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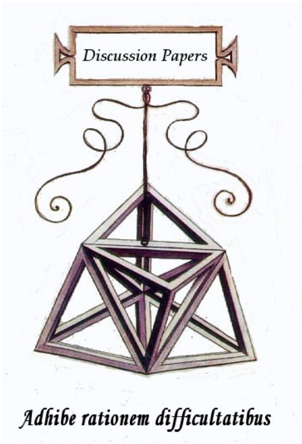

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Port emissions and abatement investments in an international oligopoly: a tale of three policies

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n. 329

Adhibe rationem difficultatibus

Domenico Buccella, Nicola Meccheri, Marcella Scrimitore

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JEL CLassification: D43; F18, H23; L33, R48

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Domenico Buccella†, Nicola Meccheri‡ and Marcella Scrimitore*

March 17, 2026

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1 Introduction

Human population is highly exposed to marine-related emissions. UNEP (2024) estimates that approximately three-quarters of all world's large cities are located on coasts, 50 percent of the world's population lives within 60 km from the ocean's coastal area, and 70 percent of marine emissions occur within 400 km of the coast. In this respect, maritime ports are transport nodes and catalysers of industrial, logistic and economic activities, and thus major producers of air emissions. Accordingly, cutting emissions from ports and other maritime sources would improve both the environmental quality of over 3.5 billion people and give a substantial contribution to fight climate change.

The ports' environmental damage caused by low air quality is due to various causes: the type of fuel used by ships, principally diesel; loading and unloading operations; heavy vehicle traffic; and power generation and machinery use. Mobile sources at ports release pollutants including particulate matter (PM), nitrogen oxides (NOx), sulfur oxides (SOx), carbon dioxide (CO2), volatile organic compounds (VOCs) and air toxics. In the port cities, port activities have a heavy impact on local emissions of those pollutants: for example, the three major air pollutants of the Shanghai port, namely, SO_2, NO_x and $PM_{2.5}$ constitute a substantial proportion of Shanghai's emissions: 12.4%, 11.6% and 5.6%, respectively (Fung et al., 2014); the Port of Hamburg accounts for at least 28% of the NO_x emissions of the whole city (HPA, 2019). Because of the environmental and health impacts of those emissions, several ports have developed air quality programs with a central focus on reducing NO_X, SO_X and PM.

Nonetheless, forecasts about seaborne trade estimate an increasing trend (UNCTAD, 2022, 2023). At the same time, public opinion's demand and support for actions to reduce air pollution and cut greenhouse gas (GHG) emissions exert political pressure, leading policymakers to place stricter environmental policies on their agenda.[1] Indeed, ports will play a focal role in Europe's decarbonisation agenda. In fact, the 2021 EU Green Deal set a target of 90% emissions reductions for transport and EU port cities by 2050 (EEA, 2024). Furthermore, the EU has publicly declared a need to bring shipping under the ETS, although no date has been set yet (European Commission, 2024). Compared to 2008 levels, the International Maritime Organization (IMO) fixed a CO2 reduction target of at least 40% for international shipping by 2030, carrying out efforts towards net-zero GHG emissions by or around, i.e. close to, 2050 (IMO, 2023). North American coasts fall under an Emission Control Area (ECA) in which international emission standards apply for ships. The ECA extends up to 200 nautical miles from the coasts of the United States, Canada and the French Territories, with the exclusion of U.S. territories or the western coast of Alaska, and whose aim is to provide significant reductions in $PM_{2.5}$, NO_X, SO_X and toxic compounds, both in the near term and the long term (EPA, 2024). The United Nation Environment Program (UNEP) is now conducting Sustainable clean port program (SCP) projects in Southeast Asia (ASEAN), Africa, Latin America and the Caribbean.

There is a wide range of abatement measures that can be implemented by policy makers to drive ports in reducing their emissions (Lam and Notteboom, 2014; Acciaro et al., 2014a, 2014b; Gibbs et al., 2014; Gonzalez-Aregall et al., 2018; Bergqvist and Monios, 2019; Sornn-Friese et al., 2021). Central and local authorities can adopt an enforcement approach by setting minimum technical and environmental standards regulation to green port development (Lam and Notteboom,

[1] In 2008, a global alliance of port authorities formed the multi-stakeholder World Port Climate Initiative in response to public pressure to address climate change and air quality concerns (WPCI, 2008). Similarly, the International Association of Ports and Harbors (IAPH) has released a toolkit providing ports with "...quick access to the tools needed to start the planning process for addressing port-related air quality and climate change related issues" (IAPH, 2020).

2014; Poulsen et al., 2018). This measure can include compulsory fuel switch programs (e.g., the use of low sulphur fuel and MDO) or the installation of emission control equipment on ships (e.g., scrubbers).[2]

Other programs are based on voluntary policies: the authorities set standards and requirements providing economic incentives, training and traffic management programs to comply with them. The economic incentives, also including subsidies, can be granted for piloting program implementation, rebate or concession of fees and dues. In such a way, port stakeholders get incentives to invest in emissions reduction activities or implement environmental-friendly organizational, managerial and behavioural changes (Bergqvist and Egels-Zandén, 2012; Bergqvist et al., 2015; Gonzalez-Aregall et al., 2018; see also UNEP, 2024).

Finally, given that pollution can be measured and traced (Villalba and Gemechu, 2011; Geerlings and Van Duin, 2011; Gibbs et al., 2014), the idea that governments directly design and implement environmental regulations by imposing emission control taxes has been acquiring increasing attention (Wang et al., 2009; Tseng and Pilcher, 2016; Cui and Notteboom, 2017; Zheng et al., 2017; Sheng et al., 2017). For instance, faced with the challenges of limiting global warming, the European Commission unveiled its European Green Deal in December 2019, which also provided for the extension of the EU Emission Trading System to maritime transport providing that European shippers must pay a carbon tax based on declared emissions. Also, a worldwide carbon tax on the shipping industry is being seriously considered as a powerful incentive for the shipping actors to innovate, by investing in cleaner, more efficient technologies to reduce their carbon footprint and minimize tax liabilities.[3]

Motivated by the growing interest in adopting policies aimed at reducing port pollution, this paper investigates three different port air emissions abatement measures–(i) emission taxes; (ii) subsidies on abatement technology investments; and (iii) emission standard–in a two-country model *à la* Brander and Krugman (1983), in which each government regulates its domestic polluting port. Two firms (one firm located in each country) compete in quantities, choosing the quantity to export and the quantity of domestic trade. Ports allow each firm to export its output to the other country,[4] set usage fees and determine abatement efforts under the policy constraints.

By accounting for differences in port ownership observed in the real world, the analysis also aims to investigate how the degree of privatization of ports shapes the ports' incentives to set the usage fees and invest in emission abatement. Indeed, starting from 1980s, the ownership and governance of ports has changed dramatically and private sector investment and involvement in ports has emerged as a significant issue (e.g., Rodal and Mulder, 1993; Trujillo and Nombela, 1999; Baird, 2000; Brooks, 2004; Midoro et al., 2005; Tongzon and Heng, 2005). Many ports around the world have been moving away from a completely public ownership and management model (the so-called *''public service'' port*), in which the government owns the port infrastructures and superstructures, to other ownership structures and organizational models, which provide for an ever-increasing role for private companies and operators.

Specifically, according to the general category (ownership structure) defined by The World Bank (2025), ownership and management models that combine public and private participation in port activities include *''tool'' ports*, where all the port infrastructures and superstructures are

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[2] The port authorities of Rotterdam, Antwerp, Amsterdam, Le Havre, Hamburg and Bremen in cooperation with IAPH have developed the Environmental Ship Index (ESI) to give scores to ships ranging from 0 to 100 with 100 points corresponding to a zero-emission ship (Lam and Notteboom, 2014).

[3] See: https://port-xchange.com/blog/the-impact-of-a-global-carbon-tax-on-the-shipping-industry/.

[4] Ports have always been involved in international trade, insofar as they handle their country's maritime imports and exports (e.g., Trujillo and Nombela, 1999; González and Trujillo, 2009).

publicly owned, whilst some services, especially cargo handling, are provided as concessions to the private sector to run (the Port of Chittagong in Bangladesh exemplifies the tool port), and *''landlord'' and "corporatized" ports*, in which the port authority acts as regulatory body and as landlord, while port operators are carried out by private companies. Examples are Rotterdam, Antwerp, New York, and since 1997, Singapore. A recent example in Europe is the Port Authority of Santander (Spain) which, in October 2019, allocated the administrative concession for the construction and operation of a port terminal of solid fertilizers open to the general traffic (The World Bank, 2024). Finally, even if less common, there is also a fully privatized port model (mainly in the UK and New Zealand), in which ownership of port land, as well as that of all infrastructures and activities is transferred by the government to private entities.[5] Generally, the higher the degree of public/state-owned stake, the stronger the focus of port decisions on the overall domestic welfare, including not only port profits but also consumer surplus, environmental damage and other firms' profits (e.g., Cui and Notteboom, 2017; Notteboom et al., 2026).

The main results of this study suggest that the degree of port ownership and the level of shipping costs play a role in determining the ranking of the considered environmental policies. We find that the environmental damage is minimized under emission standard regardless of any degree of port privatization, as each government decides upon the standard by fully internalizing the social costs and benefits of the abatement imposed to ports. However, emission standards turn out to never dominate the other policies in the perspective of consumer surplus and overall domestic welfare. Indeed, under a standard policy, environmental protection imposes higher costs to ports, translating into higher port fees at detriment of both consumers and overall welfare.

Conversely, under environmental taxation and abatement subsidies, semi-public ports choose the optimal abatement investment. In particular, the trade-off between environment and economic welfare is softened by the fact that ports take the impact of the abatement investment on the trade flows, via port usage fees, into account. Specifically, by inducing abatement investments and large port fees reductions, a subsidy-based policy enhances trade volumes to a larger extent, yielding the highest consumer surplus and, if shipping costs are sufficiently low to encourage trade, the highest domestic welfare. Increased product market competition under subsidies, however, produces the highest level of environmental damage.

By contrast, as it implies higher unit cost for ports, environmental taxation limits abatement investments and leads to higher port fees, hence reducing international trade. This results in neither economic welfare dominance nor improved environmental quality of emission taxation with respect to abatement subsidies. However, when international trade declines due to higher shipping costs, the advantages of abatement subsidization are mitigated as well as the inefficiencies associated with environmental taxation. As a result, the latter turns out to become the domestic welfare maximizing policy, provided that ports are highly privatized and abatement investments are sufficiently large.

Finally, we find that, when the policy choice is endogenized, environmental taxation by the two governments emerges as the unique Nash equilibrium in dominant strategies. Taxation, indeed, by directly raising port usage fees, is strategically adopted by each government to reduce trade

[5] Several projects of port privatizations are currently under consideration. A public discussion/debate is ongoing in Italy on the idea of privatizing state-ports (Port News, 2023). In Africa, the Philippines' International Container Terminal Services Inc has been selected as an equity partner to run and expand the Durban Container Terminal Pier 2, becoming partially owner of the infrastructure (Bloomberg, 2023). Brazil is progressing with the development of a new container terminal at the Port of Santos, which the Ministry of Ports and Airports intend to privatize (The Maritime Executive, 2024). In India, the government plans to increase private sector participation in the port sector, increasing the public-private partnerships in state-owned ports to 80% by 2023. In December 2022, India's ministry of ports, shipping and waterways published a list of 81 public-private partnerships to be allocated prior to March 2025 (Policycircle.org 2024).

volumes and reallocate production toward domestic markets, which lets the equilibrium be the most favourable outcome for each country when shipping costs and the degree of port privatization are sufficiently high (in the other cases a prisoner-dilemma-type equilibrium emerges).

By adopting an industrial organization perspective, such results contribute to the growing literature on the environmental regulation of port activity by highlighting the crucial role of port ownership in determining the relative effectiveness of alternative environmental policies. The line of thinking adopted, admittedly abstract, could provide guidance for policymakers facing the challenge of improving environmental sustainability while preserving welfare in increasingly privatized and globally interconnected port systems.

The remainder of the article is as follows. Section 2 describes the contribution of this work with respect to the related literature. Section 3 presents the basic ingredients of the model and derives the outcomes under the three considered policies. Section 4 compares the environmental and welfare effects of policies. Section 5 analyses the endogenous policy choice by governments. Section 6 provides a discussion of the main results and highlights their main policy implications; finally, Section 7 concludes outlining directions for future research. The final Appendix provides further technical details.

2 Related literature

In Industrial Organization (IO), there is a well-established literature investigating different tools of environmental policy intervention in standard oligopoly industries. A first strand studies price-based emissions reduction policies such as “environmental” taxes and subsidies. Regarding emissions tax/subsidy in Cournot oligopoly markets, pioneering contributions are Requate (1993, 2006), Simpson (1995), Carlsson (2000), Poyago-Theotoky and Teerasuwannajak (2002), David (2005), and the recent works of Moner-Colonques and Rubio (2015) and Buccella et al. (2021) (see also the references therein). The impact of subsidies on “green” technology (i.e., emissions-reducing) investments to reduce the environmental damage has been investigated by, e.g., Poyago-Theotoky (2003, 2007, 2010), David and Sinclair-Desgagné (2010), and Ouchida and Goto (2014). A comprehensive comparison between different environmental policies can be found in the works of Conrad and Wang (1993), Ben Youssef and Dinar (2011), Gautier (2015), and the recent works of Lee and Park (2021) and Buccella et al. (2025). A second strand deals with quantity-based emissions reduction policies. For instance, emissions standards in oligopoly markets are discussed, *inter alia*, by Besanko (1987), Ebert (1999), Montero (2002), Moraga-Gonzalez and Padron-Fumero (2002), Farzin (2003), Bruneau (2004), Kayalica and Lahiri (2005), Amir and Nannerup (2005), Requate (2006), Lahiri and Ono (2007), Carrión-Flores and Innes (2010), Heuson (2010), Perino and Requate (2012), and the more recent contributions of Bárcena-Ruiz and Campo (2017). Amir et al. (2018), and Garella and Trentinaglia (2019).

While the above-mentioned strands of IO literature consider environmental policies directed to abate pollution by firms that compete directly with one another in product markets, this paper instead focuses on policies to limit pollution by ports, which provide complementary transportation services to firms, an aspect that has not yet been addressed in the literature. In this way, its contribution is directed to complement the literature on alternative environmental policies involving firms in product markets.

This work also relates more specifically to the industrial organization and game-theoretical literature applied to port economics (see Hidalgo-Gallego et al., 2017, and Pujats et al., 2020, for two surveys). Specifically, it adopts the basic model of Matsushima and Takauchi (2014), which is extended by introducing and investigating port emission abatement policies and investments.[6] In this strand of IO literature, contributions directed to investigate and compare alternative environmental policies to control polluting emissions by ports are yet relatively scarce. Cui and Notteboom (2017) study the effects of an emission tax policy on vessels and port operations, with a private port that competes with a landlord (partial public) port under Cournot and Bertrand competition, as well as cooperation with differentiated service. Yuan and Wang (2023) study the competition and cooperation between mixed duopoly ports with service differentiation when both emission tax and partial privatization policies are implemented together.Furthermore, recent works investigate the adoption of an emission tax policy under port supply-chain competition (Wang et al., 2022), also considering knowledge sharing (Liu et al., 2023), in comparison with a cap-and-trade policy (Wang et al., 2025), in the presence of vertical integration of shipping lines and ports (Takebayashi, 2025) and with environmental corporate social responsibility (Xu et al., 2025b). Finally, Jin et al. (2026) compare alternative subsidy policies in affecting the adoption of clean technology to reduce emission in the presence of port co-opetition. This work differs from the existing literature in several aspects. First, while those works mainly concentrate on a single policy tool, the main objective of this paper is to compare the relative performance of three alternative environmental policies (i.e., emission taxes, investment subsidies and environmental standards) in pursuing both environmental and welfare goals. Second, in investigating environmental policies, this work does not consider the role of port (supply-chain) competition but, instead, following Matsushima and Takauchi (2014), focuses on the complementary service provided by ports. This assumes particularly relevance in international trade, where ports typically serve different functions along the same transportation network.

To the best of our knowledge, the only work that considers port emission abatement and privatization policies in a model where ports play a complementary role, is Pian et al. (2020) which, however, differs from ours because: i) they only concentrate on an emission tax policy, and ii) they analyse the impact of the tax policy on port usage fees only, neglecting to consider that on ports' incentives to invest in abatement technologies, which represents instead a main driver of our results.

3 The model

Consider a two-country model *à la* Brander and Krugman (1983) where two firms located in two different countries compete in both countries. Each country has a port and when a firm exports, it must use the two ports. Products are homogeneous and, in each market (country), the inverse demand function is given by:

$$p_i = 1 - (q_{ii} + q_{ji}) \tag{1}$$

where p_i denotes the price in country *i*, q_{ii} is the quantity supplied in market *i* by the firm located in that country and q_{ji} is the quantity supplied in market *i* by the firm located in country *j*, with *i*, *j* = *H* (*home*), *F* (*foreign*), $i \neq j$.

[6] In Matsushima and Takauchi (2014) environmental issues are not considered. Indeed, their focus is on the endogenous choice of port ownership structure, and how it affects port usage fees and welfare (see also, Xiao et al., 2012; Czerny et al., 2014; Wan et al., 2016; Lee et al., 2017; Choi and Lim, 2018; Meccheri, 2024; Xu and Lee, 2024; Xu et al., 2025a).

To export, firms incur a per unit shipping fee for competitive shippers, indicated by $\tau \in \left(0, \frac{1}{4}\right)$,[7] as well as a unit fee for usage of each port indicated by f_i. No other cost is incurred by firms other than those associated with transportation, hence, the profit of firm *i* is given by:

$$\Pi_i = \pi_{ii} + \pi_{ij} = p_i q_{ii} + \left[p_j - (\tau + f_i + f_j)\right] q_{ij}. \tag{2}$$

We consider that each port is partially privatized and aims at maximizing the following objective function:

$$\psi_i = \lambda R_i + (1 - \lambda) W_i \tag{3}$$

where R_i are the port's profits[8] and $\lambda \in (0,1)$ represents the degree of port privatization which, to keep the analysis as simple as possible, is assumed to be the same in both countries. In particular, as special cases, Eq. (3) includes an almost fully privatized port that maximizes its profits R_i when $\lambda \to 1$, and an almost fully public (social welfare W_i-maximizing) port when $\lambda \to 0$. More generally, ports are partially privatized and, according to the degree of privatization λ, maximize a combination between profits and domestic welfare.[9]

Port activity is polluting because it produces air emission. The environmental damage (air emission) determined by the port in country *i* is given by $ED_i = (q_{ij} + q_{ji} - z_i)^2/2$; specifically, it is assumed to be a quadratic function of port activity, given by the total amount of goods handled by the port $\left(q_{ij} + q_{ji}\right)$, less an R&D abatement investment level z_i the port realizes to reduce its emissions. The latter requires the port to bear a (quadratic) cost given by $z_i^2/2$.

In order to reduce port emissions in its country, a government may adopt one of the following air emission abatement policies: i) imposing a tax to the port per each unit of pollutant emitted; ii) providing the port with a subsidy per each unit of realized R&D abatement investment; or iii) establishing an upper bound (a standard) on pollution that limits the amount of port air emissions.

For each of those policies, we study a multi-stage game with the following timing: in the first stage, one country's government chooses the optimal design of the abatement policy; in the last two stages, ports choose the usage fees and then firms choose their quantities in the two countries. Under emission taxation and abatement subsidies, ports also decide upon their abatement investments at a stage prior to the fees-setting stage.[10] At each stage, the agents involved make their decisions simultaneously and, as usual, the game is solved through backward induction.

Starting from the last stage (market game), which is common to all policy scenarios, we solve the profit-maximization problem of firm *i* in country *i* with respect to q_{ii} and q_{ij}. Solving the system of first-order conditions, this leads to the following subgame equilibrium quantities at the final stage:

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[7] The upper bound for τ ensures that, in equilibrium, ports always export positive quantities, hence they are active.

[8] The expression of R_i is detailed later, as it differs according to the assumed environmental policy.

[9] This can well be a stylized representation of the "tool", "landlord" and "corporatized" port management models that, depending on the value of λ, pursue a different mix between public and private objectives (The World Bank, 2025; Notteboom et al., 2026).

[10] Indeed, we solve a four-stage game under emission taxation and abatement subsidies, while we solve a three-stage game under environmental standards, which imply that the governments, by choosing the standards, decide upon the abatement investment levels to impose to ports. Furthermore, in Section 5, a further pre-play stage (i.e., stage 0) is added, to find out which abatement policy is *endogenously* chosen by governments.

$$q_{ii} = \frac{1+\tau+f_i+f_j}{3}; \qquad q_{ij} = \frac{1-2(\tau+f_i+f_j)}{3}. \tag{4}$$

Higher usage fees set by ports discourage firms from selling abroad and make it relatively more convenient to sell their output at home. Moreover, each firm "dumps" the product in the other country by "subsidizing" the transportation cost (e.g., Shy, 1995, par. 6.6). Also notice that, as environmental policies do not apply to firms but to ports, they can affect output decisions only indirectly through their impact on port usage fees.

In what follows, the stages before the market game are studied for each of the abatement policies chosen by governments.

3.1 Emission tax

When governments use emission taxes, port profits are given by the following expression (where t_i represents the emission tax rate):

$$R_i = f_i(q_{ij} + q_{ji}) - t_i(q_{ij} + q_{ji} - z_i) - \frac{z_i^2}{2}$$

and domestic welfare is equal to:

$$W_i = \Pi_i + R_i + CS_i - ED_i + \underbrace{t_i(q_{ij} + q_{ji} - z_i)}_{\text{tax revenue}} = \Pi_i + f_i(q_{ij} + q_{ji}) - \frac{z_i^2}{2} + CS_i - ED_i$$

where $CS_i = (q_{ii}^2 + q_{ji}^2 + 2q_{ii}q_{ji})/2$ is the country *i*'s consumer surplus, while tax revenue collected by the government cancels out with the corresponding value paid by port.

At the third stage, each port maximizes (3) with respect to f_i taking (4) into account. This leads to the port *i*'s best-reply function in the usage fees space:

$$f_i(f_j) = -\frac{(5f_j+12z_i+12h_i+5\tau-4)\lambda-17f_j-12z_i-17\tau+10}{5\lambda-29}. \tag{5}$$

From Eq. (5), it arises that $\partial f_i/\partial f_j < 0$, hence port usage fees are strategic substitutes. Solving the system of best-reply functions, we obtain the following subgame equilibrium usage fees:

$$f_i(z_i, z_j, t_i, t_j) = \frac{5(z_i-z_j+t_i-t_j)\lambda^2-(34z_i-22z_j+29t_i-17t_j+5\tau-4)\lambda+29z_i-17z_j+17\tau-10}{10\lambda-46} \tag{6}$$

From Eq. (6), we have that, when ports are at least partially privatized ($\lambda > 0$), $\partial f_i/\partial z_i < 0$ and $\partial f_i/\partial t_i > 0$. The negative relationship between abatement and port usage fees can be explained as follows. As long as a port is only partially privatized ($\lambda < 1$) and cares about social welfare besides its own profits, larger abatement investments result in lower environmental damage, which drives the port to reduce its fees, fostering international trade.[11] As far as the positive relationship between the tax rate and the port fees, consider that an increase of the tax

[11] When $\lambda \to 1, \partial f_i/\partial z_i \to 0$. This is because the decision to abate by a fully private port is made to gain from a lower tax burden only. Instead, such port does not internalize the benefits of international trade with reduced air emission, which occurs with higher abatement investments.

rate pushes the port tax burden of its emissions up, leading the port to react by increasing its usage fees (pass-through).

At the second stage, ports choose the R&D abatement investment level to maximize (3), taking (4) and (6) into account, and we obtain the system of best-reply functions at this stage:

$$z_i(z_j) = \frac{(20z_j-5t_i+20t_j-5)\lambda^3-(156z_j-94t_i+136t_j-20\tau-29)\lambda^2+(252z_j-413t_i+116t_j-136\tau+5)\lambda-116z_j+116\tau-29}{5\lambda^3-124\lambda^2+737\lambda-942} \tag{7}$$

from which we can note that investments by ports are strategic complements ($\partial z_i/\partial z_j > 0$). An increase of port *i*'s investment (provided that $\lambda < 1$) also leads to a decrease of its usage fees, which stimulates international trade and both ports' activities. The increase of port *j*'s activity makes air pollution more severe also in that country, which leads the port *j* to increase its abatement investment.

Solving the system of best-reply functions, we obtain the following subgame equilibrium investment level:

$$z_i(t_i,t_j) = \frac{(-15t_i+5)\lambda^4+(52t_i+20t_j-20\tau-39)\lambda^3+(349t_i-136t_j+176\tau+53)\lambda^2-(710t_i-116t_j+388\tau-39)\lambda+232\tau-58}{15\lambda^4-62\lambda^3-421\lambda^2+1796\lambda-1652} \tag{8}$$

Clearly, an increase of the tax rate by the government makes polluting more costly for the port and drives it to increase its abatement investment ($\partial z_i/\partial t_i > 0$).[12] At the first stage, governments set optimal emission tax rates t_i to maximize domestic welfare, taking subgame equilibrium variables into account, which leads to the following best-reply functions:

$$t_i(t_j) = \frac{\begin{bmatrix} 9880-395520\tau+(532880\tau-197760t_j)\lambda-(262688\tau-167560t_j+204680)\lambda^2+(67756\tau-47564t_j+135627)\lambda^3 \\ -(12136\tau-10096t_j+33926)\lambda^4+(1020\tau-1020t_j+2148)\lambda^5+550\lambda^6-75\lambda^7 \end{bmatrix}}{450\lambda^7-1320\lambda^6-31152\lambda^5+97896\lambda^4+553358\lambda^3-2225896\lambda^2+1978616\lambda} \tag{9}$$

Tax rates chosen by governments are strategic substitutes ($\partial t_i/\partial t_j < 0$). When the government in country *i* increases its tax rate, this leads to an increase of its port's usage fees, which discourages international trade and, as a result, lowers air pollution of both ports. Accordingly, the incentive for the government *j* to lower its tax rate is twofold: first, air pollution is a less severe issue; secondly, as port usage fees positively depend on tax rate, lowering t_j acts not to penalize international trade (and consumer surplus) further.

[12] Notice that, when $\lambda \to 0$ (i.e., ports are almost fully public), both the abatement levels and the port usage fees turn out to be independent of the tax rate. This is because domestic welfare does not depend on the tax rate, as port profits in its expression cancels out with tax revenue. This also lets the government's optimization problem with respect to the tax rate be undetermined and explains why the case with fully public ports ($\lambda = 0$) has been ruled out in our analysis.

By solving the system of best-reply functions, the following Subgame Perfect Nash Equilibrium (SPNE) result is obtained in relation to emission taxes:

$$t_i^* = -\frac{75\lambda^6 - 400\lambda^5 - (1020\tau + 2948)\lambda^4 + (10096\tau + 28030)\lambda^3 - (47564\tau + 79567)\lambda^2 + (167560\tau + 45546)\lambda - 197760\tau + 49440}{2\lambda(225\lambda^5 - 210\lambda^4 - 15486\lambda^3 + 12928\lambda^2 + 326317\lambda - 544094)} \quad (10)$$

Lemma 1: *Under emission taxes, we always have* $\partial t_i^*/\partial\lambda < 0$ *and* $\partial t_i^*/\partial\tau < 0$.

According to Lemma 1, the equilibrium tax rate decreases with the degree of port privatization, regardless of any degree of port privatization and any level of shipping costs. To understand the mechanism at work, first let us assume ports are almost fully public and maximize social welfare in the limit. The latter does not depend on the tax rate, as the government's tax revenue and the ports' tax burden cancel each other out. In such circumstances, the ports' incentive to abate is associated with the incentive to reduce the environmental damage only. However, when ports become more privatized (i.e., λ increases), their incentive to abate emissions increases as ports are pushed to reduce their tax burden to a greater extend (i.e., $\partial z_i^*/\partial\lambda > 0$). Also consider that decision of the government regarding the tax rate considers, on the one hand, the positive effect of a higher tax rate on the port incentives towards abatement and, on the other hand, the negative effect on trade and consumer surplus (because increasing the tax rate leads to higher port fees). When λ increases and ports tend to abate more, the latter effect dominates the former and, as a result, the government optimally sets a progressively lower tax rate to foster international trade, production volumes and consumer surplus through a reduction of the port fees (i.e., $\partial f_i^*/\partial\lambda < 0$).

Furthermore, Lemma 1 also states that the equilibrium tax rate always decreases with the unit shipping cost. Indeed, as an increase of τ is harmful for international trade and consumer surplus, the latter is raised through a lower tax rate by the government.

By substituting t_i^* back, SPNE values of abatement investments, port usage fees, firm quantities and corresponding welfare outcomes (profits, consumer surplus, environmental damage and overall domestic welfare) can be determined (for sake of space they are all presented in the final Appendix).

3.2 Investment subsidy

In case governments choose to subsidize abatement investment by ports, port profits are given by the following expression (where s_i is the government subsidy per unit of investment):

$$R_i = f_i(q_{ij} + q_{ji}) + s_i z_i - \frac{z_i^2}{2}$$

and domestic welfare, in which (similarly to the case with emission taxes) subsidies paid by government and gained by port cancel out each other, is equal to:

$$W_i = \Pi_i + R_i + CS_i - ED_i - \underbrace{s_i z_i}_{\text{subsidy expenditure}} = \Pi_i + f_i(q_{ij} + q_{ji}) - \frac{z_i^2}{2} + CS_i - ED_i.$$

At the third stage, each port maximizes (3) with respect to f_i taking (4) into account, which leads to the following best-reply functions in the usage fees space:

$$f_i(f_j) = -\frac{(5f_j+12z_i+5\tau-4)\lambda-17f_j-12z_i-17\tau+10}{5\lambda-29}. \quad (11)$$

As under emission taxes, port usage fees are strategic substitutes. By solving the system of best-reply functions, we obtain:

$$f_i(z_i, z_j) = \frac{(5z_i-5z_j)\lambda^2-(34z_i-22z_j+5\tau-4)\lambda+29z_i-17z_j+17\tau-10}{10\lambda-46}. \quad (12)$$

It can be easily checked that the relationship between port fees and abatement investments parallels the case under emission taxes, that is $\partial f_i/\partial z_i < 0$ as long as ports are partially privatized, and the same logic applies. However, in contrast to taxation policy, port fees do not depend directly on s_i. Indeed, investment subsidies are not related to port activity and affect port usage fees only through the abatement investment.

At the second stage, ports choose the R&D abatement investment level to maximize their profits, taking (4) and (12) into account. As for the case with emission taxes (and for the same logic) investments by ports are strategic complements. Solving the system of best-reply functions, the following investment level is obtained:

$$z_i = \frac{(5s_i+20s_j+5)\lambda^4-(124s_i+156s_j+20\tau+39)\lambda^3+(737s_i+252s_j+176\tau+53)\lambda^2-(942s_i+116s_j+388\tau-39)\lambda+232\tau-58}{15\lambda^4-62\lambda^3-421\lambda^2+1796\lambda-1652}$$

(13)

Clearly, unless ports are fully state-owned, abatement investment levels are positively related to subsidies per unit of investment ($\partial z_i/\partial s_i > 0$), which implies that higher subsidies induce higher abatement investments.[13]

At the first stage, each government sets the optimal subsidy rate (per unit of investment) s_i to maximize domestic welfare by taking the subgame equilibrium variables into account, which leads to the following best-reply function:

$$s_i(s_j) = \frac{\begin{bmatrix}13456-53824\tau-(241648\tau-26912s_j+2124)\lambda+(478752\tau+107368s_j+153848)\lambda^2-(311156\tau+306516s_j+265925)\lambda^3\\+(94780\tau+241696s_j+161009)\lambda^4-(14460\tau+82120s_j+39470)\lambda^5+(900\tau+13560s_j+1954)\lambda^6-(900s_j-655)\lambda^7-75\lambda^8\end{bmatrix}}{2\lambda(300\lambda^7-2545\lambda^6-4856\lambda^5+105830\lambda^4-420328\lambda^3+933239\lambda^2-1271300\lambda+764636)}$$

(14)

Subsidies are strategic complements ($\partial s_i/\partial s_j > 0$). Indeed, when the government in country *i* increases its subsidy rate, its port is driven to increase its abatement investment and, in turn, to decrease usage fees. This fosters international trade and port activities. As a result, air pollution increases in both ports, which leads the government *j* to increase its subsidy in order to incentivize the abatement investment.

[13] As for emission taxes, both the abatement levels and the port usage fees do not depend on the subsidy rate when ports are almost fully public (i.e., $\lambda \to 0$) and domestic welfare does not depend on the subsidy rate.

By solving the system of best-reply functions, we obtain the following equilibrium subsidy:

$$s_i^* = -\frac{\begin{bmatrix} 75\lambda^7-505\lambda^6-(900\tau-2964)\lambda^5+(12660\tau+33542)\lambda^4-(69460\tau+93925)\lambda^3 + \\ +(172236\tau+78075)\lambda^2-(134280\tau-2302)\lambda-26912\tau+6728 \end{bmatrix}}{2\lambda(300\lambda^6-1495\lambda^5-14626\lambda^4+117638\lambda^3-305900\lambda^2+474697\lambda-375590)}. \quad (15)$$

Lemma 2: *Under investment subsidies, unless the degree of port privatization is low, we have* $\partial s_i^*/\partial\lambda > 0$. *Instead, we always have* $\partial s_i^*/\partial\tau < 0$.

According to Lemma 2, the equilibrium investment subsidy increases with the degree of port privatization, unless the latter is very low. Indeed, the government uses the subsidy to induce the emission abatement and, in turn, reduce the port usage fees. However, ports abate emissions increasingly as they become more privatized, i.e. $\partial z_i/\partial\lambda > 0$. This is because, when λ increases, they perceive the cost of paying the abatement subsidy to a lesser extent. In addition, this also causes a downward pressure on port fees ($\partial f_i^*/\partial\lambda < 0$). As long as ports are sufficiently public (i.e., λ is low) and set relatively low usage fees to positively affect trade and consumer surplus, the government decides upon reducing the optimal subsidy when λ increases, since the welfare gains associated with larger abatement levels and lower fees are low relative to the cost of subsidization. Conversely, when ports are largely privatized (i.e., λ is high) and tend to set higher fees, the government's incentive to expand trade and enhance consumer surplus through larger abatement levels and lower fees becomes stronger and prevails on the cost of subsidization. As a result, the government tends to increasingly subsidize more private ports in this case. Furthermore, as air emissions decrease when shipping costs increase, s_i^* decreases with τ.[14]

By substituting s_i^* back, SPNE values of abatement investments, port usage fees, firm quantities and corresponding welfare components can be determined (for sake of space they are provided in the final Appendix).

3.3 Emission standard

When an emission standard policy is adopted by governments, ports have not to pay taxes and do not receive any subsidy, but the government *i* imposes an upper bound on pollution, which is denoted by h_i, that limits the amount of air emission that port *i* may emit. In particular, the lower $h_i$is, the stricter the emission standard set by the government. In such case, port *i* is forced to realize an abatement investment level equal to $(q_{ij} + q_{ji} - h_i)$. Hence, port profits and domestic welfare are given by, respectively:

$$R_i = f_i(q_{ij} + q_{ji}) - \frac{(q_{ij} + q_{ji} - h_i)^2}{2}$$

[14] Notice that there could be even the possibility that the optimal subsidy becomes negative, which means that ports are taxed for investing to abate pollution. Indeed, this occurs ($s_i^* < 0$) for a very small set of combinations between λ and τ, with very small λ and very high τ. Specifically, in such a case, since τ is very high, international trade and ports' activity are negligible and, as a result, air pollution is not a relevant problem. In addition, when λ is very small, the effectiveness of subsidies in stimulating abatement investment is low and, accordingly, investing mainly represents a cost, which decreases social welfare. Importantly, even when $s_i^* < 0$, the equilibrium investment level is positive (see the final Appendix) as the port takes also the effect of the investment on usage fees into account and, when the port is largely state-owned, a negative investment would imply too high usage fees.

$$W_i = \Pi_i + R_i + CS_i - ED_i = \Pi_i + R_i + CS_i - \frac{{h_i}^2}{2}.$$

At the port fees-setting stage, each port maximizes (3) with respect to f_i taking (4) into account. This leads to the port *i*'s best-reply function in usage fees space:

$$f_i(f_j) = \frac{(-11f_j - 11\tau + 4)\lambda - 17f_j - 17h_i - 17\tau + 10}{11\lambda + 29}. \quad (16)$$

As before, usage fees are strategic substitutes. Solving the system, the following subgame equilibrium usage fees are obtained:

$$f_i(h_i, h_j) = \frac{(-11h_i + 11h_j - 11\tau + 4)\lambda - 29h_i + 17h_j - 17\tau + 10}{22\lambda + 46}. \quad (17)$$

Port usage fees in country *i* negatively depend on h_i ($\partial f_i / \partial h_i < 0$), which means that the stricter the emission standard set by the government (lower h_i), the higher the fee chosen by the port. This is because a standard, which forces the port to invest, increases the latter's costs,[15] driving the port to react by increasing its fees.

Ports are forced to realize their investments according to the standard h_i set by the government, so that the abatement is $(q_{ij} + q_{ji} - h_i)$. Taking the subgame equilibrium variables into account, domestic welfare maximization by government *i* with respect to h_i leads to the following best-reply functions:

$$h_i(h_j) = \frac{11\lambda^2 + (88h_j - 88\tau + 28)\lambda + 116h_j - 116\tau + 29}{242\lambda^2 + 924\lambda + 942}. \quad (18)$$

Standards set by governments are strategic complements ($\partial h_i / \partial h_j > 0$). When the government *i* chooses to reduce h_i, making its emission standard stricter, the port in its own country reacts by raising its usage fees which, in turn, negatively impacts on international trade. Since port fees are strategic substitutes, the government in country *j* anticipates that its port would reduce the fees. On the one hand, this makes it less costly for port *j* to meet a stricter emission standard; on the other hand, it expands the output handled, with a subsequent pollution increase. As a result, the government *j* decreases h_j.

Solving the system of the best-reply functions, we get the following equilibrium standard in country *i*:

$$h_i^* = \frac{11\lambda^2 - (88\tau - 28)\lambda - 116\tau + 29}{242\lambda^2 + 836\lambda + 826}. \quad (19)$$

Lemma 3: *Under emission standard,* u*nless both the degree of port privatization and shipping costs are very low, we have* $\partial h_i^* / \partial \lambda > 0$. *By contrast, we always have* $\partial h_i^* / \partial \tau < 0$.

[15] Obviously, this holds true also with emission taxes and investment subsidies. However, in those cases, an increase in abatement investment has also a positive effect on port profits related to the reduction in tax expenditure or to the increase in subsidy revenue, respectively. In other words, increasing abatement investment penalizes port profits much more under an emission standard than under emission taxes or investment subsidies.

According to Lemma 3, equilibrium emission standards become looser with the degree of port privatization, provided that both λ and τ are large enough. This can be explained by considering that more private ports, one the one hand, care less about consumer surplus, then tend to raise usage fee at detriment of international trade; on the other hand, they internalize to a lesser extent the environmental damage, hence encouraging international trade through lower usage fees. The former effect dominates the latter when both λ and τ are large enough, namely trade volumes are relatively low, which lets the government impose a looser standard (i.e, $\partial h_i^*/\partial\lambda > 0$), which reduces port fees ($\partial f_i/\partial h_i < 0$). Instead, the opposite occurs when both λ and τ are low enough. In this case, international trade is favoured by low shipping costs, and the government sets a stricter standard to abate emissions to a greater extent, also reducing port fees. As far as the negative relationship between h_i^* and τ is concerned, this relates to the fact that, when shipping costs increase, international trade is reduced and this makes it less costly for ports to meet stricter standards.

From Eq. (19), by substituting back, SPNE values of abatement investments, port usage fees, firm quantities and corresponding welfare components can be obtained for this case (for sake of space they are provided in the final Appendix).

4 Environmental damage and welfare: a comparison among different abatement policies

In this section, the effects of alternative abatement policies are compared in terms of their effectiveness in containing the environmental damage and affecting consumer surplus, profits of both firms and ports, as well as domestic welfare. The levels of port usage fees and abatement investments are preliminary compared across the three considered policies, which will contribute to point out how the degree of port privatization and the level of shipping costs alter the welfare outcomes and the environmental quality in each country.

The following lemma clarifies the policy ranking of port usage fees and abatement investment, respectively.

Lemma 4. *When the degree of port privatization is sufficiently high, the following policy ranking of port usage fees applies:* $f^h > f^t > f^s$. *Otherwise, we have* $f^t > f^h > f^s$.

Relative to abatement investment, the following policy ranking applies: when the degree of port privatization is not high, we have: $z^h > z^t > z^s$; *when the degree of port privatization is sufficiently high but not too high, we have:* $z^h > z^s > z^t$; *when the degree of port privatization is very high, we have:* $z^s > z^h > z^t$.

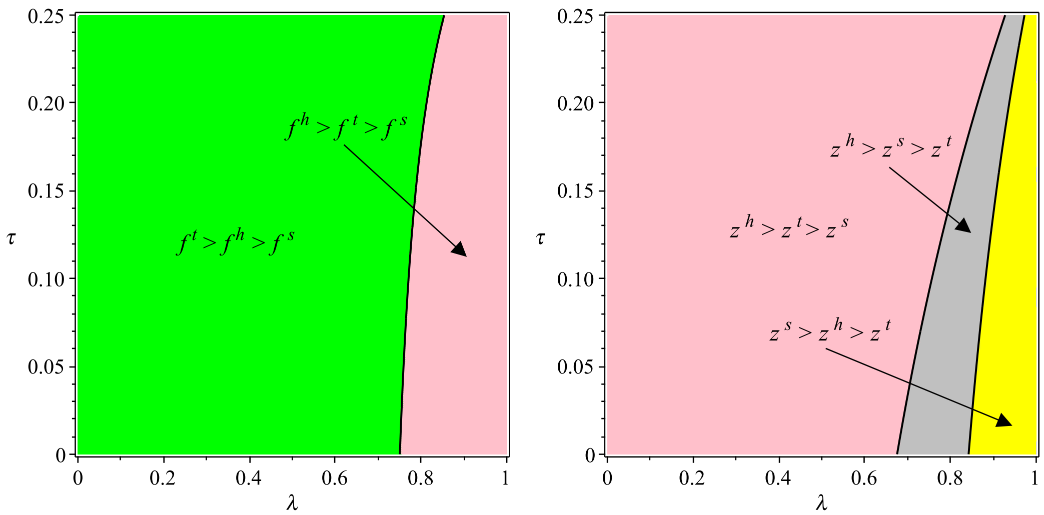

Figure 1. The equilibrium policy rankings of port usage fees and abatement investments

Figure 1 provides a graphical proof of Lemma 4, an intuition of which is provided as follows. Regardless any λ and τ, the equilibrium port usage fees are the lowest under a subsidy policy. Indeed, as shown in the analysis in Section 2, while port fees are affected by subsidization only through abatement investments (i.e., larger subsidization induces larger abatement reducing in turn the port fees), they are directly affected by environmental taxation and stricter standards raising ports' costs. Moreover, privatization induces increasing abatement investments under both subsidies and taxation, causing a downward pressure on port fees, but decreasing investments under a standard avoiding further fees' reductions. The two combined effects lead to lower usage fees under subsidization. In addition, when the degree of privatization is not excessively high, ports abate less under subsidization and most under a standard, which also makes f^h lower that f^t. Instead, when the degree of privatization is very high, ports abate most under subsidization and less under taxation, which makes f^t lower that f^h. Finally, notice that larger τ does not alter significantly the equilibrium policy ranking of port usage fees and abatement investments.

The above analysis allows to state the proposition concerning the welfare outcomes and the environmental quality in each country.

Proposition 1. *By comparing equilibrium outcomes under alternative abatement policies, the following results are obtained.*

i) Relative to environmental damage, we always have (i.e., for any $\lambda \in (0,1)$ and any $\tau \in (0,1/4)$) $ED^s > ED^t > ED^h$.

ii) Relative to consumer surplus, when the degree of port privatization λ is sufficiently high, we have $CS^s > CS^t > CS^h$. Otherwise, $CS^s > CS^h > CS^t$ applies (see Figure 2).

iii) Relative to firm profits, when the degree of port privatization λ is sufficiently high, we have $\pi^h > \pi^t > \pi^s$. Otherwise, $\pi^t > \pi^h > \pi^s$ holds (see Figure 2).

iv) Relative to port profits, we always have $R^s > R^h > R^t$.

v) Relative to domestic welfare, unless τ is sufficiently high, we have $W^s > W^h > W^t$ when the degree of port privatization λ is sufficiently low, and $W^s > W^t > W^h$ otherwise. The same rankings apply under sufficiently high τ, provided that λ is not too high; as λ increases further, we first get $W^t > W^s > W^h$ and then $W^t > W^h > W^s$ (see Figure 3).

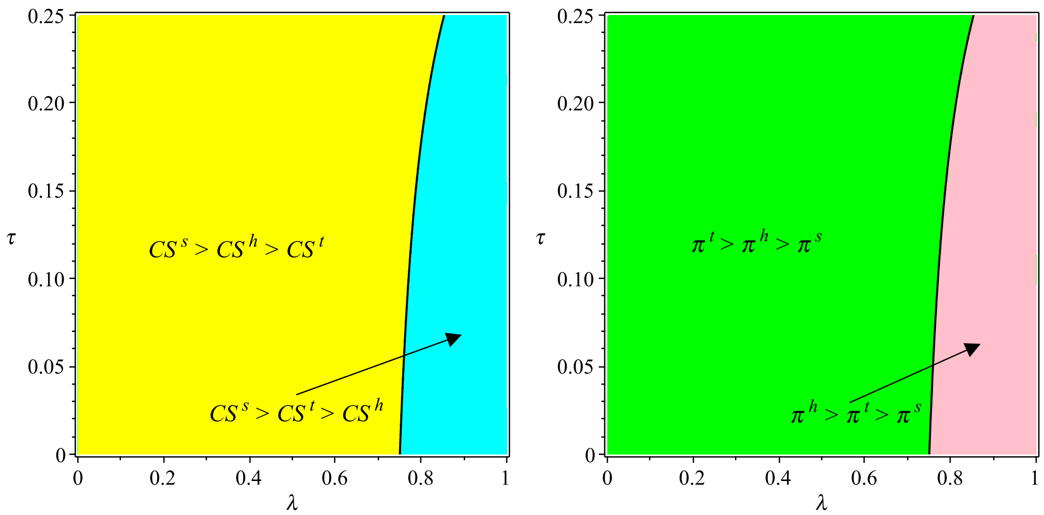

Figure 2. Equilibrium policy rankings of consumer surplus and firm profits

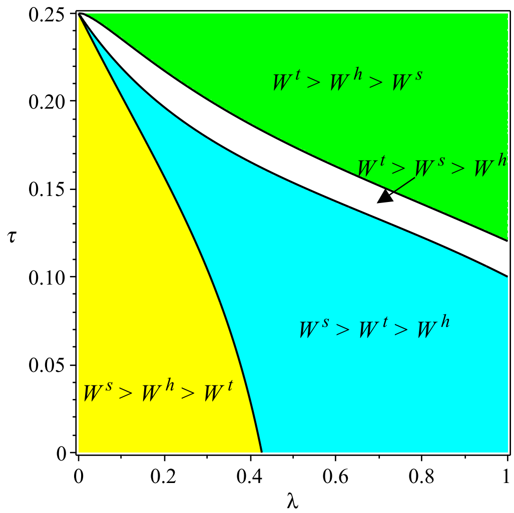

Figure 3. Equilibrium policy rankings of domestic welfare

According to Proposition 1, emission standards always outperform other policies in abating air emission and, in equilibrium, permit to reach the lowest environmental damage. Instead, investment subsidies lead to the worst outcome in relation to environmental damage, with emission taxes falling in between other policies. This result can be explained by considering that, as stated in Lemma 4, port usage fees under subsidies are lowest and foster international trade, thus port activities and emissions, making such policy the less effective in reducing environmental damage.[16] Furthermore, the higher level of abatement investments under a standard than under a tax policy, observed for any degree of privatization and any level of shipping costs, lets the former policy always outperform the latter in lowering environmental damage.

[16] Notice that this holds true even when the degree of port privatization is very high and, under subsidies, the abatement investment by ports reaches its highest equilibrium level.

The rankings of consumer surplus and firm profits exactly parallel (inversely or directly, respectively) that of usage fees in Lemma 4.[17] This leads consumer surplus to be the highest under subsidies, regardless any degree of port privatization. Moreover, emission taxes outperform standards (i.e., $CS^t > CS^h$) when ports are sufficiently private and their fees are lower under taxes (i.e, $f^h > f^t$). Notice that, despite one firm pays the lowest port fees under subsidies, it gains the lowest profits in this policy scenario, while the ranking $\pi^h > \pi^t$ holds true provided that $f^h > f^t$, namely ports are sufficiently private.

Turning to port profits, we observe that their ranking across policies holds regardless of any degree of privatization and any level of shipping costs: they are the highest under investment subsidies and the lowest under emission taxes, while they fall in between under emission standards. The result is driven by the profit gains acquired by ports under subsidies, due to larger international trade and subsidized abatement costs, despite the negative impact of lower usage fees.[18] Moreover, it derives from the profit losses associated with higher production costs imposed by either per unit taxation or abatement investments imposed by the government through a standard, which limits trade and port profits to some extent.

Regarding overall domestic welfare, the ranking of domestic social welfare across the three policies mimics that of consumer surplus when τ is sufficiently low, for any degree of port privatization. Specifically, as long as low shipping costs let firms compete fiercer on the product market and push both international trade and domestic production up in each country, consumer surplus becomes decisive in determining the overall domestic welfare. This means that there is an unambiguous welfare dominance occurring under the subsidy policy despite a detrimental environmental performance. Instead, when shipping costs become sufficiently large and discourage international trade at the advantage of domestic production and, moreover, ports are sufficiently privatized, the inefficiencies of per-unit taxation relative to the other policies are mitigated, as well as the welfare gains of abatement subsidies. As a result, the emission tax policy leads to the highest level of domestic welfare.

5 Endogenous abatement policy

While in the previous section the results obtained under alternative policies have been compared, in this section we aim at investigating the endogenous choice by governments of the policy to be implemented. Accordingly, we now introduce a further initial (pre-play) stage to the sequence of the events studied in Section 2, in which the abatement policy is selected by each country government to maximize its domestic welfare. In other words, at this stage, governments (simultaneously and independently) decide the abatement policy and the payoff matrix is represented by the 3 x 3 Table 1.

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[17] An inspection of Eq. (4) reveals that usage fees set by one country's port positively affect the quantity of goods sold by the domestic firm at home and negatively affect the quantity sold abroad. As also pointed out in the literature (see Matsushima and Takauchi, 2014, p. 386), the negative impact of port usage fees on goods sold abroad is larger than the positive impact on goods sold at home, leading overall consumption in each country, then consumer surplus, to negatively depend on port usage fees. The opposite applies relative to firm profits.

[18] Recall that no operation costs are considered for ports. Hence, port profits are driven by port revenue.

i/j	t	s	h
t	W^t, W^t	W^{ts}, W^{st}	W^{th}, W^{ht}
s	W^{st}, W^{ts}	W^s, W^s	W^{sh}, W^{hs}
h	W^{ht}, W^{th}	W^{hs}, W^{sh}	W^h, W^h

Table 1. Endogenous abatement policy: normal form

In particular, in Table 1, while W^t, W^s and W^h represent the SPNE domestic welfare values when both governments adopt the same policy, as determined with the analysis of Section 2 (see the final Appendix), in order to solve for the equilibrium of the normal game-form of Table 1, we need to derive also the equilibrium outcomes of asymmetric cases, W^{xy} with $x, y = t, s, h$ and $x \neq y$, in which governments adopt different policies.[19]

At this point, comparing equilibrium welfare outcomes for any pair of strategies represented in Table 1, the following proposition defines the SPNE decisions by governments in relation to the abatement policy to be adopted.

Proposition 2. *Regardless of the degree of port privatization and shipping costs, adopting an emission tax policy is a strictly dominant strategy for both governments. Accordingly, there is only one SPNE of the game between governments on the choice of abatement policy, in which both governments decide to adopt an emission tax policy (t, t).*

The proof of Proposition 2 can be obtained straightforwardly by considering that, for any $\tau \in \left(0, \frac{1}{4}\right)$ and $\lambda \in (0,1)$, the following inequalities apply: $W^t > W^{st}$; $W^t > W^{ht}$; $W^{ts} > W^s$; $W^{ts} > W^{hs}$; $W^{th} > W^{sh}$; $W^{th} > W^h$.

According to Proposition 2, regardless of the degree of port privatization and shipping costs, environmental taxation emerges endogenously as the policy chosen by each government in the strategic game. This is because it represents the government best response, whatever policy is adopted by the other government. The intuition for this result is as follows. Starting from any symmetric outcome, in which both governments adopt either subsidies or standards, each country has an incentive to deviate unilaterally from the assumed strategy choosing taxation. The latter policy, indeed, raises the per-unit operating cost of the domestic port, hence leading an increase of port fees. Furthermore, it also induces larger abatement investments.[20] The result is a reduction of the trade volumes and an increase of domestic welfare through the combined effect of a shift towards domestic production and lower environmental damage.

Moreover, the symmetric adoption of a taxation policy in equilibrium, by causing a reduction of overall trade and social welfare in each country, implies the existence of a prisoner-dilemma-type equilibrium whenever τ and λ are sufficiently low. In such circumstances, although taxation is individually optimal for each government, symmetric adoption of subsidies or standards yields higher welfare in each country. By contrast, the Nash equilibrium (*t, t*) of the strategic game arises as the most favourable outcome with respect to (*s,s*) or (*h, h*) when τ and λ are sufficiently high and international trade is limited.

[19] Equilibrium analysis and outcomes with governments that choose different policies, i.e., asymmetric cases, are very cumbersome and, for sake of space, are not reported. All details are available from authors upon request.
[20] Under an emission tax policy, one government directly affects the port's per-unit operating cost and therefore port usage fees. Under subsidies or emission standards, instead, port fees may be altered only indirectly, through changes of the abatement investments realized by ports.

6 Discussion and policy implications

Although the results of the model are theoretical and rely on a number of simplifying assumptions, they nonetheless provide useful policy implications for environmental protection in the maritime-port sector and in the context of international trade. In particular, the analysis highlights the existence of a structural trade-off between environmental effectiveness and economic performance when different regulatory instruments are implemented. Emission standards emerge as the policy instrument that most effectively minimizes environmental damage, since they directly constrain pollution levels associated with port activities and force ports to undertake the abatement investments required to comply with regulatory limits. However, the analysis also shows that this policy may entail non-negligible economic costs, as stricter standards increase port operating costs and tend to translate into higher port usage fees, thereby discouraging trade flows and reducing consumer surplus and overall domestic welfare. From a policy perspective, this suggests that purely command-and-control approaches, while environmentally effective, may require complementary measures aimed at mitigating their potential adverse effects on trade competitiveness and port activity.

By contrast, policies based on subsidies to abatement investments stimulate the adoption of cleaner technologies and encourage ports to reduce their usage fees, which in turn promotes international trade and increases consumer surplus. Yet, this pro-trade effect may also lead to higher levels of port activity and transport volumes, ultimately resulting in higher overall emissions despite the presence of abatement investments. Environmental taxation represents an intermediate policy instrument, balancing environmental and economic objectives. Specifically, its relative welfare performance improves when shipping costs are relatively high and the degree of port privatization is substantial, circumstances under which the trade-expansion effects associated with subsidies become less pronounced. In this respect, price-based instruments such as environmental taxes may offer policymakers greater flexibility in addressing environmental externalities while limiting distortions in international trade and competition.

More broadly, the analysis underscores the importance of accounting for institutional and market characteristics, such as port ownership structures and international transport costs, when designing environmental regulation in maritime transport systems. In particular, the results suggest that the effectiveness of environmental policies may vary significantly depending on the governance structure of ports, with more privatized ports responding differently to regulatory incentives compared to predominantly public ones. In addition, when governments strategically select environmental policies in an international setting, emission taxation emerges as the equilibrium outcome, reflecting incentives to indirectly limit trade volumes and reallocate production towards domestic markets. This result also points to the potential relevance of international policy coordination mechanisms aimed at avoiding inefficient strategic policy interactions across countries. Ultimately, the findings indicate that environmental regulation in port systems cannot be evaluated solely on the basis of its environmental effectiveness, but must also consider its interaction with trade incentives, market structure, and the evolving governance of increasingly privatized port infrastructures. In this perspective, effective environmental policy in maritime transport requires a careful balance between environmental objectives, trade efficiency, and the institutional design of port governance.

7 Concluding remarks

In this paper, the role of alternative environmental policies in regulating port emissions has been investigated within an international oligopoly, focusing on how port ownership and trade costs interact with public intervention. By considering emission taxes, abatement subsidies and emission standards in a reciprocal trade model, the analysis has pointed out a fundamental trade-off between environmental and welfare performance. Indeed, emission standards are shown to always achieve the lowest level of environmental damage, but at the cost of reduced consumer and domestic welfare. Investment subsidies, by contrast, stimulate trade and consumer surplus at detriment of the environment, while taxation policy represents an intermediate case whose relative welfare performance improves when trade is limited by high shipping costs and ports are highly privatized. When the policy choice is endogenized, emission taxation emerges as the unique equilibrium outcome, despite not being welfare-dominant in all parameter configurations, which also highlights the existence of a prisoner's dilemma-type equilibrium. Overall, our results may provide guidance for policymakers facing the challenge of improving environmental sustainability while preserving welfare in increasingly privatized and globally interconnected port systems.

To keep the formal analysis as simple as possible, the model has been based on a set of simplification hypotheses. Future research could extend the analysis to the presence of consumer environmental awareness, firm product differentiation, country (market) size asymmetry, different degree of port privatization between countries, as well as to international coordination mechanisms in port environmental regulation.

Appendix

A.1 Equilibrium outcomes with (symmetric) environmental policies

A.1.1 Emission tax

$$z_i^t = \frac{(2-\lambda)(23-5\lambda)(15\lambda^3-32\lambda^2-485\lambda+826)(45\lambda^4-120\lambda^3\tau-21\lambda^3-84\lambda^2\tau-1723\lambda^2+6124\lambda\tau+1497\lambda-9736\tau+2434)}{(225\lambda^5-210\lambda^4-15486\lambda^3+12928\lambda^2+326317\lambda-544094)^2(15\lambda^4-62\lambda^3-421\lambda^2+1796\lambda-1652)};$$

$$q_{ii}^t = \frac{\left[\begin{array}{c}(2-\lambda)(23-5\lambda)(15\lambda^3-32\lambda^2-485\lambda+826)\\(75\lambda^5+150\lambda^4\tau+110\lambda^4-810\lambda^3\tau-6706\lambda^3-5578\lambda^2\tau+92\lambda^2+38978\lambda\tau+163695\lambda-49588\tau-259650)\end{array}\right]}{(225\lambda^5-210\lambda^4-15486\lambda^3+12928\lambda^2+326317\lambda-544094)^2(75\lambda^5-655\lambda^4-679\lambda^3+18663\lambda^2-49568\lambda+37996)};$$

$$q_{ij}^t = \frac{\left[\begin{array}{c}(23-5\lambda)^2(\lambda-2)(15\lambda^3-32\lambda^2-485\lambda+826)\\(15\lambda^4-60\lambda^3\tau-17\lambda^3+48\lambda^2\tau-493\lambda^2+2452\lambda\tau+281\lambda-4312\tau+1078)\end{array}\right]}{(225\lambda^5-210\lambda^4-15486\lambda^3+12928\lambda^2+326317\lambda-544094)(75\lambda^5-655\lambda^4-679\lambda^3+18663\lambda^2-49568\lambda+37996)};$$

$$f_i^t = \frac{\left[\begin{array}{c}(23-5\lambda)(\lambda-2)(15\lambda^3-32\lambda^2-485\lambda+826)\\(225\lambda^5\tau-660\lambda^4\tau-540\lambda^4-13056\lambda^3\tau+4632\lambda^3+29662\lambda^2\tau+12652\lambda^2+209383\lambda\tau-164768\lambda-395330\tau+234856)\end{array}\right]}{2(225\lambda^5-210\lambda^4-15486\lambda^3+12928\lambda^2+326317\lambda-544094)(75\lambda^5-655\lambda^4-679\lambda^3+18663\lambda^2-49568\lambda+37996)};$$

$$\pi_i^t = \frac{\left[\begin{array}{c} 2(2-\lambda)^2\left(15\lambda^3-32\lambda^2-485\lambda+826\right)^2(23-5\lambda)^2 \\ (5625\lambda^{10}-11250\lambda^9\tau+56250\lambda^8\tau^2-24000\lambda^9+206250\lambda^8\tau-607500\lambda^7\tau^2-560000\lambda^8-751050\lambda^7\tau \\ -2543250\lambda^6\tau^2+1116860\lambda^7-1071430\lambda^6\tau+51824400\lambda^5\tau^2+31362806\lambda^6+101243194\lambda^5\tau+117266690\lambda^4\tau^2 \\ -29913468\lambda^5-171987706\lambda^4\tau-886265020\lambda^3\tau^2-1032204348\lambda^4-1617950062\lambda^3\tau+5181220530\lambda^2\tau^2 \\ +1794021284\lambda^3+8895213182\lambda^2\tau-9664205320\lambda\tau^2+13058739641\lambda^2 \\ -16411520144\lambda\tau+6147424360\tau^2-42476802788\lambda+10416554456\tau+34016432448) \end{array}\right]}{(225\lambda^5-210\lambda^4-15486\lambda^3+12928\lambda^2+326317\lambda-544094)^2(75\lambda^5-655\lambda^4-679\lambda^3+18663\lambda^2-49568\lambda+37996)^2};$$

$$R_i^t =$$

$$\frac{\left[\begin{array}{c} (23-5\lambda)(27000\lambda^{10}\tau-108000\lambda^9\tau^2+7875\lambda^{10}-145800\lambda^9\tau+475200\lambda^8\tau^2-101775\lambda^9-1976160\lambda^8\tau+9951840\lambda^7\tau^2 \\ -12205\lambda^8+9474096\lambda^7\tau-44750544\lambda^6\tau^2+6348733\lambda^7+44165976\lambda^6\tau-291744528\lambda^5\tau^2-27140367\lambda^6-44750544\lambda^6\tau^2 \\ +6348733\lambda^7+44165976\lambda^6\tau-291744528\lambda^5\tau^2-27140367\lambda^6-138571656\lambda^5\tau+1444764496\lambda^4\tau^2-87313585\lambda^5-339592432\lambda^4\tau \\ +1797978000\lambda^3\tau^2+771717161\lambda^4-1487771040\lambda^3\tau-13601070720\lambda^2\tau^2-1147060329\lambda^3+9602465280\lambda^2\tau \\ +15431657792\lambda\tau^2-673539184\lambda^2-10877712128\lambda\tau-2971146240\tau^2+175494920\lambda+1485573120\tau-185696640) \end{array}\right]}{8\lambda(225\lambda^5-210\lambda^4-15486\lambda^3+12928\lambda^2+326317\lambda-544094)^2(75\lambda^5-655\lambda^4-679\lambda^3+18663\lambda^2-49568\lambda+37996)^2}$$

;

$$ED_i^t = \frac{(2-\lambda)^2\left(15\lambda^3-120\lambda^2\tau-17\tau^2+36\lambda\tau-283\lambda+3756\tau-939\right)^2(5\lambda-23)^2}{8[(225\lambda^5-210\lambda^4-15486\lambda^3+12928\lambda^2+326317\lambda-544094)^2(75\lambda^5-655\lambda^4-679\lambda^3+18663\lambda^2-49568\lambda+37996)^2]};$$

$$CS_i^t = \frac{\left[\begin{array}{c} 2(23-5\lambda)^2(2-\lambda)^2\left(15\lambda^3-32\lambda^2-485\lambda+826\right)^2 \\ \left(75\lambda^5-75\lambda^4\tau-160\lambda^4+405\lambda^3\tau+2789\lambda^2\tau-6418\lambda^2+19489\lambda\tau+81311\lambda+24794\tau-142222\right)^2 \end{array}\right]}{(225\lambda^5-210\lambda^4-15486\lambda^3+12928\lambda^2+326317\lambda-544094)^2(75\lambda^5-655\lambda^4-679\lambda^3+18663\lambda^2-49568\lambda+37996)^2};$$

$$W_i^t =$$

$$-\frac{\left[\begin{array}{c} (23-5\lambda)^2(2-\lambda)^2\left(15\lambda^3-32\lambda^2-485\lambda+826\right)^2 \\ (67500\lambda^{10}\tau-270000\lambda^9\tau^2-61875\lambda^{10}-585000\lambda^9\tau-78000\lambda^9-4459200\lambda^8\tau+22888800\lambda^7\tau^2+10837600\lambda^8+45811080\lambda^7\tau \\ -212895720\lambda^6\tau^2-7310580\lambda^7+77260776\lambda^6\tau-489409104\lambda^5\tau^2-649901130\lambda^6-1180298824\lambda^5\tau+7410998088\lambda^4\tau^2 \\ +1171621508\lambda^5+87372976\lambda^4\tau-6254460672\lambda^3\tau^2+16301164724\lambda^4+9093127896\lambda^3\tau-81945644856\lambda^2\tau^2-44069851116\lambda^3 \\ +11773989196\lambda^2\tau+227810818080\lambda\tau^2-133727957835\lambda^2-88966932976\lambda\tau-170928679008\tau^2 \\ +540644922508\lambda+85464339504\tau-454740463692) \end{array}\right]}{4(225\lambda^5-210\lambda^4-15486\lambda^3+12928\lambda^2+326317\lambda-544094)^2(75\lambda^5-655\lambda^4-679\lambda^3+18663\lambda^2-49568\lambda+37996)^2}$$

.

A.1.2 Investment subsidy

$$z_i^s = -\frac{\left[\begin{array}{c} 450\lambda^7\tau+225\lambda^7-4620\lambda^6\tau-2745\lambda^6-772\lambda^5\tau+10412\lambda^5+98104\lambda^4\tau+5410\lambda^4 \\ -98766\lambda^3\tau-178731\lambda^3-334700\lambda^2\tau+462847\lambda^2+399536\lambda\tau \\ -347218\lambda+80736\tau-20184 \end{array}\right]}{6(600\lambda^6-5465\lambda^5+418\lambda^4+86050\lambda^3-105496\lambda^2-246721\lambda+375590)\lambda};$$

$$q_{ii}^s =$$

$$\frac{\left[\begin{array}{c} (2-\lambda)(15\lambda^3-32\lambda^2-485\lambda+826)(23-5\lambda)^2 \\ (60\lambda^5\tau+150\lambda^5-308\lambda^4\tau-665\lambda^4-870\lambda^3\tau-2979\lambda^3+2604\lambda^2\tau+6627\lambda^2+2222\lambda\tau+12173\lambda-5652\tau-23082) \end{array}\right]}{3(600\lambda^6-5465\lambda^5+418\lambda^4+86050\lambda^3-105496\lambda^2-246721\lambda+375590)(75\lambda^5-655\lambda^4-679\lambda^3+18663\lambda^2-49568\lambda+37996)};$$

$$q_{ij}^s =$$

$$\frac{\left[\begin{array}{c} (2-\lambda)(15\lambda^3-32\lambda^2-485\lambda+826)(23-5\lambda)^2 \\ (120\lambda^5\tau-60\lambda^5-616\lambda^4\tau+293\lambda^4-1740\lambda^3\tau+1257\lambda^3+5208\lambda^2\tau-5187\lambda^2+4444\lambda\tau+2815\lambda-11304\tau+2826) \end{array}\right]}{3(600\lambda^6-5465\lambda^5+418\lambda^4+86050\lambda^3-105496\lambda^2-246721\lambda+375590)(75\lambda^5-655\lambda^4-679\lambda^3+18663\lambda^2-49568\lambda+37996)};$$

$$f_i^s = \frac{\left[\begin{array}{c}(2-\lambda)(15\lambda^3-32\lambda^2-485\lambda+826)(23-5\lambda)^2 \\ (60\lambda^5\tau+30\lambda^5-233\lambda^4\tau+124\lambda^4-1535\lambda^3\tau+574\lambda^3+3543\lambda^2\tau-480\lambda^2+4955\lambda\tau-4966\lambda-10678\tau+6752)\end{array}\right]}{2(600\lambda^6-5465\lambda^5+418\lambda^4+86050\lambda^3-105496\lambda^2-246721\lambda+375590)(75\lambda^5-655\lambda^4-679\lambda^3+18663\lambda^2-49568\lambda+37996)};$$

$$\pi_i^s = \frac{\left[\begin{array}{c}2(2-\lambda)^2(23-5\lambda)^4\left(15\lambda^3-32\lambda^2-485\lambda+826\right)^2 \\ (9000\lambda^{10}\tau^2+1800\lambda^{10}\tau-92400\lambda^9\tau^2+13050\lambda^{10}-13980\lambda^9\tau-23840\lambda^8\tau^2-117330\lambda^9-29668\lambda^8\tau+2121000\lambda^7\tau^2-258233\lambda^8 \\ -65250\lambda^7\tau-1451310\lambda^6\tau^2+3654606\lambda^7+2487750\lambda^6\tau-16444880\lambda^5\tau^2+957549\lambda^6-4825192\lambda^5\tau+15990420\lambda^4\tau^2 \\ -37164002\lambda^5-20464080\lambda^4\tau+53516640\lambda^3\tau^2+18863685\lambda^4+55825458\lambda^3\tau-61245830\lambda^2\tau^2+138382626\lambda^3 \\ +15348590\lambda^2\tau-62793720\lambda\tau^2-89569799\lambda^2-139352016\lambda\tau+79862760\tau^2-273021996\lambda+98514360\tau+270382500)\end{array}\right]}{9(600\lambda^6-5465\lambda^5+418\lambda^4+86050\lambda^3-105496\lambda^2-246721\lambda+375590)^2(75\lambda^5-655\lambda^4-679\lambda^3+18663\lambda^2-49568\lambda+37996)^2};$$

$$R_i^s = \frac{\left[\begin{array}{c}(2-\lambda)^2(23-5\lambda)^4\left(15\lambda^3-32\lambda^2-485\lambda+826\right)^2 \\ \left(60\lambda^5\tau+30\lambda^5-233\lambda^4\tau+124\lambda^4-1535\lambda^3\tau+574\lambda^3+3543\lambda^2\tau-480\lambda^2+4955\lambda\tau-4966\lambda-10678\tau+6752\right) \\ \left(120\lambda^5\tau-60\lambda^5-616\lambda^4\tau+293\lambda^4-1740\lambda^3\tau+1257\lambda^3+5208\lambda^2\tau-5187\lambda^2+4444\lambda\tau+2815\lambda-11304\tau+2826\right)\end{array}\right]}{3(600\lambda^6-5465\lambda^5+418\lambda^4+86050\lambda^3-105496\lambda^2-246721\lambda+375590)^2(75\lambda^5-655\lambda^4-679\lambda^3+18663\lambda^2-49568\lambda+37996)^2};$$

$$CS_i^s = \frac{\left[\begin{array}{c}2(2-\lambda)^2(23-5\lambda)^4\left(15\lambda^3-32\lambda^2-485\lambda+826\right)^2 \\ (30\lambda^5\tau-105\lambda^5-154\lambda^4\tau-479\lambda^4-435\lambda^3\tau+2118\lambda^3+1302\lambda^2\tau \\ -5907\lambda^2+1111\lambda\tau-4679\lambda-2826\tau+12954)^2\end{array}\right]}{9(600\lambda^6-5465\lambda^5+418\lambda^4+86050\lambda^3-105496\lambda^2-246721\lambda+375590)^2(75\lambda^5-655\lambda^4-679\lambda^3+18663\lambda^2-49568\lambda+37996)^2};$$

$$ED_i^s = \frac{\left[\begin{array}{c}(2-\lambda)^2(23-5\lambda)^2\left(15\lambda^3-32\lambda^2-485\lambda+826\right)^2 \\ (1950\lambda^7\tau-1425\lambda^7-18740\lambda^6\tau+14125\lambda^6+22644\lambda^5\tau-12228\lambda^5+166136\lambda^4\tau-224794\lambda^4-291490\lambda^3\tau+712235\lambda^3-300228\lambda^2\tau \\ -665307\lambda^2+640432\lambda\tau+87226\lambda-80736\tau+20184)^2\end{array}\right]}{72(600\lambda^6-5465\lambda^5+418\lambda^4+86050\lambda^3-105496\lambda^2-246721\lambda+375590)^2(75\lambda^5-655\lambda^4-679\lambda^3+18663\lambda^2-49568\lambda+37996)^2\lambda^2};$$

$$W_i^s = \frac{\left[\begin{array}{c}(2-\lambda)^2(23-5\lambda)^2\left(15\lambda^3-32\lambda^2-485\lambda+826\right)^2 \\ (967500\lambda^{14}\tau^2-292500\lambda^{14}\tau-17556000\lambda^{13}\tau^2+2131875\lambda^{14}+4812000\lambda^{13}\tau+77154400\lambda^{12}\tau^2 \\ -37869000\lambda^{13}-4964350\lambda^{12}\tau+328423640\lambda^{11}\tau^2+159053125\lambda^{12}-306207140\lambda^{11}\tau-3225121844\lambda^{10}\tau^2 \\ +708403400\lambda^{11}+1667448140\lambda^{10}t+3342551920\lambda^9t^2-6028980038\lambda^{10}+1651322516\lambda^9t+28213834732\lambda^8t^2 \\ -223537556\lambda^9-33677348368\lambda^8\tau-67396379864\lambda^7\tau^2+79035079786\lambda^8+77797944044\lambda^7\tau-64211662376\lambda^6\tau^2 \\ -107899816604\lambda^7+30452995856\lambda^6\tau+307343854240\lambda^5\tau^2-431160880769\lambda^6-337792467748\lambda^5\tau \\ -102269866892\lambda^4\tau^2+1244000427964\lambda^5+393857579150\lambda^4\tau-617545046543\lambda^4-425028356208\lambda^3\tau^2 \\ -6001170456\lambda^3\tau+375157268432\lambda^2\tau^2-990693844428\lambda^3-194356942664\lambda^2\tau-22532448768\lambda\tau^2 \\ +916175773508\lambda^2+51203740032\lambda\tau-6518301696\tau^2-11392656960\lambda+3259150848\tau-407393856)\end{array}\right]}{18(600\lambda^6-5465\lambda^5+418\lambda^4+86050\lambda^3-105496\lambda^2-246721\lambda+375590)^2(75\lambda^5-655\lambda^4-679\lambda^3+18663\lambda^2-49568\lambda+37996)^2\lambda^2}.$$

A.1.3 Emission standard

$z_i^h = \frac{2(5\lambda-39)(1+\lambda-4\tau)}{15\lambda^2-50\lambda-801}$; $q_{ii}^h = \frac{5\lambda^2+10\lambda\tau-8\lambda-78\tau-381}{15\lambda^2-50\lambda-801}$; $q_{ij}^h = \frac{(5\lambda-39)(1+\lambda-4\tau)}{15\lambda^2-50\lambda-801}$;

$f_i^h = \frac{80\lambda\tau+26\lambda+567\tau-15\lambda^2\tau-342}{2(15\lambda^2-50\lambda-801)}$;

$$\pi_i^h = \frac{2(25\lambda^4-50\lambda^3\tau+250\lambda^2\tau^2-210\lambda^3+990\lambda^2\tau-3900\lambda\tau^2-1490\lambda^2-7710\lambda\tau+15210\tau^2+4374\lambda+23634\tau+73341)}{(15\lambda^2-50\lambda-801)^2};$$

$$R_i^h = \frac{(5\lambda-39)(1+\lambda-4\tau)(80\lambda\tau+26\lambda+567\tau-15\lambda^2\tau-342)}{(15\lambda^2-50\lambda-801)^2}; \qquad CS_i^h = \frac{2(5\lambda^2-5\lambda\tau-21\lambda+39\tau-210)^2}{(15\lambda^2-50\lambda-801)^2};$$

$$ED_i^h = \frac{[11\lambda^2-(88\tau-28)\lambda-116\tau+29]^2}{2(242\lambda^2+836\lambda+826)};$$

$$W_i^h = -\frac{\begin{pmatrix} 75\lambda^4\tau-3000\lambda^3\tau^2-100\lambda^4-710\lambda^3\tau+3390\lambda^2\tau^2+710\lambda^3-3360\lambda^2\tau \\ +7740\lambda\tau^2-8892\lambda^2+25998\lambda\tau-121914\tau^2-37002\lambda+60957\tau-248220 \end{pmatrix}}{(15\lambda^2-50\lambda-801)^2}.$$

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