Shipping market dynamics of green research and development investment[⋆,⋆⋆]

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ABSTRACT

The shipping industry contributes significantly to global carbon dioxide emissions, amounting to about 3% of the total. The International Maritime Organization aims to achieve net-zero emissions for ships by 2050, with an estimated investment cost of up to $1.9 trillion. Recent research highlights the shift to alternative fuels through green shipping, driven by research and development (R&D) investments. This study focuses on the economic assessment of green shipping and the influence of Green R&D investments on the maritime transport sector. It reveals that green shipping affects the economic dynamics, influencing port and shipping line decisions. Moreover, it shows that shipping lines are incentivized to invest in green R&D, while ports are motivated to engage with environmentally friendly shipping lines. Additionally, in competitive markets, significant innovation resulting from green R&D could lead to market exits and entry barriers. However, the presence of spillovers discourages shipping lines from investing in green R&D.

1. Introduction

The shipping industry is vital for global trade by transporting goods throughout the world. However, it also contributes significantly to carbon dioxide (CO2) emissions, accounting for approximately 3% of global emissions, similar to the aviation sector. Concern has been raised about the use of fossil fuels such as marine gas oil and heavy fuel oil (HFO) in maritime transport, as they release harmful gases such as CO2, methane, and nitrous oxide, which contribute to climate change. Emissions in the shipping industry vary depending on economic cycles and fuel prices, which affect ship design efficiency and the adoption of new technologies. Efforts are currently underway to address CO2 emissions from shipping, including the International Maritime Organization's (IMO) plan to revise its greenhouse gas emissions reduction strategy in 2023. The goal is to establish a net-zero emissions target for ships by around 2050, with interim reduction goals for 2030 and 2040. Additionally, regulatory measures and mitigation efforts have been proposed and implemented to mitigate the impact of shipping on climate change. As an illustration, the European Union has broadened the scope of its Emissions Trading System (EU ETS) to include CO2 emissions from large vessels that are entering ports within the EU. This is in line with the EU's "fit for 55" package, which reaffirms the inclusion of shipping in the EU ETS. Under the EU ETS, vessels weighing over 5000 gross tons and operating exclusively within the EU are mandated to compensate for their total carbon dioxide emissions. Concurrently, ships that enter and exit

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the EU are obliged to cover the cost of 50% of their carbon dioxide emissions. This is a significant regulatory measure aimed at reducing emissions from large ships entering EU ports, (Dong, Zeng, Yang and Wang (2022)). One notable practice that has shown potential for reducing emissions is slow steaming, which involves reducing ships' operational speed to conserve fuel and decrease CO2 and air pollutant emissions. It has been found that a 10% reduction in the speed of the vessel leads to a 27% decrease in emissions and an overall CO2 savings of 19% if adopted universally. Slow steaming is an example of an operational measure that can contribute to reducing emissions in the shipping industry, Lee and Nam (2017). However, the shipping industry faces the challenge of transitioning to low-carbon and zero-emission technologies to achieve the net-zero emissions target set for around 2050. This necessitates the embracement of renewable energy sources and the investigation of technologies, fuels, and energy sources that emit minimal or no greenhouse gases (GHGs) by 2030. This shift is vital for the industry to achieve its bold emissions reduction goals and play its part in the worldwide fight against climate change.

In this study, we investigate the impact of a shipping company's decision to invest in environmentally friendly research and development (R&D) on the market structure. Additionally, we examine how the behavior of ports influences the decision-making process of the company. Green R&D plays a crucial role in driving the advancement of sustainable and eco-friendly practices in the shipping industry. This includes the adoption of technologies, practices, and policies aimed at reducing the carbon footprint and ecological impact of maritime transport. The industry has recognized the importance of operating environmentally responsible, leading to the adoption of alternative fuels, the optimization of vessel designs, and the integration of advanced energy management systems. In recent years, shipping companies have made significant investments in green shipping initiatives, such as the use of liquefied natural gas (LNG) and the exploration of biofuels, ammonia, and hydrogen Tsouri, Hansen, Hanson and Steen (2022). Moreover, the industry is exploring innovative solutions like battery-powered ship engines, rotor sails for harnessing wind power, and the development of smart ports to improve efficiency and reduce carbon emissions. The estimated cost of investment required to meet the International Maritime Organization's (IMO) emission targets for 2050 is substantial, reaching up to $1.9 trillion. To fund sustainable shipping projects, the industry is actively seeking financial support, and the European Union is leading the way in financing green shipping initiatives. Other countries, including Korea and Japan, are also investing in the construction of vessels designed to operate on zero-emission fuels. The Poseidon Principles serve as a global framework for financial institutions to assess whether their shipping investments align with the IMO targets, ensuring that climate goals are met in shipping finance.

Recent research on green shipping has emphasized the transition to alternative fuels, the optimization of vessel design and energy management systems, the embrace of digitization and data analytics, the improvement of port infrastructure and operations, and the encouragement of collaboration in the industry to drive sustainable practices. These efforts aim to reduce the environmental impact of the industry and contribute to a more sustainable future for global trade. This paper examines the economic evaluation of green shipping and the impact of Green R&D investments on the maritime sector. The concept of investing R&D was first introduced by d'Aspremont and Jacquemin (1988) in microeconomic models, where two rival companies must decide whether to allocate resources to R&D. The decision to invest in R&D alters the cost structure, creating a trade-off for the company on the optimal level of investment to minimize costs, enhance competitiveness, and increase profits. Research in this area has evolved to include the concept of Green R&D in addition to traditional R&D investments.

Green R&D involves systematic and innovative efforts to expand knowledge and develop new applications, with a specific emphasis on environmental sustainability. It plays a vital role in the promotion of eco-innovation, which seeks to enhance both environmental and financial performance by integrating sustainable practices into R&D processes. In their sense, Chen, Wang and Zhou (2019) explore the impact of green R&D cooperation on individual firms' financial performance, considering the technological spillover, power relationships, and coordination in the supply chain. They examine the incentives and effects of green R&D cooperation on the total profit of the supply chain and the financial performance of individual firms, providing insights into the implications of cooperation on environmental and economic performance within the supply chain. Similarly, Peng, Wang and Goh (2023), investigates the impact of green R&D cooperation on individual firm financial performance, considering technological spillover, power relationships, and coordination in the supply chain. They examine the incentives and effects of green R&D cooperation on the total profit of the supply chain and the financial performance of individual firms, providing insights into the implications of cooperation on environmental and economic performance within the supply chain. We contribute to the literature on maritime transport economics by including the concept of Green R&D in shipping lines, known as green shipping. Green shipping refers to the concept of making the shipping industry more environmentally friendly and sustainable. It involves reducing the environmental impact of maritime transport through the use of cleaner fuels, energy-efficient technologies, and the adherence to strict environmental regulations. Several research papers have explored various aspects of green shipping. For example, Brânză (2023) discusses the need for cleaner maritime transport, presents the concepts of green shipping and ecoships, and outlines the regulations and sustainable options for decarbonization in shipping. Ong, Yeo, Kang, Liu and Tan (2022) focuses on promoting a sustainable shipping industry by introducing green shipping practices and rational culture to achieve sustainability based on the triple bottom line framework. Furthermore, Song, Chhetri, Ye and Lee (2023b) discusses the concept of green maritime logistics coalition and green shipping corridors as a new paradigm for the decarbonization of the maritime industry. This paper analyzes the impact of investing in green R&D by a shipping line on port pricing and competitive dynamics.

In the economic literature on maritime transport, the typical analytical framework is akin to a supply chain. Within this construct, an upstream market is represented by a port, whereas a shipping line characterizes the downstream market. Álvarez-SanJaime, Cantos-Sánchez, Moner-Colonques and Sempere-Monerris (2013) was among the pioneers to consider this framework in the literature being referenced. This paper delves into the intricate dynamics of integration between maritime ports and shipping lines, facilitated through revenue-sharing agreements. It scrutinizes the repercussions of competition contracts of shipping lines under diverse modalities of vertical integration, particularly in scenarios involving a hybrid ownership structure of an amalgamated public port. Liu and Wang (2019) explores the motivations behind carriers' formation of alliances and suggests a contract for sharing revenue and allocating service costs, complemented by a compensation system, to efficiently manage the maritime transport chain. This study emphasizes the competition in carrier services and vertical collaboration. Zheng and Luo (2021) delves into the strategic responses of ports in the face of growing negotiation strength of shipping alliances, scrutinizing the tactics of shipping lines and ports from the perspectives of competition, collaboration, and scale economies, and contrasting the social welfare and local welfare in various situations. Nerja and Sánchez (2023) investigates the impact of revenue-sharing agreements on concurrent shipping alliances, discovering that such contracts can mitigate the detrimental effects of shipping alliances on traffic and welfare. Furthermore, it is found that vertical integration via revenue-sharing contracts is a more effective strategy for ports compared to horizontal integration, resulting in a more consolidated market structure. Lastly, Xu and Lee (2024) probes into the effects of competitive agreements among shipping lines under various forms of vertical integration involving combined ownership of a unified public port, scrutinizing the implications on welfare and the socially preferred integration in the context of non-cooperative tactics. Previous research has concentrated on examining various types of integration, including both vertical and horizontal, within the sector.

The main contribution we make to the literature corresponds to the analysis of incorporating the concept of green shipping through investment in R&D for the maritime transport economy. This contribution is reflected in three aspects. First, we consider the competitive effects in the maritime market when a shipping line decides to invest in R&D for decarbonization. Although previous studies such as Chen et al. (2019) and Peng et al. (2023) analyze investment in Green R&D in a general supply chain model, we adapt this to the specific case of Green Shipping. We find that investment by a shipping line in Green shipping increases the total market traffic. In addition, analysis of the maritime transport economy in the last decade has examined the market similarly to supply chains, where two vertically connected markets, ports, and shipping lines, are distinguished. In this regard, from the perspective of transport economics, various studies have been conducted on a single supply chain consisting of a port and one or more shipping lines, as well as on more competitive markets where two supply chains, i.e., two nearby ports, compete. In this context, we make two significant contributions. The first is to consider R&D investment in a context where two supply chains compete, and the second is to adapt the model to the maritime sector. While the literature on Green R&D and more general literature on R&D investment easily find articles analyzing investment in R&D in a single supply chain, the case of two competing supply chains is not common. In this sense, we find that the shipping line investing in green shipping has incentives to do so, and the ports have incentives to work with green shipping lines. Furthermore, due to the effect on port pricing, in small and highly competitive markets, drastic innovation may occur where the green shipping line displaces its competitor. Finally, a noteworthy aspect in our model is the spillover effects of knowledge. Several articles analyze the spillover effects between industries, such as Tsouri et al. (2022), which examines the transfer of knowledge between technological fields and its influence on the emergence of green shipping. However, we focus on knowledge spillovers between shipping lines, knowing that their existence discourages further efforts in green shipping investment.

The following section includes a review of the literature. Section 3 presents the benchmark model in which a shipping line invest in green R&D. Section 4 analyzes the effects of spillovers in the maritime industry. Section 5 summarizes key findings and discusses policy implications.

2. Literature review

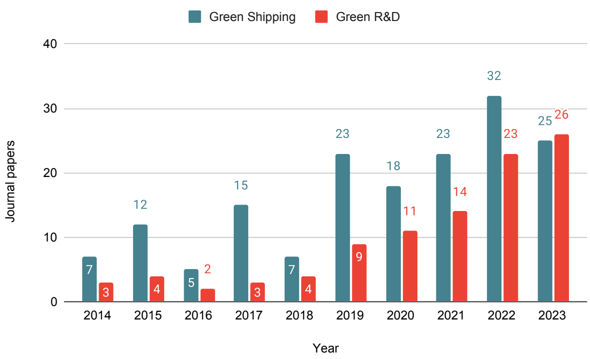
For numerous decades, the International Maritime Organization (IMO) has been dynamically involved in tackling greenhouse gas (GHG) emissions from maritime vessels. This participation is characterized by the endorsement of resolutions and the release of GHG research, including the First IMO GHG Study in 2000, the Second IMO GHG Study in 2009, and the Third IMO GHG Study in 2014. The IMO has also been involved in initiatives such as the Green Voyage 2050 project, which supports countries in assessing maritime emissions and implementing low- and zero-carbon pilot projects. The culmination of these efforts is the 2023 IMO Strategy on Reduction of GHG Emissions from Ships, which sets ambitious targets to reduce annual GHG emissions from international shipping by at least 20% by 2030 and at least 70% by 2040, with a long-term ambition to completely eliminate GHG emissions from international shipping by 2050. These initiatives underscore the commitment of the IMO to address GHG emissions from ships and its commitment to achieving decarbonization in the shipping market.

The process of decarbonization requires shipping companies to make substantial investments in research and development. As a result, there are various strands of literature that are pertinent to this article. Initially, there is a range of studies that categorize and discuss green shipping practices. In addition, there is a focus on research and development investments that target sustainability. Figure 1 illustrates the progression of publications that specifically examine the concepts of "green shipping" and "green R&D." These two themes are closely linked, and the volume of publications in these areas is anticipated to continue to grow.

2.1. Green Shipping

In 1995, the initial academic work introducing the concept of Green Shipping was published Mair (1995). However, it was not until 2014 that the exploration of this field began to gain traction. According to Mendeley, between 2014 and

Figure 1: Journal papers in the last decade



Source: Mendeley

2023, 167 scholarly articles have been published specifically addressing the topic of 'green shipping'. The literature encompasses a variety of articles, some aiming to elucidate the concept and promote awareness, others delving into policies and practices related to environmentally friendly shipping, and also technological papers concentrating on pioneering new research and development within the shipping industry.

Several articles have contributed to a comprehensive understanding of the multifaceted nature of “green shipping”, highlighting the importance of regulatory frameworks, technological advancements, stakeholder perspectives, and the need for innovative solutions to address environmental and sustainability challenges in maritime transport. The significance of green shipping lies not only in its literal interpretation, but also in how it is perceived from social, economic, and environmental standpoints. According to Prokopenko and Miśkiewicz (2020), the term "green shipping" embodies a new economic philosophy that aims to satisfy the increasing needs of society while simultaneously mitigating the environmental impact on marine and air ecosystems. This improved understanding of the concept is strongly underpinned by scholarly research. Shi, Xiao, Chen, McLaughlin and Li (2018) examine the progression of green shipping research, noting a substantial increase in publications and journals dedicated to environmental effects, alternative energy technologies, and policy implementation, with a growing contribution from researchers in Europe and Asia. However, the most significant influence comes from the various stakeholders involved, including ports, shipping companies, and regulatory bodies. Lister (2015) highlights that the historical maritime shipping regulatory framework has been ineffective in addressing environmental consequences, largely due to inadequate governance and oversight resulting from the principles of freedom of navigation and the flags of convenience system. However, new dynamics are emerging, such as conflicts over ocean utilization rights, public unease with respect to environmental impacts, and demands for more sustainable shipping practices from major sea freight clients, which are reshaping the environmental governance landscape in the maritime industry. Hence, it is imperative to listen to the voices of key industry players. Lee and Nam (2017) investigate the perspectives of stakeholders in the maritime sector, offering valuable insights for domestic shipping firms, shipyards, and government policies, stressing the importance of ordering environmentally friendly ships, investing in research and development of environmentally friendly ship technology, and improving financial support for environmentally friendly ships. Thus, to ensure the ongoing advancement of green shipping, it is essential that all parties involved align their efforts, with institutions that facilitate industry transformation, diverse stakeholders that drive change, and increased consumer awareness that promotes environmental awareness.

To achieve the goals of decarbonization and promote the adoption of sustainable shipping practices, it is imperative to invest in green R&D technologies. However, to ensure the optimal implementation of such investments, it is crucial to secure the necessary financing for these endeavors. Metzger and Schinas (2019) emphasizes the significance of R&D investment in environmentally friendly ship technology and underscores the importance of fostering partnerships between shipping firms and shipyards to connect the ordering of eco-friendly ships with technological advances. This underscores the essential role of engaging various stakeholders in facilitating this ecological transition. One of the primary hurdles lies in the utilization of sustainable fuels. Although electric ships represent an ideal scenario, this innovative technology is not without its challenges. For example, Wang, Liu, Zhen and Wang (2022) highlight that the practical difficulties of electric ships encompass the refinement of charging station placements, charging strategies, navigation planning, ship timetabling, and ship positioning, all while adhering to the limitations of service duration stipulations. Consequently, the realization of electric ships on a large scale will require substantial investments in infrastructure and a significant amount of time to materialize. In the meantime, it is necessary to consider alternative fuel options such as hydrogen, which is a promising choice for sustainable future shipping practices due to its advantageous volumetric energy density and low thermal expansion coefficients, Wang, Wang, Afshan and Hjalmarsson (2021). Evidently, there exists a gap that must be addressed, and the active involvement of all stakeholders, coupled with a commitment to a specific technology, can propel progress toward achieving these sustainability objectives.

Ultimately, the proper operation of various policies and practices is essential. Several studies have examined the impact of investing in environmentally friendly shipping on company performance. The key finding is that incorporating eco-friendly shipping practices significantly influences firm performance, the loyalty of multinational corporations, and the environmental and financial performance of container shipping companies, underscoring the importance of integrating eco-friendly shipping management capabilities (Lun, hung Lai, Wong and Cheng (2014), Lirn, Lin and Shang (2014) and Jozef, Kumar, Iranmanesh and Foroughi (2019)). Institutions also play a crucial role by implementing policy measures that affect the market and the performance of shipping companies. Some measures that have been discussed include carbon taxes, which, however, could lead to reduced container handling volume and profits for ports and shipping firms (Song, Xu and Wang (2023a)). On the contrary, policy interventions should focus on influencing the economic attractiveness, returns, and financing of these technologies, as well as potentially influencing the choice of fuel and its impact on the economic viability of eco-friendly shipping technologies (Metzger (2022)). However, for any policy measure and practice in the realm of eco-friendly shipping to be effective, it must be quantifiable. This is vital because the evaluation of measures is essential to make well-informed decisions, improve operational efficiency, and ensure compliance with environmental regulations (Lai, Lun, Wong and Cheng (2013)). Furthermore, it is crucial to consider the interplay of various policy measures, as analyzing the interdependencies and dynamic effects of policies on each other offers valuable insights for practical implementation and decision-making, potentially fostering system evolution and uncovering the true impacts of policies (Fan, Xu, Luo and Yin (2022)).

2.2. Investing in Green R&D

Studying green R&D is crucial as it plays a significant role in tackling environmental issues and advancing sustainable progress. Organizations can make a difference by supporting green R&D, which aids in the advancement and implementation of eco-friendly innovations. Numerous empirical studies explore different aspects of green R&D, offering various insights. To begin with, companies are inclined to invest in green R&D only if such investments lead to improved firm performance beyond emission reduction Lee and Min (2015). Financial considerations also play a pivotal role in influencing companies' decisions regarding green R&D investments. Wu (2023) underscores the importance of financial factors in shaping R&D endeavors and the diverse impacts of financial restrictions on such activities. Therefore, to make environmentally beneficial investments, a balanced approach that combines adequate financing with favorable returns, both financially and competitively, is essential. Additionally, other studies underscore the environmental benefits of green R&D investments, particularly in terms of reducing SO2 emissions Stucki and Woerter (2019), Tang, Chen and Huang (2021), and Magnani and Tubb (2012).

In the field of theoretical research on green R&D, the primary focus has been on the impact of various emission taxes on oligopolistic markets, where competition between firms plays a vital role. When regulators intervene in the market, they are faced with the decision of whether to penalize companies for emissions through taxes or to incentivize companies to engage in green R&D through subsidies. According to Lee and Park (2021), a subsidy for green R&D proves to be more effective than an emissions tax when green R&D is efficient, irrespective of R&D spillovers. Furthermore, companies are motivated to collaborate in green R&D investments and pricing strategies in the context of dual manufacturers (Wu, Li and Du (2022)), which is a crucial consideration for policymakers when considering the establishment of incentives or penalties for sustainability. Another aspect explored in the literature is the impact of green R&D investment in competitive markets. Lambertini, Poyago-Theotoky and Tampieri (2017) reveals an inverted-U correlation between innovation and competition, influenced by the existence of R&D spillovers. These research findings significantly contribute to improve our understanding of the interaction between innovation and competition with respect to environmental issues. Additionally, Ni, Huang, Wang and Zhou (2020) demonstrates the trade-off between investing in capacity or sustainability, highlighting that in scenarios where the risk of environmental harm is substantial, prioritizing investment in capacity is preferable, while in low-risk situations, there are advantages to investing in green R&D. Furthermore, it is important to acknowledge that corporate objectives may not always align with personal management goals. Therefore, it is imperative to establish an effective incentive system that promotes sustainable practices and fosters a dedication to green R&D among managerial leaderships (Poyago-Theotoky and Yong (2019)). It is in the best interest of both owners/principals to devise a contract that encourages their managers to deviate from solely pursuing profit maximization, leading to a reduction in emission taxes and subsequently enhancing firms' profitability. Based on this analysis, Park and Lee (2023) examine various incentive models for managers, highlighting the strategic importance for firm owners to craft appropriate incentive compensation schemes that motivate managerial efforts towards emission reduction to lower the tax burden. Undoubtedly, advancing toward emission reduction necessitates the implementation of appropriate incentives for different stakeholders in the economy, commencing with well-thought-out regulations that facilitate informed decision-making processes.

Despite the previous theoretical examination, the theoretical exploration of the maritime industry considers a vertical structure comprising ports and shipping lines. This market configuration mirrors supply chains, which warrants a closer look at research that has delved into green R&D within this context. Building on this train of thought, Zhang, Tan and Ji (2023) examines the efficacy of input versus output subsidies in a supply chain that involves a manufacturer and a supplier. The selection of the superior subsidy policy, in terms of environmental sustainability and societal well-being, is not solely dictated by production externalities but also hinges on consumers' environmental consciousness. Another facet explored in the literature on supply chains is vertical collaboration among its constituents. In this context, Chen et al. (2019) examines the collaboration between a manufacturer and a retailer about investments in green R&D, concluding that the significance of the impact depends on the level of cooperation of each party, potentially resulting in a scenario where both companies, along with customers and the environment, are likely to benefit. Likewise, Wu, Zhang and Chen (2021) investigates a similar scenario involving two manufacturers in the upstream market. They observe that suppliers are open to collaborating with any manufacturer, including both, while manufacturers prefer an exclusive partnership. These studies illustrate the dynamics of the market and the inherent incentives for cooperation among stakeholders within a supply chain, always considering their unique characteristics, contributions to green R&D, and efficiency in this domain. Lastly, Rong and Xu (2020) investigates the influence of revenue-sharing contracts on the green supply chain, discovering that such contracts can improve the environmental sustainability of the supply chain. Therefore, it is crucial to recognize that fostering collaboration within supply chains is vital to the effective progression and advancement of R&D investments. In our contribution to the literature, we examine the maritime transportation market likened to a supply chain, introducing two key innovations: integrating green R&D into the maritime sector, called green shipping, and introducing competition between two supply chains, as the impacts of green R&D are predominantly scrutinized within a single supply chain.

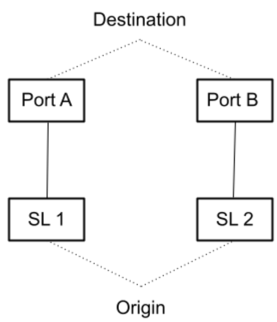
3. Benchmark model

In this section, we establish a transport network that consists of two ports in the upstream market, each having a distinct shipping line functioning in the downstream market. The pair of shipping lines are competitors, offering interchangeable services, hence the strategic dynamics between these shipping lines inherently shape the strategic interactions between the competing ports. A decision to invest in green R&D is made by one of the shipping lines, an investment that correlates directly with a reduction in unit carbon emissions.

3.1. Model description

Take into account two maritime ports, denoted as A and B, both of which proffer interchangeable shipping services. Each port is characterized by a unique shipping line in operation, thereby resulting in two distinct combinations of port-shipping services in competition. These shipping lines, offering a variety of services, concurrently determine their respective outputs. Figure 2 delineates a model exhibiting a vertical interrelation between the two markets. The upstream market is composed of the two ports, while the downstream market encompasses two shipping lines, denoted as SL.

Figure 2: The shipping distribution network



The inverse demand system for transportation services, which is derived from the utility maximization of the representative shipper,[1] [2] is defined as:

$$p_1 = a - q_1 - dq_2 \tag{1}$$

$$p_2 = a - q_2 - dq_1 \tag{2}$$

Where a and d are positive constants. The q_i's represent the quantity of output that shipping line i provides on a specific origin-destination path. The parameter $d \in (0, 1]$ serves to express the extent of service differentiation or the substitutability level among the services offered by the shipping line. If $d = 0$, it means the services are not related, whereas if $d = 1$, it implies that the services are perfectly interchangeable.

The total cost for the shipping companies for each route, which includes the freight rate of the ship and port charges, is denoted by p_i $(i = 1, 2)$. Thus:

$$p_1 = f_1 + w_A \tag{3}$$

$$p_2 = f_2 + w_B \tag{4}$$

For each shipping line, denoted as $i = 1, 2$, the shipping freight rates are represented by f_i, and w_j signifies the port charges that the shipping lines pay, where $j = A, B$. The duty of shipping companies is to transport cargo from the point of origin to the destination. The fees they charge encompass the cost of inland transportation and port charges. In the real-world scenario, shipping lines employ inland transportation services, and the cost for these services is integrated into the shipping lines' charges. Therefore, in this model, f_i symbolizes the charges that the shipping lines collect. The freight rates are ultimately derived from solving the equalities in 1 and 2 in conjunction with 3 and 4, as follows:

$$f_1 = a - q_1 - dq_2 - w_A \tag{5}$$

$$f_2 = a - q_2 - dq_1 - w_B \tag{6}$$

The shipping lines are the ones who impose the freight rates. Subsequently, their profit function, denoted as π_i, is constructed from the typical operating profits, which are $(f_i - c)q_i$. Here, the parameter c stands for the constant marginal costs. We assume that a shipping line, *SL1*, invests in Green R&D with the goal of increasing the efficiency of its production system, resulting in lower marginal costs. The cost of innovation for *SL1* is e, which is determined

[1] The inverse demand system is derived by maximizing the utility of the representative shipper, denoted as $U(q_1, q_2) = a(q_1 + q_2) - \frac{1}{2}(q_1^2 + q_2^2) - dq_1q_2$, with respect to q_1 and q_2. The system adheres to the standard properties: (i) the demand curve is downward-sloping, as indicated by $\frac{\partial p_i}{\partial q_i} = -1 < 0$; (ii) the system's own effects are more significant than the cross effects, as shown by $\frac{\partial p_1}{\partial q_1}\frac{\partial p_2}{\partial q_2} - \frac{\partial p_1}{\partial q_2}\frac{\partial p_2}{\partial q_1} = 1 - d^2 > 0$.

[2] Variations may exist among shipping lines in terms of the services they offer. These differences can be factored into the analysis by postulating diverse demand intercepts, which could be associated with factors like reliability, the safeguarding of port operations, improved departure timetable, priority, and so forth. The ensuing outcomes persist provided that these disparities are not overly significant.

by the equation $\frac{1}{2}te^2$, where t is the parameter that shows how costly it is to innovate and e is the R&D effort that *SL1* chooses. This innovation leads to a decrease in the marginal costs of γe, where γ is the sensitivity of carbon emission reduction. This model is consistent with the ideas presented in the seminal paper on R&D investment by d'Aspremont and Jacquemin (1988), and Chen et al. (2019), which focuses on Green R&D investment. The shipping lines' profit functions are then:

$$\pi_1 = (f_1 - (c - \gamma e))q_1 - \frac{1}{2}te^2 \tag{7}$$

$$\pi_2 = (f_2 - c)q_2 \tag{8}$$

The profits of ports are largely determined by the payments made by the shipping companies. These payments usually include charges for the utilization of port infrastructure and equipment, such as piers, cranes, and loading equipment. Moreover, these payments might encompass charges for services like berthing, upkeep of port installations, and protection. They might also incorporate governmental levies, charges and duties, along with agency charges for services such as paperwork handling and port navigation. The marginal costs have been adjusted to zero. As a result, the profit functions of the ports are:

$$R_A = w_A q_1 \tag{9}$$

$$R_B = w_B q_2 \tag{10}$$

This model stipulates that decision-making occurs in three stages. Initially, the *SL1* makes autonomous decisions about their individual green R&D investments with the aim of profit maximization. Subsequently, every port independently and concurrently determines the port charges w_A and w_B to optimize their profits. In the final and third stage, shipping lines engage in quantity competition. We define the subgame-perfect Nash equilibrium and resolve the game using a conventional backward approach.

3.2. Third phase: Competitive shipping in the downstream market

Each shipping line independently selects an output to maximize its own objective function, π_i, for all $i = 1, 2$. The result for each shipping line and the total outcome, taking into account the R&D effort and port fees, is as follows:

$$q_1^* = \frac{(a-c)(2-d) - 2w_A + dw_B + 2\gamma e}{4-d^2} \tag{11}$$

$$q_2^* = \frac{(a-c)(2-d) - 2w_B + dw_A - d\gamma e}{4-d^2} \tag{12}$$

$$Q^* = \frac{2(a-c) - w_A - w_B + \gamma e}{2+d} \tag{13}$$

where the superscript $*$ stands for the equilibrium in the benchmark case. From equations 11 and 12, it is evident that when ports reduce their port charges, their own outcome is improved, while the outcome of the other port is diminished. This competition effect demonstrates how ports can compete indirectly through port charges, with a transfer of outcome between them when they decide to increase or decrease their charges.

Proposition 1. *Investing in Green R&D creates an asymmetry in costs between shipping lines, resulting in an increase in the traffic of the investing shipping line,* $\frac{\partial q_1^*}{\partial e} = \frac{2\gamma}{4-d^2} > 0$, *and a decrease in the traffic of its competitor,* $\frac{\partial q_2^*}{\partial e} = -\frac{d\gamma}{4-d^2} < 0$, *leading to an overall growth in traffic,* $\frac{\partial Q^*}{\partial e} = \frac{\gamma}{2+d} > 0$.

Investing in green R&D decarbonization by a shipping line incurs additional costs, but can lead to a reduction in production costs. This cost asymmetry between the investing shipping line and its competitor, which continues to operate with higher production costs, can result in the investing shipping line offering more competitive pricing. The overall growth in traffic in the maritime industry, driven by investing in green R&D, is a positive outcome that not only benefits the investing shipping line, but also contributes to the industry's efforts to reduce carbon emissions and transition to greener practices. The specific details of the cost asymmetry and traffic growth would depend on various factors such as the scale of investment, the pricing of the ports, and the dynamics of competition between the shipping lines. This highlights the importance of considering these factors when formulating policies and strategies to promote decarbonization in the maritime industry.

3.3. Second stage: Upstream port competition

Ports A and B are in competition with each other, as their shipping lines provide substitutable services. Both ports decide independently and simultaneously on the amount of fees that the shipping alliances must pay, that is, $\underset{w_j}{Max}\ R_j,\ \forall\ j = A, B$. Consequently, the charges imposed by the ports are:

$$w_A^* = \frac{(a-c)(2-d)(4+d) + (8-d^2)\gamma e}{16-d^2} \tag{14}$$

$$w_B^* = \frac{(a-c)(2-d)(4+d) - 2d\gamma e}{16-d^2} \tag{15}$$

Proposition 2. *The investment of a shipping line in Green R&D leads to an increase in the pricing of the port it operates,* $\frac{\partial w_A^*}{\partial e} = \frac{(8-d^2)\gamma}{16-d^2} > 0$. *Consequently, the price of the rival port is decreased,* $\frac{\partial w_B^*}{\partial e} = -\frac{2d\gamma}{16-d^2} < 0$.

Based on Proposition 1, where investing in green R&D leads to an increase in traffic for the investing shipping line and a decrease in traffic for its competitor, we can understand the pricing dynamics between the ports. In Proposition 2, as the investing shipping line, *SL1*, experiences an increase in traffic due to its investment, the demand for the Port A also increases. In response to this increased demand, Port A can raise its prices to capitalize on the increased traffic and potentially improve its profitability. On the other hand, the competitor shipping line, *SL2*, operating in the rival Port

B experiences a decrease in traffic. Therefore, to mitigate the loss of traffic, Port B lowers its prices in an attempt to attract traffic and remain competitive. Therefore, the result reflects the competitive dynamics between the ports, where the actions of the investment shipping line influence the pricing strategies of both ports. Port A can increase its prices due to increased demand, while Port B decreases its prices to counter the loss of traffic. This pricing adjustment is a response to the changes in market demand resulting from the investment in green R&D by one of the shipping lines.

3.4. First stage: Shipping line decision on Green R&D investment

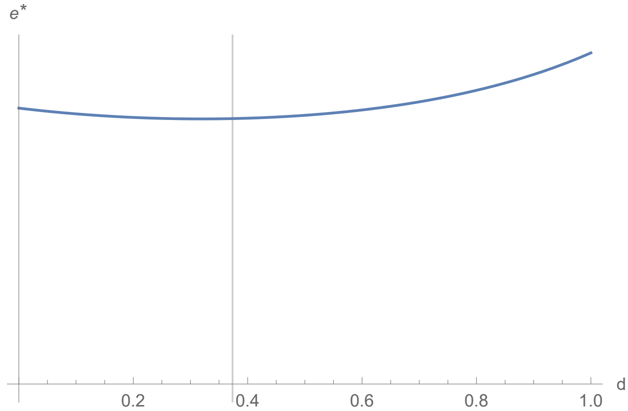
In the first stage, the *SL1* decides on its individual green R&D investment to maximize its own profit, $\underset{e}{Max}\ \pi_1$. For the result to be a maximum, t must be greater than a certain value, $t^* = \frac{8(8-d^2)^2\gamma^2}{(64-20d^2+d^4)^2}$, which depends on the degree of service substitutability and the sensitivity to carbon emission reduction. Specifically, $\frac{\partial t^*}{\partial d}, \frac{\partial t^*}{\gamma} > 0$, which means that as either of these two values increases, so does t^*. Then, the Green R&D total investment is:

$$e^* = \frac{8(a-c)(64-16d-16d^2+2d^3+d^4)\gamma}{(64-20d^2+d^4)^2 t - 8(8-d^2)^2\gamma^2} \tag{16}$$

Lemma 1. *The size of the market, $a-c$, the cost of innovation, t, the sensitivity to carbon emission reduction, γ, and the degree of substitution between services, d, all affect the level of investment in green R&D by a shipping line that invests in decarbonization, as can be seen in the equation. 16.*

1. *When the market size increases, the shipping line that invests in decarbonization tends to increase its investment in R&D. This is related to the fact that a larger market size may imply a greater demand for maritime transport services. As a result, the shipping line that invests in decarbonization can anticipate greater profits by satisfying this growing demand.*
2. *When the cost of innovation increases, the shipping line investing in decarbonization may reduce its investment in green R&D. This is because the expenses associated with the introduction of decarbonization technologies and procedures may be greater than anticipated advantages, making it more difficult for the shipping line to assign resources to R&D projects.*
3. *As the sensitivity to reducing carbon emissions increases, it can result in a greater capacity to reduce production costs through increased innovation due to R&D investment. This, in turn, leads to an increase in R&D investment. The connection between carbon emission reduction sensitivity and R&D investment implies that a higher sensitivity to carbon emission reduction leads to greater appreciation of the potential advantages of investing in R&D. This can be attributed to the understanding that investing in innovative solutions for decarbonization can not only contribute to environmental sustainability but also result in long-term cost savings and competitive advantages.*
4. *According to Figure 3, the relationship between R&D investment and the degree of substitution follows a U-shaped curve, with the minimum point occurring at $d \approx 0.37$, indicated by the vertical line on the graph. This indicates that as the competitive level of the downstream market increases, the shipping line that invests in green R&D increases its R&D efforts to counteract this competitive effect. This interpretation suggests that the shipping line that invests in decarbonization recognizes the importance of staying competitive in the market. As the degree of substitution between the services offered by the two shipping lines increases, there is a greater need for the investing shipping line to differentiate itself and maintain a competitive edge. This can be achieved through increased investment in R&D, which allows the shipping line to further reduce its costs.*

Figure 3: Effect of service substitutability on e^*



3.5. Strategic effects of Green Shipping R&D investment

The strategic decision of one shipping line, *SL1*, to invest in green R&D for decarbonization while the other does not invest creates an asymmetric market dynamic. This investment by *SL1* leads to a competitive cost advantage, resulting in increased traffic and profits for *SL1*, while its rival experiences the opposite effect. The strategic decision of *SL1* to invest in decarbonization R&D reflects a proactive approach to address environmental concerns while simultaneously gaining a competitive edge in the market. This is in line with the growing emphasis on sustainable practices and the increasing importance of environmental considerations in business strategies. Furthermore, it underscores the potential for asymmetric market effects resulting from the differential investment in green R&D within the maritime industry. We can point out the following lemma.

Lemma 2. *Shipping lines have incentives to invest in green R&D, because they increase their profits and their market power.*

The result of the lemma also extends to the upstream market, where the effect on the profits of shipping lines translates to the ports. Therefore, ports also have incentives for the shipping lines operating within them to invest in decarbonization, as it indirectly enhances their competitiveness in the market. The interconnected nature of the maritime industry means that the decisions and actions of one stakeholder, such as shipping lines investing in decarbonization, can have cascading effects on other stakeholders, including ports. This underscores the importance of considering the incentives and motivations of various actors within the maritime supply chain when examining the dynamics of green R&D investment and decarbonization efforts. The result of the lemma highlights the interconnected incentives within the maritime industry, where the strategic decisions of the shipping lines to invest in green R&D for decarbonization can indirectly influence the competitiveness and incentives of ports, creating a network of aligned interests in the pursuit of sustainable and decarbonized practices.

Once we have examined the strategic effects of investing in green R&D, we must ensure that the freight rates of *SL1* are positive, which means that $t > t_1^f > t^*$. This additional condition that ensures positive freight rates for the shipping line investing in R&D stipulates that the cost of innovation must exceed a sufficiently large threshold. This condition can be interpreted as a mechanism to guarantee that the investment in R&D for decarbonization is substantial and effective. The lemma we discussed before, combined with this condition, leads to the following proposition, which has an impact on the market structure.

Proposition 3. *If the shipping line market is sufficiently small and competitive and $t^{f_1} < t < t^{q_2}$, a drastic innovation occurs where SL2 is expelled from the market.*

According to Proposition 3, for the production of the rival company to be positive, $q_2^* > 0$, it is necessary that $t > t^{q_2} > t^*$. The relationship between the different conditions, t^{f_1} and t^{q_2}, is dependent on the size and competition of the market. When $t > t^{q_2}$, the innovation is not drastic and the competitor can remain in the market. This is the case when $t^{f_1} > t^{q_2}$ and when the markets are either large, $a > \frac{5}{3}c$, or small but not competitive, $a \leq \frac{5}{3}c$ and $d < \hat{d} = \sqrt{\frac{7a^2-12ac+6c^2}{(a-c)^2}} - \frac{a}{a-c}$. On the other hand, if the market is small but highly competitive, $d > \hat{d}$, then $t^{q_2} > t^{f_1}$ and two scenarios can occur. The first is $t > t^{q_2} > t^{f_1}$, which is the case of a non-drastic innovation, and the second is that $t^{f_1} < t < t^{q_2}$, which is the case of a drastic innovation that causes the rival to be expelled from the market.

This analysis emphasizes the influence of market size and competition on innovation results in the maritime sector. In small and highly competitive markets, radical innovation can lead to the elimination of competitors, possibly due to the limited room for multiple businesses to prosper. On the other hand, in larger or less competitive markets, the dynamics may permit the coexistence and rivalry among multiple players, decreasing the probability of drastic innovation causing the removal of competitors.

4. The effects of R&D Spillovers

In the context of green shipping R&D investment and the competition between shipping lines, it is essential to consider the concept of spillovers and their relevance. Spillovers play a crucial role in understanding the broader impact of green R&D activities in the maritime industry. Specifically, in the context of this study, R&D spillovers refer to the diffusion of knowledge, technology, and innovation from one shipping line to another, which could influence decarbonization efforts and technological advancements in the industry. Understanding the dynamics of R&D spillovers is vital for comprehending how investments in green shipping R&D by one company may have effects beyond its immediate scope, potentially influencing the competitive landscape and the overall progress towards decarbonization in the maritime sector.

4.1. R&D Spillovers in the model

Given the presence of R&D spillovers, this implies that the competing shipping line possesses the ability to assimilate knowledge produced by the shipping line that invests in environmentally friendly technology. This assimilation of knowledge has the potential to impact the production and profitability of the competing shipping line, thereby transforming the competitive landscape in the maritime industry. Within the framework of the model, the incorporation of R&D spillovers prompts a revision of Equation 8, culminating in a newly formulated profit function for the competing shipping line, which is articulated as:

$$\pi_2 = (f_2 - (c - \theta\gamma e))q_2 \tag{17}$$

The parameter θ, which ranges from 0 to 1, represents the spillover effect. A higher value of θ indicates a higher absorption capacity and a lower cost for the rival shipping line, *SL2*. Therefore, adjusting the model to account for R&D spillovers allows for the assessment of their impact on the competitive dynamics and the performance of the shipping lines involved.

4.2. Third stage: Shipping competition considering R&D spillovers

Each shipping line independently chooses an output to maximize its own objective function, π_i, for all $i = 1, 2$. The outcome for each shipping line and the total result, considering the R&D effort, R&D spillovers, and port fees, is as follows:

$$q_1^S = q_1^* - \frac{\theta d\gamma e}{4 - d^2} \tag{18}$$

$$q_2^S = q_2^* + \frac{2\theta\gamma e}{4 - d^2} \tag{19}$$

$$Q^S = Q^* + \frac{\theta\gamma e}{2 + d} \tag{20}$$

where the superscript S stands for the equilibrium when considering spillovers. Equations 18 to 20 demonstrate that the spillover effect has a significant impact on competition in the downstream market. Specifically, as the output of *SL2* increases, *SL1* experiences a decrease in its output. This decrease can be attributed to the intensified competition caused by the spillover effect, which affects the strategic decisions of the shipping lines. Despite the decrease in *SL1*'s output, the total output of the shipping lines increases. This suggests that, while the spillover effect may lead to more competition and a redistribution of market share between shipping lines, it ultimately contributes to an overall increase in the total output of the shipping industry. This finding provides a deeper understanding of the observed result, emphasizing the implications of the spillover effect on competition and total output of shipping lines.

Proposition 4. *When taking into account spillovers, investing in Green R&D has a greater effect on output than if there were no spillovers. Moreover, if the spillover is sufficiently high, SL1's investment in Green R&D can increase SL2's traffic, that is,* $\frac{\partial q_2^S}{\partial e} = \frac{\gamma(2\theta - d)}{4-d^2} > 0$ *if* $\theta > \frac{d}{2}$.

Proposition 1 suggests that investments in decarbonization by *SL1* can lead to an asymmetry in costs, which can benefit *SL1* at the expense of its rival's outcome. According to Proposition 4, the competitive dynamics between the shipping lines is affected by the cost reductions that come from green R&D investments and technological spillovers. This can lead to an increase in demand, which can have a positive effect on *SL2*'s traffic if the knowledge spillovers are significant. This implies that if shipping lines are able to effectively absorb the knowledge of those investing in green R&D, they can also increase their traffic, thus creating incentives to develop the capacity to absorb such knowledge. Furthermore, the ability to appropriate the knowledge of competitors investing in green R&D can lead to increased traffic and competitive advantages for the shipping lines, highlighting the importance of knowledge absorption capacity and the potential to leverage spillovers to improve competitiveness and outcome. It is accurate to say that this is the case where θ is greater than 0.5. This is the highest value of d which is equal to 1, and is when services are perfect substitutes.

4.3. Second stage: Port pricing

Competition between ports has intensified as port B has seen a surge in traffic and has become more competitive due to the spillover effect, allowing the shipping line to generate more business. Therefore, the fees charged by the ports are as follows:

$$w_A^S = w_A^* - \frac{2\theta d\gamma e}{16 - d^2} \tag{21}$$

$$w_B^S = w_B^* + \frac{\theta(8 - d^2)\gamma e}{16 - d^2} \tag{22}$$

It is easily observed how the existence of spillovers reduces the pricing of Port A, while increasing the pricing of Port B, with respect to the result of Proposition 2. The effect that is produced is the same as before, but in reverse, because now it is *SL2* that expands the market. So Port B can raise its prices to capitalize on the increased traffic and potentially improve its profitability. Whereas Port A reduces its price to mitigate the outcome loss. The effect on prices will depend mainly on the absorption capacity, θ.

Proposition 5. *When considering spillovers, the influence of Green R&D investment on airport pricing is more pronounced, so that* $\frac{\partial w_A^S}{\partial e}, \frac{\partial w_B^S}{\partial e} > \frac{\partial w_A^*}{\partial e}, \frac{\partial w_B^*}{\partial e}$. *On the other hand, the price of port B, which previously decreased with the investment in Green RD, can now increase if the spillover is significant, that is,* $\frac{\partial w_B^S}{\partial e} > 0$ *if* $\theta > \frac{2d}{8-d^2}$.

The outcome of this proposition is consistent with the explanation of Proposition 4. This is because the competitiveness of the upstream market is dependent on the competition in the downstream. This relationship is essential to comprehend the effect of investing in green R&D on the ports pricing strategies and general market trends. From Proposition 2, we can see that the effect of investment in R&D caused the price of port B to decrease, a strategic move to increase its competitiveness. In this case, the relationship is reversed if the absorption capacity of *SL2* is large enough. Specifically, it would always be fulfilled if $\theta > \frac{2}{7} \approx 0.286$. Therefore, if $0.286 < \theta < 0.5$ when $d = 1$, it implies that Port B has the ability to increase its prices, but its traffic does not increase, only when $\theta > 0.5$. This is applicable to any value of d, with thresholds varying.

4.4. First stage: Green R&D investment with spillovers

To maximize the investment level, it is necessary to satisfy the following condition: $t > t^S = \frac{8\gamma^2(8-2\theta d-d^2)^2}{(64-20d^2+d^4)^2}$. The introduction of spillovers leads to a reduction in the value of t, hence $t^S < t^*$ due to $\frac{\partial t^S}{\partial \theta} < 0$. With this information, the level of investment in Green R&D can be determined.

$$e^S = \frac{8\gamma(a-c)(2-d)(4+d)(8-2\theta d-d^2)}{(64-20d^2+d^4)^2 t - 8(8-2\theta d-d^2)^2\gamma^2} \tag{23}$$

Proposition 6. *When comparing it with e^*, we observe that if $t^* > t^S$, then when the comparison condition is satisfied by t^*, we find that $e^* > e^S$. Thus, spillovers diminish the motivation to invest in decarbonization. Moreover, the impact increases with the expansion of the spillover, for instance, when $\frac{\partial e^S}{\partial \theta} < 0$.*

The existence of R&D spillovers can diminish the motivation of individual shipping companies to engage in green R&D, as the advantages of such endeavors might be distributed among other shipping lines. This occurrence is the result of the spread of technology and expertise among companies, which could reduce the perceived competitive edge obtained from individual R&D initiatives. Furthermore, the potential for sharing knowledge and diffusion of technology could create a scenario in which companies expect to enjoy the benefits of R&D investments made by others without bearing the related costs, thus diminishing their own drive to invest in green R&D. Additionally, the influence of R&D spillovers on the competitive environment and market dynamics shapes the investment choices of shipping companies.

4.5. Strategic effects of spillovers

Even with the consideration of spillovers, Lemma 2 remains valid. Therefore, the shipping line that chooses to invest in green shipping has an incentive to do so, and ports also find it advantageous to engage with shipping lines that are committed to green R&D. Furthermore, although the incentives of investing in green R&D are on the rise, there is a reduction in their profits due to the presence of spillovers. In such scenarios, drastic innovation could potentially occur, leading to the displacement of a competitor from the market. However, the circumstances for this to occur are more stringent because of the positive impact that spillovers have on competitors who do not invest in green R&D. Consequently, the essence of Proposition 4 is sustained, resulting in a situation where radical innovation occurs, potentially driving out the competitor, provided that two conditions are satisfied: i) it is a relatively small market, smaller than in the absence of spillovers, such that $a > c\frac{(6-d^2)(1-\theta)}{d(2+d)-2(3+\theta)}$; ii) the absorption capacity of the spillover is not excessively high, meaning $0 < \theta < \frac{2d}{8-d^2}$, with the maximum limit being $\frac{2}{7}$ when $d = 1$, which equates to slightly less than 30% absorption capacity with the spillover.

5. Conclusions and policy implications

The shipping industry faces the significant challenge of decarbonization, which requires substantial investment in R&D to meet the restrictions imposed in the industry. The issue of sustainability has been approached from various perspectives in the literature. The integration of multiple strands of literature has led to the concept of green shipping, which involves the adoption of sustainable measures and investment in R&D by shipping lines in the maritime transport industry. Our contribution focuses on analyzing the investment in green R&D by a shipping line in a competitive market. We examine a model where two ports coexist, sharing an area of influence, with each port exclusively served by a shipping line. These shipping lines compete as they offer substitutable services, and one of them decides to invest in green R&D. Our aim is to analyze how the decision of a shipping line to invest in R&D affects market dynamics and port pricing, taking into account spillover effects. We find that shipping lines have incentives to invest in green R&D, and ports prefer to operate with more sustainable companies.

In light of the policy outcomes from this study, the encouragement for shipping lines to invest in Green R&D could be amplified through policy actions such as financial rewards, tax deductions or grants for the adoption of green technology and investment in R&D. Moreover, ports can be motivated to partner with shipping lines that invest in Green R&D by providing benefits like lower port charges or priority access for vessels that are environmentally friendly. These policies are designed to foster a supportive atmosphere for the uptake of green technologies and R&D investment in the shipping industry, ultimately aiding in the decrease of greenhouse gas emissions and the encouragement of sustainable practices in maritime transport. These initiatives are in line with worldwide efforts to lessen climate change and foster environmental sustainability in the shipping field. Conversely, the existence of spillovers might discourage shipping lines from investing in green shipping R&D. This underscores the necessity for synchronized international actions to guarantee fair competition and encourage the use of environmentally friendly technologies and practices. By cultivating a regulatory climate that backs sustainable initiatives and provides incentives for green R&D investment, policymakers can lessen the negative spillover impacts and establish a favorable environment for the extensive adoption of green shipping practices.

In this article, we have focused on analyzing the effects of a shipping line investing in green shipping, recognizing that many insights stem from this point. Two avenues of analysis emerge, including the consideration of both vertical and horizontal collaboration, common in supply chain analysis and particularly within the maritime transport market, taking into account green R&D investment. Furthermore, the impact of emission taxes and subsidies in this new approach is worth exploring, as previous analyses were conducted on competitive models without considering the interaction between two markets or their cooperation. Therefore, this serves as a stepping stone for further research in the field of green shipping focused on investment in green R&D to continue growing.

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Declaration of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Writefull and Afforai to enhance the quality and accuracy of the content by leveraging AI-powered language and writing assistance tools. After using these tools, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Adrián Nerja: Conceptualization, Methodology, Formal analysis, Writing - Original Draft, Writing - Review Editing. **Mariola Sánchez:** Conceptualization, Validation, Writing - Original Draft, Writing - Review & Editing, Visualization.

References

Álvarez-SanJaime, Ó., Cantos-Sánchez, P., Moner-Colonques, R., Sempere-Monerris, J.J., 2013. Vertical integration and exclusivities in maritime freight transport. Transportation Research Part E: Logistics and Transportation Review 51, 50–61.

Brânză, G., 2023. Green shipping. study on regulations and sustainable options for decarbonisation. Journal of Marine Technology and Environment .

Chen, X., Wang, X., Zhou, M., 2019. Firms' green r&d cooperation behaviour in a supply chain: Technological spillover, power and coordination. International Journal of Production Economics 218, 118–134.

d'Aspremont, C., Jacquemin, A., 1988. Cooperative and noncooperative r&d in duopoly with spillovers. The American Economic Review 78, 1133–1137.

Dong, J., Zeng, J., Yang, Y., Wang, H., 2022. A review of law and policy on decarbonization of shipping. Frontiers in Marine Science 9, 1076352.

Fan, L., Xu, Y., Luo, M., Yin, J., 2022. Modeling the interactions among green shipping policies. Maritime Policy & Management 49, 62–77.

Jozef, E., Kumar, K.M., Iranmanesh, M., Foroughi, B., 2019. The effect of green shipping practices on multinational companies' loyalty in malaysia. The International Journal of Logistics Management 30, 974–993.

Lai, K.H., Lun, Y.V., Wong, C.W., Cheng, T., 2013. Measures for evaluating green shipping practices implementation. International Journal of Shipping and Transport Logistics 5, 217–235.

Lambertini, L., Poyago-Theotoky, J., Tampieri, A., 2017. Cournot competition and "green" innovation: An inverted-u relationship. Energy Economics 68, 116–123.

Lee, K.H., Min, B., 2015. Green r&d for eco-innovation and its impact on carbon emissions and firm performance. Journal of Cleaner Production 108, 534–542.

Lee, S.H., Park, C.H., 2021. Environmental regulations in private and mixed duopolies: Taxes on emissions versus green r&d subsidies. Economic Systems 45, 100852.

Lee, T., Nam, H., 2017. A study on green shipping in major countries: in the view of shipyards, shipping companies, ports, and policies. The Asian Journal of Shipping and Logistics 33, 253–262.

Lirn, T.C., Lin, H.W., Shang, K.C., 2014. Green shipping management capability and firm performance in the container shipping industry. Maritime Policy Management 41, 159–175. doi:10.1080/03088839.2013.819132.

Lister, J., 2015. Green shipping: Governing sustainable maritime transport. Global Policy 6, 118–129.

Liu, J., Wang, J., 2019. Carrier alliance incentive analysis and coordination in a maritime transport chain based on service competition doi:10.1016/j.tre.2019.06.009.

Lun, Y.H., hung Lai, K., Wong, C.W., Cheng, T.C., 2014. Green shipping practices and firm performance. Maritime Policy Management 41, 134–148. doi:10.1080/03088839.2013.819133.

Magnani, E., Tubb, A., 2012. Green r&d, technology spillovers, and market uncertainty: an empirical investigation. Land Economics 88, 685–709.

Mair, H., 1995. Green shipping. Marine Pollution Bulletin 30, 360–360.

Metzger, D., 2022. Market-based measures and their impact on green shipping technologies. WMU Journal of Maritime Affairs 21, 3–23.

Metzger, D., Schinas, O., 2019. Fuzzy real options and shared savings: Investment appraisal for green shipping technologies. Transportation Research Part D: Transport and Environment 77, 1–10. doi:10.1016/J.TRD.2019.09.016.

Nerja, A., Sánchez, M., 2023. The impact of revenue-sharing contracts on parallel shipping alliances. Transport Economics and Management 1, 77–85. doi:10.1016/j.team.2023.06.004.

Ni, J., Huang, H., Wang, P., Zhou, W., 2020. Capacity investment and green r&d in a dynamic oligopoly under the potential shift in environmental damage. Economic Modelling 88, 312–319.

Ong, C.H., Yeo, H.Y., Kang, H.S., Liu, Y.L., Tan, O.K., 2022. A conceptual analysis of green shipping practices, rational culture and sustainability for a safer and sustainable ocean, in: 2022 IEEE International Conference on Industrial Engineering and Engineering Management (IEEM), IEEE. pp. 1033–1037.

Park, C.H., Lee, S.H., 2023. Emission taxation, green r&d, and managerial delegation contracts with environmental and sales incentives. Managerial and Decision Economics 44, 2366–2377.

Peng, Q., Wang, C., Goh, M., 2023. Green innovation decision and coordination of supply chain under corporate social responsibility and risk preferences. Computers & Industrial Engineering 185, 109703.

Poyago-Theotoky, J., Yong, S.K., 2019. Managerial delegation contracts,"green" r&d and emissions taxation. The BE Journal of Theoretical Economics 19, 20170128.

Prokopenko, O., Miśkiewicz, R., 2020. Perception of green shipping in the contemporary conditions. Entrepreneurship and Sustainability Issues 8, 269.

Rong, L., Xu, M., 2020. Impact of revenue-sharing contracts on green supply chain in manufacturing industry. International Journal of Sustainable Engineering 13, 316–326.

Shi, W., Xiao, Y., Chen, Z., McLaughlin, H., Li, K.X., 2018. Evolution of green shipping research: Themes and methods. Maritime Policy & Management 45, 863–876.

Song, J., Xu, C., Wang, C., 2023a. Impacts of the carbon tax on green shipping supply chain under the port competition. Expert Systems , e13229.

Song, Z.Y., Chhetri, P., Ye, G., Lee, P.T.W., 2023b. Green maritime logistics coalition by green shipping corridors: a new paradigm for the decarbonisation of the maritime industry. International Journal of Logistics Research and Applications , 1–17.

Stucki, T., Woerter, M., 2019. Competitive pressure and diversification into green r&d. Review of Industrial Organization 55, 301–325.

Tang, Y., Chen, S., Huang, J., 2021. Green research and development activities and so2 intensity: an analysis for china. Environmental Science and Pollution Research 28, 16165–16180.

Tsouri, M., Hansen, T., Hanson, J., Steen, M., 2022. Knowledge recombination for emerging technological innovations: The case of green shipping. Technovation 114, 102454.

Wang, W., Liu, Y., Zhen, L., Wang, H., 2022. How to deploy electric ships for green shipping. Journal of Marine Science and Engineering 10, 1611.

Wang, Z., Wang, Y., Afshan, S., Hjalmarsson, J., 2021. A review of metallic tanks for h2 storage with a view to application in future green shipping. International Journal of Hydrogen Energy 46, 6151–6179.

Wu, A., Li, H., Du, D., 2022. Quantum game analysis of green technology r&d cooperation between competing manufacturers under government subsidies. Technology Analysis & Strategic Management , 1–18.

Wu, R., 2023. Innovation or imitation? the impacts of financial factors on green and general research and development. International Review of Economics & Finance 88, 1068–1086.

Wu, Y., Zhang, X., Chen, J., 2021. Cooperation of green r&d in supply chain with downstream competition. Computers & Industrial Engineering 160, 107571.

Xu, L., Lee, S.H., 2024. Port supply chain integration under mixed ownership. Transport Policy 146, 371–385.

Zhang, Y., Tan, Q., Ji, Y., 2023. Input subsidy versus output subsidy for green r&d in a supply chain. Journal of International Development 35, 97–126.

Zheng, S., Luo, M., 2021. Competition or cooperation? ports' strategies and welfare analysis facing shipping alliances doi:10.1016/j.tre.2021.102429.