones with protocols related to climate change. The Master Plan, typically outlined in five years, takes into consideration the impacts of climate change on port operations and facilities [117]. The notion of "green ports" has surfaced in the most recent scientific studies, though it is still slowly developing [118], and it is one of the objectives to be pursued through the Recovery Plan [119]. Kirchherr et al. [120] claim that the circular economy contributes to sustainable development [121]. In addition to having a solid growth pattern and a strong scale effect, it involves balancing initiative-taking environmental practices with economic priorities using sustainable resources, aiming to reduce pollution [122].

From the standpoint of environmental sustainability, Moscow is mistreating the so-called Ice Silk Route or Northern Sea Route, which runs from Chinese ports and the Russian port of Vladivostok through the Russian coasts of the Pacific, Arctic, Barents, and White Seas to the port of Arkhangelsk in European Russia. Currently, these coasts have been free of ice for about half a year. However, due to global warming, this period is extending and causing the formation of a major sea route inside the Arctic Circle: one that is shorter than the ones that go through the Suez Canal, the Mediterranean, the Strait of Malacca, and the Strait of Aden, easier for the US to control. On the other hand, goods being transported by train over non-US-controlled lines linking China's ports and Pacific Ocean areas with Italy, Germany, and other EU nations take around 15 days [123]. According to Caroli and Soriani [124], to increase the sustainability of port facilities, additional actions are necessary, including limiting the efficiency of engines, reducing consumption, conducting research on green fuels, using more efficient ship designs, and slowing down. More specifically, shipping companies typically employ the latter strategy in times of crisis. In the medium run, fossil fuels will still be the mainstay of maritime transportation, despite having a serious negative influence on coastal and metropolitan regions, degrading the ecosystem, and contributing to climate change.

Given all these challenges, which illustrate how maritime authorities should improve the "green" strategies and energy efficiency, we can state that a sustainable port development requires a strategic and technologically driven approach. However, the literature highlights obstacles that interfere with the full port development, particularly emphasizing the critical need to optimize both land and sea areas, while taking climatic parameters into account for a sustainable port development. Consequently, due to topographical difficulties and the proximity to urban areas, resources remain insufficient, suggesting the limitation of port's expansion or the adoption of an offshore perspective [108]. Technological advancements offer solutions, enabling faster cargo handling, increased trade, and more efficient resource utilization [125,126]. Additionally, non-tariff barriers can facilitate trade operations [125]. This forward-looking focus on innovation positions technology as a practical means to counteract obstacles in port expansion, showcasing an approach that balances operational efficiency with sustainability.

Furthermore, another way to counteract the obstacles that limit port expansion is the development of optimal coordination among port authorities, concessionaires, operators, and ship owners. Public works are often hampered by insufficient coordination in investment choices at different government levels, which impedes a country's physical capital growth [45]. Competition for funding among ports may increase inefficiencies in maritime transport by causing congestion and rivalry [127].

To summarize, we can conclude that an effective port development requires a coordinated approach to overcoming both operational and structural challenges. In this regard, port authorities have a crucial role, serving as key drivers in implementing solutions for the complex obstacles outlined above.

5. Port Authority

The concept of port authority, extensively discussed in the reviewed literature, delves into critical issues requiring a meticulous analysis. Recent decades have witnessed reforms challenging traditional models, expanding the port authority's influence beyond the port premises [128]. In fact, the cost of doing business is increased by unnecessary bureaucracy and ineffective export and import processes. Errors in shipping declarations that lead to customs clearance delays and unclear shipping document complicates customs processes and prolongs delivery [129]. The reduction in these delays is attributed to corrupt trading practices; therefore, enhancing port efficiency through improved supervision by port authorities can be the solution [130]. Its objectives are to increase trade volume and lower the cost of maritime transportation [45].

Port authorities can actively participate in inland freight distribution, intramodality, and networking with market players by implementing strategies that involve stakeholder cooperation, long-term strategic planning, infrastructure enhancement, and skill development [131–133]. Improved management contributes to better logistics performance, leading to increased seaborne trade and economic growth. This is particularly vital for developing countries aiming to enhance their trade capabilities [134]. Efficient port management can significantly reduce maritime transport costs, thereby facilitating trade; to that extent, studies have shown that enhancing port performance in regions like South Asia could lead to substantial reductions in transport costs and boost trade volumes [135].

Moreover, port authorities play a strategic role in shaping energy policies to foster economic development, reduce GHG emissions, enhance competitiveness, improve energy efficiency, and attract investments to port regions. This role involves a multi-faceted approach that integrates infrastructure development, incentives, sustainability, and green innovations, all aimed at creating a supportive ecosystem for industrial growth. To date, only a few port authorities have realized energy management plans. Port authorities need to control their energy flow due to their responsibility in the improvement of commercial activities in the port, as well as from the growing emphasis placed on sustainability within port management strategies [136].

Effectively managing the interactions between maritime traffic and the environment is crucial to ensure the sustainability of port activities. Port cities face particularly the challenge of balancing their role as maritime hubs with the protection of local ecosystems and cultural heritage, given the intensity of port traffic and the environmental impacts of maritime navigation [137]. A paradigm shift in planning and design toward sustainability now prioritizes the port-marine relationship in new projects. This includes safeguarding critical assets, revitalizing waterfronts, and allocating funds for environmental restoration. Cities such as Venice exemplify these efforts by repurposing spaces for cultural events, educational institutions, and eco-friendly projects. These strategies contribute to Green and Blue Growth and circular economic initiatives [138], offering financial resources through self-sustaining, environmentally conscious investments that generate income and jobs. For instance, the landlord port authority model is currently being applied by the port authorities in Italy to manage the port through private terminal operators as a portion of state property, integrating public and private interests to ensure growth benefits all stakeholders [139].

Building on these sustainable and inclusive strategies, the direction of development for commercial ports reveals a parallel shift towards technological advancements that drive efficiency and environmental responsibility.

6. The Direction of Development for Commercial Ports: Examples of Best Practices

Many theoretical studies demonstrate that assessing sustainable development in the port industry is crucial for several reasons. According to Aksoy and Durmusoglu [140], ports can reduce health risks associated with air and water pollution by controlling and mitigating environmental impacts, ultimately contributing to healthier communities. In addition, ports can enrich local culture by preserving historic sites and hosting cultural events. A port is not only a center of economic business, but also a crucial hub of the transportation network. It matches economic, logistics, and industrial activities with the creativity of the inhabitants [141]. However, competing theories continue emphasizing the negative impact of ports on the environment. Ports contribute significantly to marine emissions, posing considerable health and environmental risks. The idea of green port management practices has recently emerged as an innovative method for balancing port economic growth with ecological issues [142]. The development of sustainable ports under the green port concept requires active involvement of local stakeholders. Furthermore, port developers must adopt strategies to mitigate the environmental impact of their activities, such as using renewable energy sources, implementing water recycling systems, and transitioning electric vehicles. These procedures help ensure that port operations are as sustainable as possible [143].

Europe's major ports are experiencing significant advancements in environmental sustainability, logistics, and technology, with resilience being a key factor in adapting to these changes. This shift enables ports to better withstand disruptions and respond to evolving industry demands through flexible and sustainable practices. One notable trend is the advent of autonomous ships, which will reduce the need for manual maintenance. Furthermore, handling exceptional situations is set to drive further growth at the port level. This resilience-driven evolution is closely tied to the deployment of 5G networks, which provide the rapid responsiveness essential for autonomous navigation. Consequently, many ports have initiated their own 5G projects to support this technological leap.

In addition to 5G, the Internet of Things is transforming port operations, as its networks provide ideal channels for robust communication. Key European ports such as Valencia, Hamburg, and Rotterdam are actively pursuing a lot of projects, enhancing connectivity and efficiency across logistics systems [144].

In Rotterdam, NextLogic- a bottom-up project created by and for the market- was essential to initiate their project. It consists of a data integration platform, which is focused on resilience and provides port optimization options to logistics and transport companies. Another important development in Rotterdam's port, the largest in Europe, is the Cool Port initiative: a logistics cluster for making port activities more sustainable and efficient. Due to recent growth in exports, the port has received new quality certificates based on sustainability factors like air quality, CO_2 emissions, and road transport reduction [145]. In addition, in 2023 Distro Energy, a division of the port authority, was launched. This department developed a smart and automated trading platform, which requires firms to trade the green energy that they produce [146]. Another example of a useful development tool for commercial ports is Avantida, a software developer. It also represents a crucial step as it strives to provide ship owners and other container owners with an effective method of using containers. Specifically, empty containers are repurposed by export operations so that their trips can be combined with full transport orders. If we keep exploring innovative and

modern realities, Akureyri, Iceland's second-biggest port, must be mentioned. It focuses on offering modern safety tools to the people, such as satellite tracking systems, environmental equipment, and emergency vessels. This is an example of how a modern port should combine environmental needs with customers' needs [147]. According to the website The Fishing Daily [148], it will be the first port in Iceland to electrify and reduce noise pollution and greenhouse gas emissions, ushering in a more environmentally friendly future.

In addition, CargoStream, a different data integration project that is an excellent illustration of co-innovation, needs to be mentioned: it depends on the participation of every supply chain player. Another example of port innovation is EuroTransCon, a ground-breaking concept that uses container exchanges to improve coordination and communication in road transportation. It allows empty containers to be filled close to the unloading site instead of being returned to the port area depots [149].

Finally, the most developed seaport in the Baltic States, Klaipeda, is known for its crucial role in the economic development of the region and for improving a sustainable society. This has become possible due to its modern scale industrial, which can satisfy the energetic and environmental needs [150]. Furthermore, the logistics development of Klaipeda's port emphasizes the geographical advantages and its political environment. Sustainability is promoted through planned interventions and by identifying waste and pollution sources [151]. This suggests resilience and growth, despite potential economic challenges discussed before, such as the modern factors that limit port expansion. If we focus on 2020, it was a record year and the best one overall, overseeing 47,743,409.4 million tons of cargo, with a growth of +3.2% [152]. Another example of growth is exposed during the five-year period of 2014–2019: bulk and dry bulk cargo handling grew by 6.91%, while general cargo and liquid cargo increased by 2.74% and 1.72%, respectively [152]. To summarize, these great performances indicate strong operational efficiency and strategic advantages, which reinforce the port's role as a key development hub. It would be logical to think that the impact of external factors, like innovation and sustainability initiatives, has influenced the analyzed results.

7. Port Policies Around the World

To gain more geographical insights, a further analysis has been conducted based on a corpora of 1352 English academic papers published in a broad timeframe ranging from 1961 to 2024. All sources were collected from the CORE database [153], a comprehensive bibliographic database of the world's scholarly literature and the world's largest collection of full-text open-access research papers. The collection process was conducted prioritizing objectivity and diversity. Thanks to the extensive metadata of the source, relevant results for our research have been selected using a thorough selection of keywords and topics.

The aim of our analysis was to identify the main focus of research involving maritime transportation across different continents, to further analyze which subjects raise most frequent interest.

As shown in Figure 3, terms regarding the subjects we analyzed in previous chapters occur with different values of frequency. "Sustainability", among others, is the most discussed topic, with 7 out of the total 30 visualized (i.e.,: "climate", "energy", "environmental", "impact", "environment", "impacts", "temperature"). Some of these, like "climate" and "energy", are also among the top three most frequent.

"Governance" follows behind, with five out of 30 (i.e., "management", "policy", "government", "law", "planning").

Figures 4 and 5 show the variety of topics discussed among all the analyzed papers in the different continents. The spotlight of research is surely on Europe, Asia, and North America; while South America, Africa, and Oceania stay under-represented. Analyzing

the topic of distribution, some more important insights arise. Sustainability, as expected, is widely covered among all regions, although particularly relevant in Oceania and Europe. "Governance" takes almost half of the focus in the South American continent, and "Social Impact" is particularly relevant in Africa. In Latin America, it is noticeable that the lack of attention to sustainable policy is signaling that nations' governments are following other priorities. Despite progress, many still see environmental protection and sustainable development as obstacles to economic and social growth. The South American port field, particularly in relation to container handling, has faced significant economic, social, and environmental challenges requiring continuous adjustments from both public and private stakeholders. These challenges have driven substantial shifts in strategies and structures within the port industry, revealing deficiencies in public policies. To address these issues, a market-oriented institutional framework is essential, with a particular interest in the cooperation between public and private sectors. This approach could help in the creation of a more balanced commercial environment, ensuring healthier competition and more efficient port management [154]. Environmental institutions are only beginning to develop the necessary skills to create effective policies across different sectors and regions. Their weakness is especially concerning when environmental harm is linked to exports and national economic strategies [155]. In addition, if we analyze the African territories, is it possible to notice that environmental policies only capture limited attention. Although there have been successes on the continent, including in policy frameworks and coordinating dynamics, there is still great concern over the general lack of a coordinated response to environmental issues [156]. Some of these risks may include poor governance and bureaucracy, high disease, absence of health care, wars, conflicts, and inequalities among the population [157]. This lack of focus towards sustainability may represent a missed opportunity for African regions, as the adoption of environmentally friendly technologies could offer a pathway for "leapfrogging" their economies and societies, building on the advantage of lower initial levels of pollution.

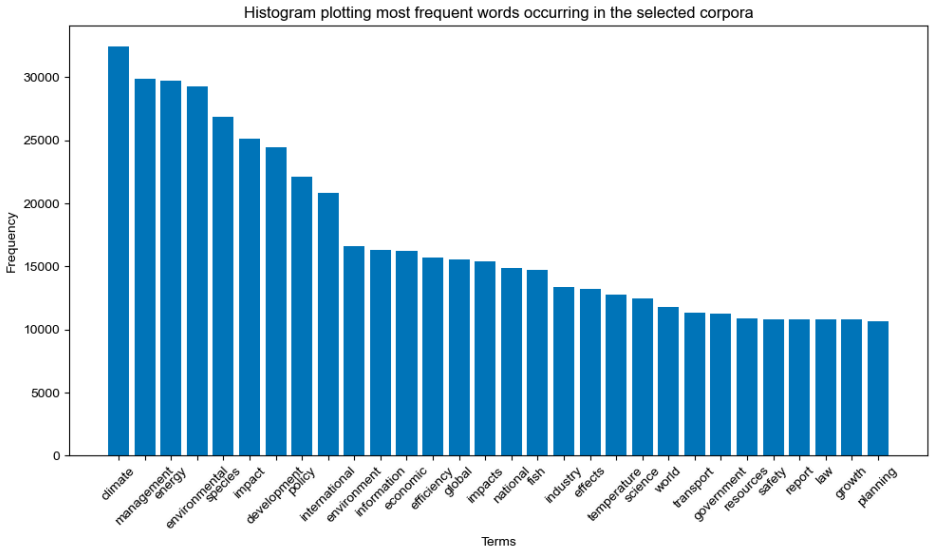

Figure 3. Histogram of the frequency of the 30 most used words.

While, as seen in previous chapters, maritime transport is mainly an intercontinental industry; widely diverse economic priorities, political frameworks, and environmental aspects make the global priorities of the industry divergent.

European ports distinguished themselves for sustainability and digital innovation, driven by stringent environmental regulation and supportive economic frameworks. Recent policies like the European Green Deal are playing a pivotal role in making ports such as

Rotterdam and Hamburg international examples for green technologies and adopting alternative fuels, such as liquified natural gas (LNG) and hydrogen. The port of Rotterdam, for example, has developed LNG facilities and can be considered one of the first ports where the "LNG bunkering to inland ships is legally regulated" [93].

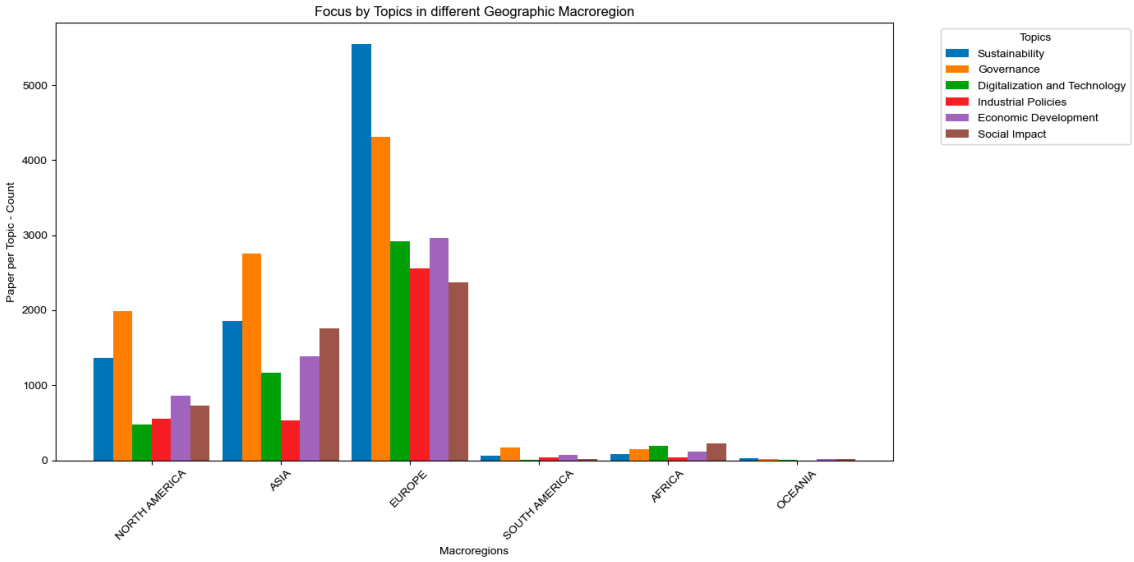

Figure 4. Histogram of frequency of different topics across different continents.

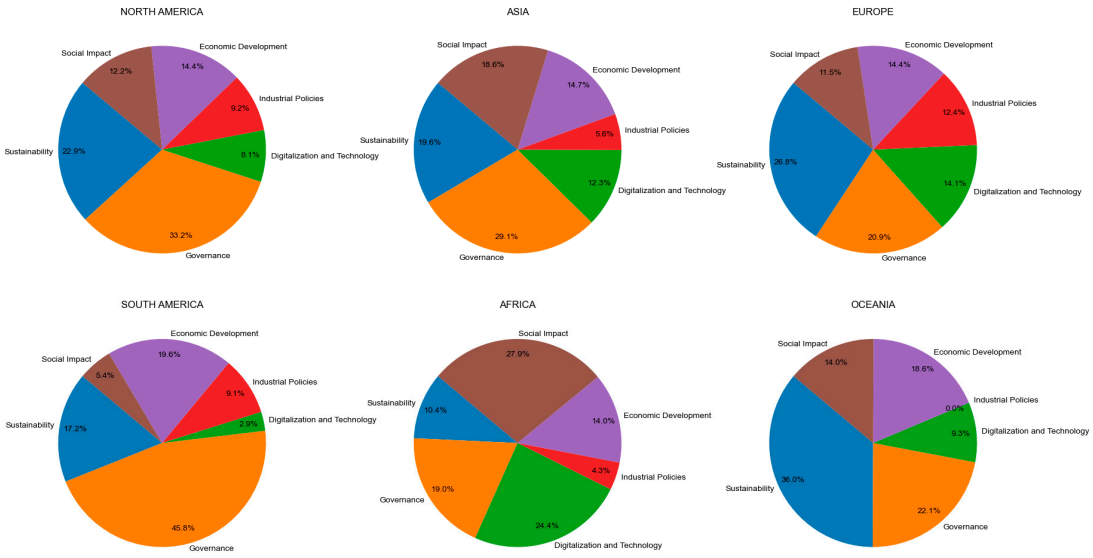

Figure 5. Pie chart of percentages of topics discussed across different continents.

Initiatives like Onshore Power Supply (OPS), which enable ships to connect to the electrical grid when docked, represent Europe's commitment to reducing GHG emissions.

Also, new technologies like 5G, the blockchain, or the Internet of Things (IoT) are being integrated to optimize logistical processes. However, European countries continue to struggle with reconciling the conflicting priorities of urbanization and port efficiency in densely populated regions [12,93,136].

Asian ports set an example of infrastructure development and integration with national economic strategies. Governance in these countries appears to be more often centralized, allowing faster implementation of economically strategic policies. Significant investments, particularly through China's Belt and Road Initiative (BRI), have established ports such as Shanghai and Singapore as global benchmarks for operational efficiency and

automation, with innovative technologies like autonomous vessels for increasingly smart logistics [5]. The port of Singapore is also significantly relevant when it comes to green technologies. In fact, through the Green Technology Programme, local maritime companies create and adopt green technologies, minimizing environmental impact and promoting sustainability [136].

Unlike most regions, ports across North America lack a centralized governance framework, but distinguish themselves for substantial private sector participation. For this reason, "Governance" frequently appears as a key topic in academic research, alongside "Sustainability". Such a model successfully implements progressive environmental initiatives. Among these, the Clean Air Action Plan (CAAP) is remarkable for its successful reduction of GHG emissions, through measures such as adopting cleaner fuels and electrifying port equipment [130]. The Vessels Speed Program (VSP) is significant in this context as well: it consists in a voluntary program established in 2001, whose main goal is to reduce gas emissions by ensuring that ocean vessels reduce their speed within a "20 nautical mile zone on approach to the ports" [136].

Despite this, ports in North America struggle with keeping up to date with their infrastructure technology and strengthening their supply chain resilience. The COVID-19 pandemic highlighted the vulnerabilities in the current system, like the urgent need for investment in advanced digital technologies and logistics to maintain seamless operations [19].

The recent economic progress of the maritime sector in South America reveals a narrative of uneven progress. While certain hubs, such as the Port of Santos in Brazil, have expanded their capacities for the increasing trade volumes, the region as a whole struggles to keep up with the integration of green technologies and digital infrastructure. These advancements are often hindered by governance inefficiencies and political instability, which continue to impede efforts to align with global standards in port development [20]. This controversial framework of governance is widely covered and discussed in the academic literature and needs to be addressed to stimulate the growth of the maritime industry in this area.

In Africa, ports are a crucial way of enhancing regional connectivity and driving economic development. Recent investments in facilities such as Djibouti and Lamu underscore the growth potential, particularly with initiatives like the African Continental Free Trade Agreement (AfCFTA). Nevertheless, progress is often obstructed by inadequate infrastructure and governance structures that are heavily dependent on external financing. These challenges raise critical questions about the sustainability and social impact of development in the region [11,111].

Ports in Oceania emphasize sustainability, reflecting the region's unique geographical and environmental characteristics. For instance, the Port of Brisbane has integrated solar energy solutions, like other broader initiatives aimed at reducing carbon emissions. However, the region's relative isolation requires substantial investment to sustain global competitiveness, explaining its secondary role also on academic research found [14,98].

This analysis of regional approaches to port governance underscores the fragmented nature of global maritime policies. While regions such as Europe and Asia have established themselves as leaders in innovation and infrastructure, others, including Africa and South America, continue to contend with foundational challenges in connectivity and development. Nonetheless, the interconnected dynamics of global trade emphasize the necessity for a more cohesive international governance to strengthen the maritime sector.

Existing frameworks, including the United Nations Convention on the Law of the Sea (UNCLOS) and conventions established by the International Maritime Organization (IMO), serve as foundational legal structures for international cooperation.

Despite these efforts, current measures remain inadequate to address pressing contemporary issues such as supply chain disruptions, uneven technological adoption, and competition among ports. A coordinated international governance framework is crucial for harmonizing policies, improving efficiency, and promoting equitable development across regions. Key priorities for such a framework should include standardizing regulations, fostering the sharing of advanced technologies, and expanding access to financing mechanisms to support infrastructure modernization.

8. Conclusions

In this essay, we examined the dynamics of global maritime trade and the crucial need for ports to improve new sustainable and energetic policies, as they face a more uncertain future, as evidenced by the pandemic and the following conflict in Ukraine, together with increasing digitalization of global trade flows. This study seeks to present a comprehensive understanding of the forces driving port innovation, the obstacles that hinder progress, and the energy and industrial policies connected to the modern need for a sustainable development that port authorities could adopt to reshape governance structures effectively. To this, we delve into critical areas of port transformation, including digital modernization, safety enhancements, environmental sustainability, green technology development, and the strategic alignment of various port stakeholders. After a careful review of the literature, we found that the ports are significant actors capable of affecting the mechanisms contributing to structural changes. As it emerges, modernization is essential if development is to occur in all fields, which will enhance port hubs and enable the implementation of new strategies by an increasingly involved port authority. What port authorities must focus on, therefore, is digital modernization (including investment in new skills and expertise in digital technologies—which are also needed to counteract potential social disruptions coming from technological innovations), safety assurance, the promotion of resilient environmental sustainability (sustainable waste management), the application of other green practices (the deployment of carbon management and storage, innovation support, investment in start-ups, pollution prevention), the development and use of alternative fuels, and active participation in the formulation of industrial and energy policies intended as policies acting on the structure of the economy towards the achievement of wider social goals [24,37].

Recent global crises and challenges have underscored the need for resilient nations, businesses, supply chains, infrastructures, and institutions. Ports, which suffered a downfall during the pandemic, are shown to be particularly important for the growth of this kind of environment. Therefore, port systems are supposed to be resilient to the pandemic if containment measures are implemented to maintain strategic relationships between the parties involved in maritime trade hubs, eliminating the infrastructure instability that harmed international supply chains during COVID-19. The introduction of new governance models aimed at guiding the management of the port community, meanwhile the resilience and long-term reliability of major commercial ports serve as indicators of their strength. Ultimately, this resilience should incorporate both environmental and social dimensions, reflecting the interconnected nature of port operations and local communities. Establishing policies that prioritize sustainable development, pollution reduction, and community engagement can create ports that are resilient not only operationally but also socially and ecologically.

Environmental risk assessment and estimation models, paired with digitization and new technologies, can track port resilience and evaluate the effectiveness of management and energy policies, involve actors in strategic planning, and forecast the costs of sustainable operations, all of which to promote the social and environmental model of port business.

The key role that the government can play was pointed out once again: promote and regulate the previously mentioned structural changes. Additionally, to construct long-term industrial policies, authorities must concurrently engage in the development of participatory procedures. Despite our best efforts, it is possible that our research has run into countless logical dead ends and that the solutions we have proposed are just theories, the value of which is demonstrated by the problems that exist today, and the issues assessed by risk estimation models. Similarly, issues that are not predicted now could potentially topple the robust port governance structure that we previously discussed. Therefore, we expect to continue our research in this field along with essential port infrastructure systems, which have not received much attention despite their vital role in preserving the parties' strategic relationships.

This study will provide actionable recommendations based on a detailed analysis of the sociocultural and environmental components involved in port resilience. This analysis should provide a thorough understanding of the mechanisms involved in accomplishing local and environmental development goals. To determine the gaps and resources available, this study should entail a multi-level assessment of the vulnerability of a specific context by considering different thematic areas. As suggested by Messner et al. [115], emphasizing digitization and the adoption of innovative technologies in the port context will enhance resilience theory, support stakeholder engagement, and facilitate the attainment of strategic objectives. To conclude, it is possible to hypothesize that these instruments would guarantee business resilience and the mitigation of climate change risks.

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Data Availability Statement: The data used in this study were collected from CORE (Knoth et al., 2023), a comprehensive bibliographic database of global scholarly literature. The dataset consists of academic research papers retrieved via the CORE API on 08/01/2025. The selection process was based on publication year, language, and title keywords relevant to "Maritime Transport and Infrastructure", including topics such as "Governance", "Sustainability", and "Technology and Innovation". The metadata of the retrieved research papers are available through the CORE API, while access to the full-text content depends on the licensing terms of each paper. Additionally, an appendix containing detailed analyses is available upon request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Gaulier, G.; Steingress, W.; Zignago, S. The role of China in the trade slowdown. *Rue Banq.* **2016**, *30*, 1–4.
2. Marcucci, E.; Danielis, R. The potential demand for a urban freight consolidation centre. *Transportation* **2008**, *35*, 269–284. [CrossRef]
3. Altman, S.A.; Bastian, C.R. *DHL Global Connectedness Report 2024: An In-Depth Analysis of the State of Globalization*; DHL: Bonn, Germany, 2024; Available online: https://www.dhl.com/discover/it-it/news-and-insights/reports-and-press-releases/dhl-global-connectedness-report (accessed on 7 February 2025).
4. Moros-Daza, A.; Amaya-Mier, R.; Paternina-Arboleda, C. Port Community Systems: A structured literature review. *Transp. Res. Part A Policy Pract.* **2020**, *133*, 27–46. [CrossRef]

5. Chang, Y.T.; Talley, W.K. Port competitiveness, efficiency, and supply chains: A literature review. *Transp. J.* **2019**, *58*, 1–20. [CrossRef]
6. Lagoudis, I.N.; Theotokas, I.; Broumas, D. A literature review of port competition research. *Int. J. Shipp. Transp. Logist.* **2017**, *9*, 724–762. [CrossRef]
7. Lim, S.; Pettit, S.; Abouarghoub, W.; Beresford, A. Port sustainability and performance: A systematic literature review. *Transp. Res. Part D Transp. Environ.* **2019**, *72*, 47–64. [CrossRef]
8. Robinson, R. Ports as elements in value-driven chain systems: The new paradigm. *Marit. Policy Manag.* **2002**, *29*, 241–255. [CrossRef]
9. Notteboom, T.E.; Winkelmans, W. Structural changes in logistics: How will port authorities face the challenge? *Marit. Policy Manag.* **2001**, *28*, 71–89. [CrossRef]
10. Haralambides, H.; Gujar, G. The 'new normal', global uncertainty and key challenges in building reliable and resilient supply chains. *Marit. Econ. Logist.* **2023**, *25*, 623–638. [CrossRef]
11. Jansen, M.; Hein, C. Port city symbiosis: Introduction to the special issue. *Marit. Econ. Logist.* **2023**, *25*, 211–229. [CrossRef]
12. Notteboom, T.; Pallis, T.; Rodrigue, J.-P. Disruptions and resilience in global container shipping and ports: The COVID-19 pandemic versus the 2008–2009 financial crisis. *Marit. Econ. Logist.* **2021**, *23*, 179–210. [CrossRef]
13. Alkhatib, S.; Kecskés, P.; Keller, V. Green Marketing in the Digital Age: A Systematic Literature Review. *Sustainability* **2023**, *15*, 12369. [CrossRef]
14. Lam, J.S.L.; Notteboom, T. The Greening of Ports: A Comparison of Port Management Tools Used by Leading Ports in Asia and Europe. *Transp. Rev.* **2014**, *34*, 169–189. [CrossRef]
15. Durán, C.; Palominos, F.; Carrasco, R.; Carrillo, E. Influence of Strategic Interrelationships and Decision-Making in Chilean Port Networks on Their Degree of Sustainability. *Sustainability* **2021**, *13*, 3959. [CrossRef]
16. Ascencio, L.; González-Ramírez, R.; Bearzotti, L.; Smith, N.; Camacho-Vallejo, J. A Collaborative Supply Chain Management System for a Maritime Port Logistics Chain. *J. Appl. Res. Technol.* **2014**, *12*, 444–458. [CrossRef]
17. Gössling, S.; Meyer-Habighorst, C.; Humpe, A. A global review of marine air pollution policies, their scope and effectiveness. *Ocean Coast. Manag.* **2021**, *212*, 105824. [CrossRef]
18. Poulsen, R.T.; Ponte, S.; Sornn-Friese, H. Environmental upgrading in global value chains: The potential and limitations of ports in the greening of maritime transport. *Geoforum* **2018**, *89*, 83–95. [CrossRef]
19. Savona, M.; Ciarli, T. Structural Changes and Sustainability. A Selected Review of the Empirical Evidence. *Ecol. Econ.* **2019**, *159*, 244–260. [CrossRef]
20. Ferrari, C.; Costacurta de Sá Porto, P. Port and local economic development: What direction of the impacts? *Int. J. Transp. Econ.* **2020**, *46*, 27–44.
21. Scazzieri, R. The concept of 'natural economic system': A tool for structural analysis and an instrument for policy design. In *Structural Dynamics and Economic Growth*; Arena, R., Porta, P., Eds.; Routledge: London, UK, 2012.
22. Scazzieri, R. Structural dynamics and evolutionary change. *Struct. Change Econ. Dyn.* **2018**, *46*, 52–58. [CrossRef]
23. Cardinale, I.; Scazzieri, R. Explaining structural change: Actions and transformations. *Struct. Chang. Econ. Dyn.* **2018**, *51*, 393–404. [CrossRef]
24. Di Tommaso, M.R.; Prodi, E.; Di Matteo, D.; Barbieri, E. Structural Change and Its Discontents. *Struct. Change Econ. Dyn.* **2025**, *72*, 438–455. [CrossRef]
25. Mehrotra, S.K.; Biggeri, M. *Asian Informal Workers: Global Risks, Local Protection*; Routledge: London, UK, 2007; ISBN 9780415382755.
26. Pietrobelli, C.; Rabellotti, R. Global Value Chains Meet Innovation Systems: Are There Learning Opportunities for Developing Countries? *World Dev.* **2011**, *39*, 1261–1269. [CrossRef]
27. Pipkin, S.; Fuentes, A. Spurred to Upgrade: A Review of Triggers and Consequences of Industrial Upgrading in the Global Value Chain Literature. *World Dev.* **2017**, *98*, 536–554. [CrossRef]
28. Bailey, A.; Singh, H.K.A.; Nusbaumer, J. Evaluating a Moist Isentropic Framework for Poleward Moisture Transport: Implications for Water Isotopes over Antarctica. *Geophys. Res. Lett.* **2019**, *46*, 7827–7837. [CrossRef]
29. Aghion, P.; Boulanger, J.; Cohen, E. Rethinking Industrial Policy. *Bruegel Policy Brief* **2011**, *4*, 1–8.
30. Bianchi, P.; Labory, S. *International Handbook on Industrial Policy*; Edward Elgar Publishing: Cheltenham, UK, 2006.
31. Bianchi, P.; Labory, S. *Industrial Policy After the Crisis: Seizing the Future*; Edward Elgar Publishing: Cheltenham, UK, 2011.
32. Chang, H.-J. *The Political Economy of Industrial Policy*; St. Martin's Press: New York, NY, USA, 1994.
33. Chang, H.-J. *Kicking Away the Ladder: Development Strategy in Historical Perspective*; Anthem Press: London, UK, 2003.
34. Di Tommaso, M.R.; Rubini, L.; Barbieri, E. *Southern China: Industry, Development and Industrial Policy*; Routledge: London, UK, 2013; Volume 87.
35. Stiglitz, J.E.; Lin, J.Y.; Monga, C. The rejuvenation of industrial policy. In *World Bank Policy Research Working Paper No. 6628*; World Bank: Washington, DC, USA, 2013.
36. UNIDO. *Annual Report 2017*; United Nations Industrial Development Organization: Vienna, Austria, 2017.

37. Ferrannini, A.; Barbieri, E.; Biggeri, M.; Di Tommaso, M.R. Industrial policy for sustainable human development in the post-Covid19 era. *World Dev.* **2021**, *137*, 105215. [CrossRef]
38. Kaya, H. Renewable Energy Investments and Unemployment Problem. In *Circular Economy and the Energy Market. Contributions to Economics*; Dinçer, H., Yüksel, S., Eds.; Springer: Cham, Switzerland, 2022. [CrossRef]
39. Lin, J.Y.; Sun, X.; Jiang, Y. Endowment, industrial structure, and appropriate financial structure: A new structural economics perspective. *J. Econ. Policy Reform* **2013**, *16*, 109–122. [CrossRef]
40. Rodrik, D.; The Return of Industrial Policy. Project Syndicate 2010; Volume 12. Available online: http://www.project-syndicate.org/commentary/the-return-of-industrial-policy (accessed on 2 February 2025).
41. Pack, H.; Saggi, K. Is There a Case for Industrial Policy? A Critical Survey. *World Bank Res. Obs.* **2006**, *21*, 267–297. [CrossRef]
42. Ninni, A.; Croci, E.; Di Tommaso, M.M.; Fabbri, P.; Frey, M.; Giovannetti, E.; Tassinari, M. *Politica Industriale e Sviluppo Sostenibile*; Università di Parma, Dipartimento di Economia: Parma, Italy, 2014.
43. Lizhuo, L. Analysis of the Relationship Between QinHuangDao Port Logistics and Economic Growth. *Int. J. Adv. Inf. Sci. Serv. Sci.* **2012**, *4*, 105–114.
44. Merk, O.; Ducruet, C.; Dubarle, P.; Haezendonck, E.; Dooms, M. The competitiveness of global port-cities: The case of the Seine Axis (Le Havre, Rouen, Paris, Caen), France. In *OECD Regional Development Working Papers*; OECD Publishing: Paris, France, 2011. [CrossRef]
45. Carlucci, F.; Siviero, L. La governance dei sistemi infrastrutturali tra centralizzazione e decentramento: Il caso della riforma portuale in Italia. *Riv. Econ. Politica Trasp.* **2016**, *1*, 1–14.
46. Stough, R.R. Institutional barriers to port infrastructure and harbor development. *IATSS Res.* **2005**, *20*, 30–40. [CrossRef]
47. Chen, J.; Wan, Z.; Zhang, F.; Park, N.-K.; Zheng, A.; Zhao, J. Evaluation and comparison of the development performances of typical free trade port zones in China. *Transp. Res. Part A Policy Pract.* **2018**, *118*, 506–526. [CrossRef]
48. Commissione delle Comunità Europee. Comunicazione della Commissione. Comunicazione su una Politica Europea dei Porti. 2007 EUR-lex. Retrieved 22 August 2022. Available online: https://eur-lex.europa.eu/legal-content/IT/TXT/PDF/?uri=CELEX:52007DC0616&from=ES (accessed on 1 November 2024).
49. Di Palma, M. Strategie e Valutazioni Integrate per lo Sviluppo Sostenibile delle Città Portuali. Tesi di Dottorato, Università Degli Studi di Napoli Federico II, 2013Enel X & Legambiente. Porti Verdi: La Rotta per uno Sviluppo Sostenibile. Legambiente 2021. Retrieved 11 August 2022. Available online: https://www.legambiente.it/rapporti/porti-verdi-la-rotta-per-uno-sviluppo-sostenibile/ (accessed on 12 November 2024).
50. Korinek, J.; Sourdin, P. Maritime transport costs and their impact on trade. In *Organization for Economic Co-Operation and Development, OECD Trade Policy Working Papers, No. 92*; OECD Publishing: Paris, France, 2009.
51. Raballand, G. Determinants of the negative impact of being landlocked on trade: An empirical investigation through the Central Asian case. *Comp. Econ. Stud.* **2003**, *45*, 520–536. [CrossRef]
52. Limao, N.; Venables, A.J. Infrastructure, geographical disadvantage, transport costs, and trade. *World Bank Econ. Rev.* **2001**, *15*, 451–479. [CrossRef]
53. Merk, O.; Hesse, M. The competitiveness of global port-cities: The case of Hamburg, Germany. In *OECD Regional Development Working Papers*; OECD Publishing: Paris, France, 2012.
54. Girard, L.F.; Di Palma, M. La simbiosi come strumento di rigenerazione urbana nelle città portuali. *Boll. Cent. Calza Bini* **2016**, *16*, 239–250. [CrossRef]
55. Meersman, H.; Van de Voorde, E.; Vanelslander, T. (Eds.) *Port Infrastructure Finance*; Informa Law from Routledge: London, UK, 2014.
56. Barbieri, E.; Bonaldo, S.; Capoani, L.; Campanale, S. Ripensare le politiche industriali portuali in Italia. Analisi e prospettive. In *L'industria, Rivista di Economia e Politica Industriale*; Società Editrice Il Mulino S.p.A.: Bologna, Italy, 2024; pp. 37–70. [CrossRef]
57. Anwar, A.H.M.M.; Nezamuddin, N.N. A Review Approach to Understanding the Current Status of Port Resilience: Lessons Learned for GCC Ports. In *Climate-Resilient Cities*; Contributions to Economics; Arora, A., Belaïd, F., Lechtenberg-Kasten, S., Eds.; Springer: Berlin/Heidelberg, Germany, 2025. [CrossRef]
58. Shawly, H. Evaluating compact city model implementation as a sustainable urban development tool to control urban sprawl in the city of Jeddah. *Sustainability* **2022**, *14*, 13218. [CrossRef]
59. Maury, F.; Feligonde, A.; Leonard, T.; Raffi, K.; Khalfi, M.; Navarro-Roch, M.; Vermen, H. Africa's ports: Fast-tracking transformation. In *Africa CEO Forum*; OKAN Partners: Paris, France, 2020; pp. 1–60.
60. Reboredo, R.; Gambino, E. Connectivity and competition: The emerging geographies of Africa's 'Ports Race'. *Area Dev. Policy* **2022**, *8*, 142–161. [CrossRef]
61. Chovancová, J.; Majerník, M.; Drábik, P.; Štofková, Z. Environmental Technological Innovations and the Sustainability of their Development. *Ecol. Eng. Environ. Technol.* **2023**, *24*, 245–252. [CrossRef]
62. Alojail, M.; Khan, S.B. Impact of Digital Transformation toward Sustainable Development. *Sustainability* **2023**, *15*, 14697. [CrossRef]

63. Anadon, L.D.; Chan, G.; Harley, A.G.; Matus, K.; Moon, S.; Murthy, S.L.; Clark, W.C. Making Technological Innovation Work for Sustainable Development. *Proc. Natl. Acad. Sci. USA* **2016**, *113*, 9682–9690. [CrossRef] [PubMed]
64. Isensee, C.; Griese, K.-M.; Teuteberg, F. Sustainable Artificial Intelligence: A corporate Culture Perspective. *Sustain. Manag. Forum* **2021**, *29*, 217–230. [CrossRef]
65. D'amico, G.; Szopik-Depczyńska, K.; Dembińska, I.; Ioppolo, G. Smart and sustainable logistics of Port cities: A framework for comprehending enabling factors, domains and goals. *Sustain. Cities Soc.* **2021**, *69*, 102801. [CrossRef]
66. De Pascale, G.; Romagno, A.; Faccilongo, N. Globalization and ICT Capital Endowment: How Do They Impact on an Inclusive Green Growth Index? *Struct. Change Econ. Dyn.* **2024**, *69*, 463–474. [CrossRef]
67. Marcucci, E.; Musso, E. Sostenibilità, qualità e sicurezza nei sistemi di trasporto e logistica. In *Sostenibilità, Qualità e Sicurezza nei Sistemi di Trasporto e Logistica*; Franco Angeli Editore: Milano, Italy, 2011; pp. 1–496.
68. Im, I.; Shin, D.; Jeong, J. Components for Smart Autonomous Ship Architecture Based on Intelligent Information Technology. *Procedia Comput. Sci.* **2018**, *134*, 91–98. [CrossRef]
69. Lund, M.S.; Gulland, J.E.; Hareide, O.S.; Jøsok, Ø.; Weum, K.O.C. Integrity of Integrated Navigation Systems. In Proceedings of the IEEE Conference on Communications and Network Security (CNS), Beijing, China, 30 May–1 June 2018; pp. 1–5. [CrossRef]
70. Canbulat, O.; Aymelek, M.; Turan, O.; Boulougouris, E. An application of BBNs on the integrated energy efficiency of ship–port interface: A dry bulk shipping case. *Marit. Policy Manag.* **2019**, *46*, 845–865. [CrossRef]
71. Kurt, I.; Aymelek, M. Remote Working in the New Normal of a Global Pandemic: Autonomous Ships and Shore Control Centres. In *Handbook of Research on the Future of the Maritime Industry 2022*; IGI Global: Hershey, PA, USA, 2022; pp. 290–305.
72. de la Peña Zarzuelo, I.; Soeane, M.J.F.; Bermúdez, B.L. Industry 4.0 in the port and maritime industry: A literature review. *J. Ind. Inf. Integr.* **2020**, *20*, 100173. [CrossRef]
73. Bruno, M. *Smart Ports: Piers of the Future. Navigating Innovation and Collaboration on the Maritime Horizon*; Port Technology International, Smart City Expo World Congress (SCEWC): Barcelona, Spain, 2023; Available online: https://www.porttechnology.org/news/smart-ports-piers-of-the-future-navigating-innovation-and-collaboration-on-the-maritime-horizon/ (accessed on 2 February 2025).
74. Yan, Z.; Wang, Y.; Peng, X. An Artificial Intelligence Model Considering Data Imbalance for Ship Selection in Port State Control Based on Detention Probabilities. *J. Comput. Sci.* **2020**, *44*, 101171. [CrossRef]
75. Houston, D.; Ong, P.; Jaimes, G.; Winer, A. Traffic Exposure near the Los Angeles–Long Beach Port Complex: Using GPS-Enhanced Tracking to Assess the Implications of Unreported Travel and Locations. *J. Transp. Geogr.* **2011**, *19*, 1399–1409. [CrossRef]
76. Chauhan, R.; Patel, K.; Tanwar, S.; Tyagi, S.; Kumar, N. IoT Enabled Real-Time Urban Transport Management System. *Comput. Electr. Eng.* **2020**, *86*, 106739. [CrossRef]
77. Hofmann, W.; Branding, F. Implementation of an IoT-and cloud-based digital twin for real-time decision support in port operations. *IFAC-PapersOnLine* **2019**, *52*, 2104–2109. [CrossRef]
78. Ferretti, M.; Schiavone, F. Internet of Things and business processes redesign in seaports: The case of Hamburg. *Bus. Process. Manag. J.* **2016**, *22*, 271–284. [CrossRef]
79. Sánchez-González, P.L.; Díaz-Gutiérrez, D.; Leo, T.J.; Núñez-Rivas, L.R. Toward digitalization of maritime transport? *Sensors* **2019**, *19*, 926. [CrossRef] [PubMed]
80. Yoon, J.-H.; Kim, J.-S.; Park, H.-G. A Study on the Priorities of Blockchain Adoption for Port Logistics in Korea Using AHP: Focused on Busan and Incheon Ports. *J. Int. Trade Commer.* **2020**, *16*, 1–24. [CrossRef]
81. Yang, Y.; Zhong, M.; Yao, H.; Yu, F.; Fu, X.; Postolache, O. Internet of things for smart ports: Technologies and challenges. *IEEE Instrum. Meas. Mag.* **2018**, *21*, 34–43. [CrossRef]
82. Choi, S.H.; Won, S.H. A Study on the Port Technology Policy and Development Strategy. *Korean Inst. Navig. Port Res.* **2006**, *1*, 331–337.
83. Gnimpieba, Z.D.R.; Nait-Sidi-Moh, A.; Durand, D.; Fortin, J. Using Internet of Things Technologies for a Collaborative Supply Chain: Application to Tracking of Pallets and Containers. *Procedia Comput. Sci.* **2015**, *56*, 550–557. [CrossRef]
84. Bai, C.; Zhu, Q.; Sarkis, J. Joint blockchain service vendor-platform selection using social network relationships: A multi-provider multi-user decision perspective. *Int. J. Prod. Econ.* **2021**, *238*, 108165. [CrossRef]
85. Pournader, M.; Shi, Y.; Seuring, S.; Koh, S.L. Blockchain applications in supply chains, transport and logistics: A systematic review of the literature. *Int. J. Prod. Res.* **2020**, *58*, 2063–2081. [CrossRef]
86. Wang, M.; Wu, Y.; Chen, B.; Evans, M. Blockchain and Supply Chain Management: A New Paradigm for Supply Chain Integration and Collaboration. *Oper. Supply Chain Manag. Int. J.* **2020**, *14*, 111–122. [CrossRef]
87. Henríquez, R.; de Osés, F.X.M.; Marín, J.E.M. Technological drivers of seaports' business model innovation: An exploratory case study on the port of Barcelona. *Res. Transp. Bus. Manag.* **2022**, *43*, 100803. [CrossRef]
88. Yang, D.; Chin, A.T.; Chen, S. Impact of politics, economic events and port policies on the evolution of maritime traffic in Chinese ports. *Marit. Policy Manag.* **2014**, *41*, 346–366. [CrossRef]

89. Bolbot, V.; Theotokatos, G.; Boulougouris, E.; Wennersberg, L.A.L.; Nordahl, H.; Rødseth, Ø.J.; Faivre, J.; Colella, M.M. *Paving the Way Toward Autonomous Shipping Development for European Waters—The AUTOSHIP Project*; Royal Institution of Naval Architects: London, UK, 2020.
90. Mazza, N. Blue Economy: La Ripresa Viene dal Mare. ISPI 2020. Available online: https://www.ispionline.it/it/pubblicazione/blue-economy-la-ripresa-viene-dal-mare-28619 (accessed on 16 November 2024).
91. Ahmad, M.; Khan, A.; Li, F.; Usama, M.; Ahmed, A. Privacy-Preserving Deep Learning through Pixel-Based Encryption for Digital Security. *arXiv* **2021**, arXiv:2203.16780.
92. Adenso-Díaz, B.; Álvarez, N.G.; Alba, J.A.L. A fuzzy AHP classification of container terminals. *Marit. Econ. Logist.* **2020**, *22*, 218–238. [CrossRef]
93. Wang, S.; Notteboom, T. The role of port authorities in the development of LNG bunkering facilities in North European ports. *WMU J. Marit. Aff.* **2015**, *14*, 61–92. [CrossRef]
94. Wei, H.; Müller-Casseres, E.; Belchior, C.R.P.; Szklo, A. Evaluating the Readiness of Ships and Ports to Bunker and Use Alternative Fuels: A Case Study from Brazil. *J. Mar. Sci. Eng.* **2023**, *11*, 1856. [CrossRef]
95. Klymenko, O.; Halse, L.L.; Jæger, B.; Nerger, A.J. Digitalization and Environmental Sustainability: What are the Opportunities? In Proceedings of the 26th EurOMA Conference, Helsinki, Finland, 17–19 June 2019.
96. Lambert, A.; Boons, F. Eco-industrial parks: Stimulating sustainable development in mixed industrial parks. *Technovation* **2002**, *22*, 471–484. [CrossRef]
97. Chertow, M.R.; Ashton, W.S.; Espinosa, J.C. Industrial Symbiosis in Puerto Rico: Environmentally Related Agglomeration Economies. *Reg. Stud.* **2008**, *42*, 1299–1312. [CrossRef]
98. Karas, A. Smart Port as a Key to the Future Development of Modern Ports. *TransNav Int. J. Mar. Navig. Saf. Sea Transp.* **2020**, *14*, 27–31. [CrossRef]
99. Hoang, A.T.; Foley, A.M.; Nižetić, S.; Huang, Z.; Ong, H.C.; Ölçer, A.I.; Pham, V.V.; Nguyen, X.P. Energy-related approach for reduction of CO2 emissions: A critical strategy on the port-to-ship pathway. *J. Clean. Prod.* **2022**, *355*, 131772. [CrossRef]
100. Osses, J.R.P.; Palma, V.M.; Reusser, C.A.; Contreras, J. Emissions assessment of a tanker in a Chilean port using bi-directional cold ironing integrated to LNG. *Sustain. Energy Technol. Assess.* **2022**, *52*, 102135. [CrossRef]
101. Gutierrez-Romero, J.E.; Esteve-Pérez, J.; Zamora, B. Implementing Onshore Power Supply from renewable energy sources for requirements of ships at berth. *Appl. Energy* **2019**, *255*, 113883. [CrossRef]
102. León-Mateos, F.; Sartal, A.; López-Manuel, L.; Quintás, M.A. Adapting our sea ports to the challenges of climate change: Development and validation of a Port Resilience Index. *Mar. Policy* **2021**, *130*, 104573. [CrossRef]
103. Christodoulou, N.; Kyprianou, C.; Weberling, A.; Wang, R.; Cui, G.; Peng, G.; Jing, N.; Zernicka-Goetz, M. Sequential formation and resolution of multiple rosettes drive embryo remodelling after implantation. *Nat. Cell Biol.* **2018**, *20*, 1278–1289. [CrossRef]
104. Cuong, T.N.; Kim, H.S.; Long, L.N.B.; You, S.S. Seaport profit analysis and efficient management strategies under stochastic disruptions. *Marit. Econ. Logist.* **2024**, *26*, 212–240. [CrossRef]
105. Wang, X.; Du, D.; Peng, Y. Assessing the importance of the marine chokepoint: Evidence from tracking the global marine traffic. *Sustainability* **2024**, *16*, 384. [CrossRef]
106. Chen, X.; Dou, S.; Song, T.; Wu, H.; Sun, Y.; Xian, J. Spatial-Temporal Ship Pollution Distribution Exploitation and Harbor Environmental Impact Analysis via Large-Scale AIS Data. *J. Mar. Sci. Eng.* **2024**, *12*, 960. [CrossRef]
107. Emmerson, C.; Stevens, P. *Maritime Choke Points and the Global Energy System: Charting a Way Forward*; Chatham House Briefing Paper; Chatham House: London, UK, 2012.
108. Caprino, N. *Innovazioni Tecnologiche per la Riduzione Delle Emissioni Nelle Attività Portuali: Il Caso Göteborg*; Università degli Studi di Genova: Genova, Italy, 2012.
109. Iris, Ç.; Lam, J.S.L. A Review of Energy Efficiency in Ports: Operational Strategies, Technologies, and Energy Management Systems. *Renew. Sustain. Energy Rev.* **2019**, *112*, 170–182. [CrossRef]
110. Del Giudice, M.; Di Vaio, A.; Hassan, R.; Palladino, R. Digitalization and new technologies for sustainable business models at the ship–port interface: A bibliometric analysis. *Marit. Policy Manag.* **2021**, *49*, 410–446. [CrossRef]
111. Vakili, S.; Ölçer, A.; Ballini, F. The development of a policy framework to mitigate underwater noise pollution from commercial vessels: The role of ports. *Mar. Policy* **2020**, *120*, 104132. [CrossRef]
112. Becker, A.; Ng, A.K.; McEvoy, D.; Mullett, J. Implications of climate change for shipping: Ports and supply chains. *WIREs Clim. Change* **2018**, *9*, e508. [CrossRef]
113. Cerceau, J.; Mat, N.; Junqua, G.; Lin, L.; Laforest, V.; Gonzalez, C. Implementing industrial ecology in port cities: International overview of case studies and cross-case analysis. *J. Clean. Prod.* **2014**, *74*, 1–16. [CrossRef]
114. Shaw, D.R.; Grainger, A.; Achuthan, K. Multi-level port resilience planning in the UK: How can information sharing be made easier? *Technol. Forecast. Soc. Change* **2017**, *121*, 126–138. [CrossRef]

115. Messner, S.; Becker, A.; Ng, A.K. Port adaptation for climate change: The roles of stakeholders and the planning process. In *Climate Change and Adaptation Planning for Ports*; Ng, A.K.Y., Becker, A., Cahoon, S., Chen, S.L., Earl, P., Yang, Z., Eds.; Routledge: London, UK, 2015; pp. 41–55.
116. Viola, P.; Colombo, E. *Porti Turistici: Approccio Multidisciplinare per una Strategia Progettuale Integrata*; D. Flaccovio Editore: Palermo, Italy, 2010.
117. da Veiga Lima, F.A.; de Souza, D.C. Climate change, seaports, and coastal management in Brazil: An overview of the policy framework. *Reg. Stud. Mar. Sci.* **2022**, *52*, 102365.
118. Philipp, R.; Prause, G.; Olaniyi, E.O.; Lemke, F. Towards Green and Smart Seaports: Renewable Energy and Automation Technologies for Bulk Cargo Loading Operations. *Sci. J. Riga Tech. Univ. Environ. Clim. Technol.* **2021**, *25*, 650–665. [CrossRef]
119. Pavia, R.; Oltre la Pandemia. Specificità del Sistema Portuale Nazionale e Recovery Plan. 2021. Available online: https://www.inu.it/wp-content/uploads/inu-porti-oltre-la-pandemia-21-gennaio-2021.pdf (accessed on 21 November 2024).
120. Kirchherr, J.; Reike, D.; Hekkert, M. Conceptualizing the circular economy: An analysis of 114 definitions. *Resour. Conserv. Recycl.* **2017**, *127*, 221–232. [CrossRef]
121. Gurning, R.O.S.; Tangkau, D.I. The Analysis of the Conceptual Framework of Green Port Implementation in Indonesia Using Circular Economy: The Case Study of Benoa Public and Fishing Terminals. *Sustainability* **2022**, *14*, 6083. [CrossRef]
122. Maritz, A.; Shieh, C.J.; Yeh, S.P. Innovation and success factors in the construction of Green Ports. *J. Environ. Prot. Ecol.* **2014**, *15*, 1255–1263.
123. Lasserre, F. Arctic Shipping Traffic: More ships will come, but not for transit. In *Science to Policy in the Eastern Canadian Arctic*; Arctic Net: Quebec City, QC, Canada, 2018; pp. 509–521.
124. Caroli, R.; Soriani, S. (Eds.) *Fragile and Resilient Cities on Water: Perspectives from Venice and Tokyo*; Cambridge Scholars Publishing: Cambridge, UK, 2017.
125. Sénquiz-Díaz, C. The Effect of Transport and Logistics on Trade Facilitation and Trade: A PLS-SEM Approach. *ECONOMICS* **2021**, *9*, 11–24. [CrossRef]
126. Fedorenko, R.; Yakhneeva, I.; Zaychikova, N.; Lipinsky, D. Evaluating the Socio-Economic Factors Impacting Foreign Trade Development in Port Areas. *Sustainability* **2021**, *13*, 8447. [CrossRef]
127. Chlomoudis, C.; Pallis, A. European Union Port Policy: The movement towards a long-term strategy. In *European Union Port Policy*; Edward Elgar Publishing: Cheltenham, UK, 2002.
128. Tijan, E.; Jović, M.; Panjako, A.; Žgaljić, D. The Role of Port Authority in Port Governance and Port Community System Implementation. *Sustainability* **2021**, *13*, 2795. [CrossRef]
129. Trade and Development Report 2016. UN Trade and Development (UNCTAD). (2016, September 22). Available online: https://unctad.org/publication/trade-and-development-report-2016 (accessed on 2 February 2025).
130. Clark, X.; Dollar, D.; Micco, A. Port efficiency, maritime transport costs, and bilateral trade. *J. Dev. Econ.* **2004**, *75*, 417–450. [CrossRef]
131. Merk, O.; Dang, T.T. *The Effectiveness of Port-City Policies: A Comparative Approach*; OECD Regional Development Working Papers: Paris, France, 2013. [CrossRef]
132. Bocheński, T.; Palmowski, T.; Studzieniecki, T. The Development of Major Seaports in the Context of National Maritime Policy. The Case Study of Poland. *Sustainability* **2021**, *13*, 12883. [CrossRef]
133. Notteboom, T.E.; Rodrigue, J.-P. Port regionalization: Towards a new phase in port development. *Marit. Policy Manag.* **2005**, *32*, 297–313. [CrossRef]
134. Munim, Z.H.; Schramm, H.-J. The Impacts of Port Infrastructure and Logistics Performance on Economic Growth: The Mediating Role of Seaborne Trade. *J. Shipp. Trade* **2018**, *3*, 1. [CrossRef]
135. Herrera Dappe, M.; Jooste, C.; Suárez-Alemán, A. How Does Port Efficiency Affect Maritime Transport Costs and Trade? In *Evidence from Indian and Western Pacific Ocean Countries*; Policy Research Working Paper No. 8204; World Bank: Washington DC, USA, 2017.
136. Acciaro, M.; Ghiara, H.; Cusano, M.I. Energy management in seaports: A new role for port authorities. *Energy Policy* **2014**, *71*, 4–12. [CrossRef]
137. Capoani, L.; Barbieri, E. Cambiamento strutturale a livello portuale nazionale e il caso del porto di Venezia. *Riv. Econ. Politica Trasp.* **2022**, *1*, 4.
138. Greco, I.; Cresta, A. Piani e politiche di rifunzionalizzazione dei sistemi portuali per una crescita urbana sostenibile: Stato dell'arte e prospettive. *Boll. Dell'associazione Ital. Cartogr.* **2018**, *164*, 45–61.
139. Baccelli, O.; Senn, L. Prove tecniche di federalismo fiscale per le opere infrastrutturali in Italia. Il caso dei porti alla luce della più recente normativa. In *Conoscenza, Sviluppo Umano, Territorio*; Associazione Italiana di Scienze Regionali; Franco Angeli Editore: Milano, Italy, 2008.
140. Aksoy, S.; Durmuşoğlu, Y. Improving Competitiveness Level of Turkish Intermodal Ports in the Frame of Green Port Concept: A Case Study. *Marit. Policy Manag.* **2020**, *47*, 203–220. [CrossRef]

141. Ying, Z.; Zhao, J.; Shao, G. Port city sustainability: A review of its research trends. *Sustainability* **2020**, *12*, 8355. [CrossRef]
142. Mahmud, K.K.; Shaheen MM, A.; Chowdhury MM, H.; Mahmud, M.A. Opportunity Cost of Imo 2020 Compliance: A Case Study of Bangladeshi Ship Owners. In Proceedings of the 13th International Conference on Marine Technology, Tianjin, China, 12–13 August 2023.
143. Buzinkay, M. Spearheading the Future of Container Terminal Automation. *Identec Solut.* **2023**.
144. Inkinen, T.; Helminen, R.; Saarikoski, J. Technological trajectories and scenarios in seaport digitalization. *Res. Transp. Bus. Manag.* **2021**, *41*, 100633. [CrossRef]
145. Castelein, B.; van Duin, R.; Geerlings, H. Identifying dominant stakeholder perspectives on sustainability issues in reefer transportation. A Q-method study in the Port of Rotterdam. *Sustainability* **2019**, *11*, 3425. [CrossRef]
146. Hakirevic Prevljak, N. *Rotterdam on Track to Becoming Truly Sustainable Port*; Offshore Energy: Amsterdam, The Netherlands, 2024.
147. French, J. *Cruise Ship Passenger Port of Call Guide to Akureyri, Iceland*; About2Cruise: London, UK, 2024.
148. Zadorin, M.Y.; Zaikov, K.S.; Kuprikov, N.M.; Kuprikov, M.Y. Legal and Economic Prospects for the Arctic Seaport Developments of the Northern Dimension Partner Countries (Russia and the European Union). *Sustainability* **2022**, *14*, 2373. [CrossRef]
149. Caldeirinha, V.; Nabais, J.L.; Pinto, C. Port Community Systems: Accelerating the Transition of Seaports toward the Physical Internet—The Portuguese Case. *J. Mar. Sci. Eng.* **2022**, *10*, 152. [CrossRef]
150. Burskyte, V.; Belous, O. Sustainable development of deep-water seaport: The case of Lithuania. *Environ. Sci. Pollut. Res.* **2010**, *18*, 716–726. [CrossRef]
151. Audrius, K.; Darius, B. Assessment of sustainability of logistic activity of port of Klaipeda. *Sci. Pap. Univ. Pardubic. Ser. D Fac. Econ. Adm.* **2014**, *21*, 65–74.
152. Gaidelys, V.; Benetyte, R. Analysis of the Competitiveness of the Performance of Baltic Ports in the Context of Economic Sustainability. *Sustainability* **2021**, *13*, 3267. [CrossRef]
153. Knoth, P.; Herrmannova, D.; Cancellieri, M.; Anastasiou, L.; Pontika, N.; Pearce, S.; Gyawali, B.; Pride, D. CORE: A Global Aggregation Service for Open Access Papers. *Sci. Data* **2023**, *10*, 366. [CrossRef]
154. González Laxe, F.; Sánchez, R.J.; Garcia-Alonso, L. The adaptation process in port governance: The case of the Latin countries in South America and Europe. *J. Shipp. Trade* **2016**, *1*, 14. [CrossRef]
155. Guimarães, R.; Acuna, G.; Carabias Lillo, J.; Tudela Abad, F.; Provencio, E.; Samaniego Leyva, J.L. *The Sustainability of Development in Latin America and the Caribbean: Challenges and Opportunities*; CEPAL-PNUMA: México-Santiago, Mexico, 2002.
156. Van der Waldt, G. The judicious use of theory in social science research. *J. Transdiscipl. Res. S. Afr.* **2021**, *17*, 9. [CrossRef]
157. Kameri-Mbote, P.; Kabira, N. Engendering the Legal Framework for Environmentally Sustainable Development: Some Reflections. *Environ. Policy Law* **2024**, *53*, 335–346. [CrossRef]