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What drives ports around the world to adopt air emissions abatement measures?

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ABSTRACT

The reduction of Greenhouses gasses (GHG) and other air emissions represents a major challenge for ports. The world over, however, ports vary considerably in their efforts to reduce air emissions, and the causes for this variation remain under-researched. This paper examines the drivers for the adoption of air emissions abatement measures in a sample of 93 of the world's largest ports, covering all continents and mobile emitters. We test five hypotheses with a Linear Probability Model to disentangle the impacts of key port characteristics on the current adoption of abatement measures and identify three key drivers for adoption: Population density, the port landlord business model, and a specialization in servicing container shipping. We also find that ports are more likely to implement specific bundles of measures, in particular combining pricing and new energy sources. Our work has implications for ports, as we suggest that they should coordinate abatement efforts to achieve effectiveness in their work.

1. Introduction

Ports are under increasing pressure from their stakeholders, including port users, regulators and the surrounding communities, to reduce the air emissions generated by their activities, as port operations are associated with high levels of air emissions and related external costs (Tichavska et al., 2019) and air quality is a major concern among the general public (Giuliano and Linder, 2013; Poulsen et al., 2018a). Extensive research on air quality has documented the negative human health effects of port emissions (e.g., Saxe and Larsen, 2004; Corbett et al., 2007; Tzannatos, 2010; Berechman and Tseng, 2012; Song, 2014; Chatzinikolaou et al., 2015; Maragkogianni and Papaefthimiou, 2015; Dragović et al., 2018; Sorte et al., 2019), and GHG emissions from the ports' own operations have also started to attract research attention (Styhre et al., 2017).

The renewed focus on the role of ports in air emissions abatement finds support in earlier studies concluding that ports hold great potential generally in the shift to urban sustainability (Hall 2007) and specifically in contributing to reducing air emissions in maritime transport chains, whether the end-to-end shipping emissions generated at sea (Gibbs et al., 2014), emissions generated within the port (Lam and Notteboom, 2014; Cammin et al., 2020), or emissions generated in the port hinterland transport system (Gonzalez Aregall et al., 2018). Ships, trucks, trains and terminal equipment are major causes of GHG emissions as well as sulphur oxides (SOx), nitrogen oxides (NOx), and particulate matter (PM) in ports, or in association with their operations to and from ports (López-Aparicio et al., 2017; Chang et al., 2013; Winnes et al., 2015; Styhre et al., 2017).

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Such pressures might threaten ports' social licenses to operate (Dooms et al., 2013). 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; Fenton, 2017).[1] 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, 2020a, 1). At the same time, port authorities are increasingly engaging in sustainability reporting in response to institutional pressures (Santos et al., 2016) and in green marketing, aligned with overall port strategy (Lam and Li, 2019).

There is a wide range of air emissions abatement measures available for port authorities (Lam and Notteboom, 2014; Acciaro et al., 2014a; Acciaro et al., 2014b; Gibbs et al., 2014; Gonzalez Aregall et al., 2018; Poulsen et al., 2018a,b). Some aim for improved operational efficiency, such as, optimized terminal gate allocation to reduce truck idling time (Chen et al., 2013) and port call optimization processes to reduce vessel turn-around time in port (Johnson and Styhre, 2015; Poulsen and Sampson, 2020). Port pricing schemes aim to incentivize the various port users to shift to low emissions technologies (Bergqvist and Egels-Zandén, 2012; Gibbs et al., 2014, Poulsen et al., 2018b; Sköld, 2019). Finally, the provision of onshore-power systems for ships (Zis et al., 2014; Ballini and Bozzo, 2015) and alternative fuels for trucks, terminal equipment and ships (Bailey and Solomon, 2004; Iris and Lam, 2019) aim for a shift to low-emission technologies.

In recent years, major ports have achieved significant local air quality improvements through the implementation of multiple measures, of which some have high complexity and require extensive collaboration between port stakeholders (Poulsen et al., 2018a). Nevertheless, there are significant differences in ports' adoption of emissions abatement measures (Lawer et al., 2019; Lam and Li, 2019), and the causes for this variation remain under-researched. Although the port literature on air emissions is rapidly growing (Davarzani et al., 2016; Bjerkan and Seter, 2019; Bergqvist and Monios, 2019), little is known about what triggers ports to adopt specific air emissions reduction measures and of the factors that impede such adoption. In this article we focus on the impacts of key port characteristics on port adoption of air emissions abatement measures, asking: *What are the drivers of ports' adoption of air emissions abatement measures?*

The present study contributes to the port literature through a broad empirical study of 93 of the world's largest ports, covering all continents and mobile GHG emitters. We assess the effects of five key port characteristics on port adoption of air emissions abatement measures: port location, port size, a specialization in serving container lines, port ownership, and port business model. In addition, we assess the effects of infrastructure quality and GDP per capita. Among the many options available for reducing air emissions from ports and maritime shipping, we focus on twelve generic abatement measures, including performance standards and pricing measures (for an overview, please see descriptive statistics in Table 1 and further description of the measurers in Appendix B).

The next section reviews the literature on ports and air emissions to identify knowledge gaps and develop hypotheses about drivers of ports' adoption of emission abatement measures. In the third section, we present our econometric methods and data sampling and coding scheme. In the fourth section, we analyse our data before we conclude on the test result. The last section summarizes our findings, provides suggestions for how port managers can achieve more effectiveness in their abatement efforts, and points towards further research.

2. Literature review and hypotheses

This section first presents recent advances within the literature on port sustainability regarding the air emissions abatement measures available to ports and assertions about what motivates ports to adopt them. It then develops five hypotheses from the literature on port sustainability regarding what drives ports to adopt air emissions abatement measures.

2.1. Literature review

A rapidly growing literature on port sustainability (Gibbs et al., 2014, Acciaro et al., 2014b; Bergqvist and Monios, 2019; Bjerkan and Seter, 2019; Lim et al., 2019) has proposed several air emissions abatement measures available to ports. These include various energy management measures (Acciaro et al., 2014a), the provision of onshore power for ships at berth (Chang and Wang, 2012; Zis et al. 2014; Ballini and Bozzo, 2015; Innes and Monios, 2018), voluntary speed reduction zones for ships (Chang and Wang, 2012; Chang et al., 2013; Linder 2018), 'green port dues' for ships (Poulsen et al., 2018b; Sköld 2019), and various incentive, training and traffic management programs directed towards the hinterland transport system to facilitate modal shifts and improved traffic flows (Bergqvist and Egels-Zandén, 2012, Bergqvist et al. 2015; Gonzalez Aregall et al., 2018).

In an exploratory multiple case study of leading ports in Asia and Europe, Lam and Notteboom (2014) developed a typology of port environmental management measures, focusing particularly on pricing; monitoring and measuring; and market access control and environmental standard regulation. Among other things, they found that the leading ports tend to adopt an enforcement approach (i.e., market access control and environmental standard regulation) to green port development.

[1] To reflect the broader scope of its ambitions, the initiative was recently renamed as the World Port Sustainability Initiative (WPSI, 2020).

Table 1
Descriptive statistics and correlations.

Variable	Mean	Std. Dev.	Min	Max	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15
(1) Monitoring	0.548	0.801	0	2	1.000														
(2) Pricing ships	0.204	0.405	0	1	0.455*	1.000													
(3) Pricing trucks	0.032	0.178	0	1	0.180	0.209	1.000												
(4) Standard ships	0.043	0.204	0	1	0.120	0.418*	−0.039	1.000											
(5) Standard terminals	0.022	0.146	0	1	0.177	0.293*	−0.027	0.334*	1.000										
(6) Standard trucks	0.054	0.227	0	1	0.315*	0.470*	0.226	0.419*	0.622*	1.000									
(7) Port-owned vessels	0.086	0.282	0	1	0.366*	0.605*	0.161	0.502*	0.219	0.437*	1.000								
(8) Modal shift targets	0.151	0.36	0	1	0.314*	0.458*	−0.077	0.504*	0.352*	0.433*	0.407*	1.000							
(9) LNG	0.28	0.632	0	2	0.381*	0.666*	0.112	0.327*	0.170	0.197	0.535*	0.435*	1.000						
(10) Biofuels	0.011	0.104	0	1	0.059	0.206	−0.019	0.492*	−0.015	−0.025	0.340*	0.248	0.285*	1.000					
(11) On shore power	0.376	0.751	0	2	0.485*	0.673*	0.071	0.390*	0.322*	0.455*	0.513*	0.473*	0.532*	0.227	1.000				
(12) Batteries vehicles	0.129	0.471	0	2	0.271*	0.543*	−0.050	0.394*	0.275*	0.239	0.488*	0.397*	0.498*	0.416*	0.598*	1.000			
(13) Location	1.74	1.04	0	3	0.080	0.178	−0.131	0.155	0.180	0.105	0.150	0.192	0.078	0.026	0.098	0.113	1.000		
(14) Size	147.695	175.784	11.7	1010	−0.085	0.056	−0.078	0.184	−0.048	−0.106	−0.036	0.003	0.030	0.192	−0.048	0.023	−0.063	1.000	
(15) Business Model	1.634	0.857	1	3	−0.291*	−0.252	−0.136	−0.033	0.064	−0.066	−0.048	−0.066	−0.171	−0.078	−0.206	−0.043	0.051	0.242	1.0
(16) Government Ownership	0.129	0.337	0	1	−0.083	−0.127	−0.074	0.067	0.154	0.041	−0.013	0.090	−0.081	−0.042	−0.079	0.021	0.041	−0.134	0.3

Variable	Mean	Std. Dev.	Min	Max	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
(17) Container specialization	0.418	0.368	0	1	0.016	0.156	0.135	0.121	−0.001	0.226	0.194	0.058	0.039	−0.027	0.067	0.122	0.229	−0.123	0.28
(18) WEF	4.877	0.748	3.1	6.4	0.326*	0.463*	0.226	0.313*	0.074	0.225	0.329*	0.304*	0.356*	0.199	0.367*	0.252	0.036	0.102	−0.2
(19) GDP/ capita	27756.376	20673.105	1979	75,704	0.407*	0.424*	0.286*	0.245	0.106	0.292*	0.277*	0.350*	0.380*	0.105	0.343*	0.193	−0.199	−0.028	−0.3

N = 93, *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

In another multiple case study, Poulsen et al. (2018a), distinguished port environmental management tools along two dimensions: 1) implementation complexity and 2) issue visibility. Issue visibility is a construct used in organizational research for predicting green response by organizations (Bowen, 2000). People are psychologically and physiologically sensitive to visual inputs (Hyslop, 2009) and tend to react more to phenomena that are easily noticeable. Particularly, Poulsen et al. (2018a) noted that air emissions become less visible the further away from port they occur (e.g., in ocean transit or in the hinterland transport system) but also that some kinds of air pollutants (e.g., PM) are more visible than other (e.g., GHG). They concluded that ports in their capacity as community manager "…have the capacity of handling organizationally complex tools, but will implement them only when emission visibility is high" (p. 89).

In a recent study of 30 of the world's major ports, Lam and Li (2019) documented considerable differences with regard to green marketing. Their study emphasized how green marketing strategy should align with overall port strategy. They called for further studies on "… why some ports spent more effort on green port marketing" (p. 80). In a content analysis of the sustainability communication of 186 European ports, Santos et al. (2016) found that port size matters: the larger the port, the more elaborate its sustainability communication. They also found variation in port sustainability communication related to national context. They proposed future studies to investigate the effects of port ownership on sustainability communication.

The motivations of port authorities for reducing air emissions, and the barriers they face, have started to attract research attention. Giuliano and Linder (2013), Hall et al. (2013) and Linder (2018) pointed out how community and institutional pressures regarding local air quality triggered the Ports of Los Angeles and Long Beach to adopt air emissions abatement measures. Lam and Li (2019) noted how sustainability measures are adopted especially by ports "located near cities or local communities" (p. 73), and Poulsen et al. (2018a) showed how ports implement both simple and complex measures to improve local air quality (e.g., cold-ironing and port due rebates for LNG powered vessels), which is often an issue of high visibility to port city residents. The latter also found that ports tend to avoid implementing more complex measures to reduce GHG emissions from ships (e.g., virtual arrival and reduced vessel turn-around time in port), a large part of which occurs far away from and outside of the port's own jurisdiction.

Styhre et al. (2017) noted how the type of shipping traffic matters for the potential of ports to reduce maritime-related air emissions. They found that the frequency with which ships call at the same port has an impact on the potential of ports to reduce air emissions. Ports can more easily direct their abatement efforts towards the ships employed in liner services with regular calls at the same ports (e.g., container ships, or ferries and passenger ships), as opposed to ships in worldwide tramping operations, which do not call frequently at the same ports.

The literature on port sustainability relies predominantly on case research methods to study port air emissions abatement and furthermore tends to take one port or a particular abatement measure (or a few of these) as case. We believe that the variation in ports' adoption of air emissions abatement measures is an under-researched issue. Such variation is important, because it links directly to the potential and limitations of ports to reduce air emissions from maritime transportation.

In line with the call by Lam and Li (2019), we study the variation in abatement measures adopted in a global sample of 93 ports. In a quantitative analysis with a Linear Probability Model framework, this study disentangles the effects of port characteristics on the adoption of such measures and sheds new light on what triggers air emission reduction efforts in maritime transportation.

2.2. Hypotheses

We first hypothesize the following relationship:

H1: The likelihood of ports to adopt air emissions reduction measures increases with increasing population density in the port area.

The first hypothesis is based on studies indicating that community pressure from nearby residents causes ports to focus on reducing air emissions from their activities (e.g., Giuliano and Linder, 2013, Linder, 2018, Poulsen et al., 2018a; Gonzalez Aregall et al., 2018; Lam and Li, 2019). We thus expect to find that port location matters for the adoption of air emissions abatement measures. We use the population density in the cities where the ports are located as a proxy to capture such community pressure. The larger the nearby city (or city district) population is, the stronger we would expect the community pressure on ports to reduce air emissions. The choice of using population density as a proxy for community pressure is in line with World Bank studies that use population density as proxy for urbanization (Wang and Wheeler, 1996).

H2: The likelihood of ports to adopt air emissions reduction measures increases with increasing port size.

With inspiration from the management literature on organizations and the natural environment, which finds a positive relationship between firm size and environmental performance (Etzion, 2007), we furthermore expect the size of the port to impact emissions abatement. The larger a port is, the more relevant is its share in emissions in the region and the higher the visibility and public attention to its environmental performance. In addition, larger ports have larger capacity and more resources and are thus better able to adopt measures for reducing air emissions. Hence, the second hypothesis follows Mellin and Rydhed (2011) who demonstrated that authorities in large ports tend to be more concerned with GHG emissions than those in small ports, Santos et al. (2016) who argued that large ports have more resources and higher visibility and therefore are more likely than small ports to engage in public communication about their social and environmental performance, and Gong et al. (2020) who argued that the benefits of welfare investments (in their case, investments in natural disaster prevention) are likely to be higher for ports with more capacity.

H3: Ports that predominantly serve container lines are more likely to adopt emissions abatement measures than ports predominantly handling bulk commodities.

The third hypothesis is based on two arguments. First, Styhre et al. (2015) and Winnes et al. (2015) argued for a positive relationship between frequency of ship calls and ports' potential for emissions abatement. Container liner shipping is generally a round-trip service with a fixed and high frequency of calls in specific ports. Also, container ships generally carry intermediates and final goods for customers that serve increasingly environmentally conscious end-consumers, who pass sustainability requirements through their supply chain (Poulsen et al., 2016, Van den Berg and De Langen, 2017). We would therefore expect container lines to focus more on environmental performance, and container ports to respond to this with a stronger focus on air emissions abatement measures[2].

H4: Ports with a government-owned port managing body are more likely to adopt emissions abatement measures than ports with a private port managing body.

The fourth hypothesis suggests that port ownership structure is relevant in explaining the adoption of measures for reducing air emission in ports. We distinguish between government and private ownership of the "port managing body" (Brooks and Cullinane, 2006, Van der Lugt et al., 2015)[3] and, following De Langen and Van der Lugt (2017), suggest that government ownership begets a stronger focus on sustainability. We thus expect to find that government-owned port managing bodies are more likely than private-owned port managing bodies to take initiatives to reducing air emissions in the maritime transport chains of which they are part.

H5: Landlord ports are more likely to adopt emissions abatement measures than ports with a service port or mixed business model.

Finally, the fifth hypothesis posits that the business model of the port managing body is also relevant. Here, a distinction is made between ports operated under 1) a landlord model, 2) an integrated model, and 3) a mixed port model[4]. In the landlord model, the port is an entity that owns the port infrastructure and has agreements with third party operators (see, e.g., Brooks and Cullinane, 2006). In the integrated model, the port is itself an operator that provides all cargo handling services. In the mixed model, the port management body partly provides terminal-handling services in-house and partly relies on third-party operators. The majority of large ports globally operate with a landlord model (Van der Lugt et al., 2015) under which the port management is focused on developing the port as a business ecosystem that is vital in the long run. We therefore posit that the landlord model is most conducive to emissions abatement measures and in line with recent research (e.g., Munim et al., 2020) expect to find that the landlord model is a key driver for ports around the world to adopt air emissions abatement measures.

3. Methods

The following section presents the research design, data collection and processing, and modelling choices employed in this study. To analyse variation in in the likelihood adoption of measures to reduce air emissions by ports, we employ a deductive research design and use a Linear Probability Model (LPM) for hypothesis testing. Particularly, we examine the five hypotheses developed above regarding what triggers ports to adopt air emissions abatement measures. The model is presented in the equation below:

Adoption (degree of adoption) of an abatement measure = $\beta0 + \beta1$ Location + $\beta2$ Size + $\beta3$ Business Model + $\beta4$ Government + $\beta5$ Container specialization ($+\beta6$ GDP + $\beta7$ WEF) (+country-level fixed effects) + i

3.1. Sampling

We employ non-probability, purposive sampling in selecting the world's largest ports within the container, dry bulk and tanker shipping sectors. We focus on the ports with the largest cargo volumes, because they tend to have more comprehensive sustainability communication than medium-sized and small ports (Santos et al., 2016). Large ports facilitate international trade and play an important role in global maritime supply chains (Panayides and Song, 2009). Their activities stretch far beyond those related to their home region, and they have a well-developed multi-modal hinterland infrastructure (De Langen, 2008; Notteboom, 2009). This choice naturally has implications for the generalizability of our findings, as our results may not be readily applicable to medium-sized and small ports that have less developed hinterland infrastructure and generally serve mainly local or regional markets.

We rely on recognized external sources to identify the ports, as they are ranked by annual cargo throughput volume for dry and liquid bulk ports and by annual volume of container shipments measured in twenty-foot equivalent units (TEUs) for container ports.

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2 This argument also extends to cruise ships (and to a lesser extent to passenger and freight ferries), but as our study is confined to cargo ports we will focus on container shipping.

3 We classify port management bodies that are partly privately owned and partly government owned as private, since the presence of private shareholders implies a profit orientation. On the other hand, we classify port management bodies owned by a state-owned holding company as government-owned. This includes port management bodies owned by a municipality (see, e.g., De Langen and Sornn-Friese, 2020).

4 This classification is broadly in line with the World Bank's (2007) classification into landlord, service, and tool ports. Similarly to the mixed port model, the tool port is an intermediary form between landlord and service port. While the World Bank focuses on the ownership of assets, we see the mix of in-house and third-party service provision as the core of the intermediary form (see also, van der Lugt et al., 2015, Verhoeven and Vanoutride, 2012). Verhoeven and Vanoutride (2012) distinguish between conservator, facilitator, and entrepreneur models as conceptual ideal types of port governance. However, this distinction was developed specifically for European ports and focuses on explaining newly developed activities of landlord port authorities. The facilitator plays an active role as broker, matchmaker or mediator, compared to the more passive conservator. Both of these roles are included in the category of landlord ports used in the present study. Verhoeven and Vanoutride's entrepreneurial port is broadly in line with the mixed model used in the present study.

To identify the largest container ports, we use the annual list of "Top 50 World Container Ports" published by the World Shipping Council (www.worldshipping.org) and include those ports that were listed over the past five years (2015–2019). In addition, we include the top 29 liquid bulk ports listed by the Institute of Shipping Economics and Logistics in Bremen (ISL, 2015a, Table 4.4.1)[5] and the top 30 dry bulk ports listed in ISL (2015b, Tables 3.7.1 and 3.7.2). We ended up with an initial sample of 98 ports (please see Appendix A)[6].

3.2. Data sources and coding scheme

We take as unit of analysis the air emissions abatement measures adopted by the ports, as identified from their websites and most recent annual reports and sustainability reports. Organizational reports are reliable sources of data on firms and industries (Bowman, 1984) and are generally accepted for studying the interaction of organizations with their environments (Duriau et al., 2007). Previous research has also shown the usefulness of information disclosed through corporate websites (Trabelsi et al., 2014). Specifically for ports, there is increasing tendency to make "everything good the port does in terms of reducing its negative impacts" publically available (Stein and Acciaro, 2020). Data from the corporate websites were collected during the period January-June 2019. Five ports were discarded from the initial sample, as they did not disclose any information on abatement measures.[7] The final sample is listed in Appendix A, which also shows in what regions of the world the ports are located. Taken together, the ports in the final sample account for roughly 60% of the total volume handled in the world's ports.[8]

The data sets for independent variables (variables 13–18 in Table 1) were built from publicly available information. Collecting data for the independent variables for hypothesis H2 (port size), H3 (specialization in container shipping), H4 (port ownership) and H5 (business model), was uncomplicated. Numbers on cargo volumes were collected through the annual reports of the ports, national statistical agencies, and industry reports. The specialization of ports in handling container traffic is expressed as the share of container throughput volumes of total cargo throughput.[9] The data on *Ownership* and *Business model* of the port management body were assessed through information on the website and/or annual report of the ports.

Population density captures the community pressure exerted on ports. The *Location* variable is treated as an ordinal scale for the geographic concentration of population and reflects the degree of urbanization of the area where a port is located. Since, as also noted by Lam and Li (2019), the community pressure exerted on ports is likely to emanate from the part of a city's inhabitants living closest to the port, we used population density for the specific city district in which a port is located, to the extent this was possible, rather than the average population density for the whole city. To allow for such precision, we used city maps to pinpoint the exact location of each of the sampled ports. The ports were then ranked into four population density levels: Low (< 385 persons/km^2), medium–low (386–1,930 persons/km^2), medium–high (1,931–3,860 persons/km^2) and high (greater than3,861 persons/km^2).

For 91 of the ports in the final sample, population density was derived from the *City Population* database (www.citypopulation.de), which covers cities and city districts, towns and urban places in all regions of the world. For the remaining seven ports (Hanshin Ports, Jeddah Islamic Port, Keihin Ports, Port Kelang, Port of Qinhuangdao, Port of Singapore, and Port of Yokohama), the relevant population density measures were derived from *Demographia World Urban Areas* (DWUA) (www.demographia.com), which provides population statistics for about 1,100 larger urban areas. DWUA includes measures for combined urban areas and is thus appropriate for identifying population density for ports that are spread out in broader areas including more than one city and possibly more than one municipality, such as, the Port of Singapore or the Japanese Keihin Ports (Yokohama-Kawasaki-Tokyo) and Hanshin Ports (Osaka-Kobe-Kyoto).

The study uses two country level indicators as control variables: the quality of port infrastructure in a country and the country's per capita GDP. The quality of port infrastructure is an indicator from the World Economic Forum (*WEF*), presenting the perceptions of business executives in different countries on their country's port facilities.[10] The indicator is also reported by the World Bank and has previously been used in port research, for instance in a widely cited paper by Clark et al. (2004) and more recently in Munim and Schramm (2018).

[5] For the liquid bulk ports we chose to focus only on importing ports, as exporters are typically simple single-purpose terminals in remote areas and not really ports.

[6] Although data were drawn for the largest ports within each of the three segments, there are considerable size differences within the sample. The largest container and liquid bulk ports are thus more than ten times larger than the smallest container and liquid bulk ports in the sample, while the largest dry bulk port is about 30 times larger than the smallest of the dry bulk ports.

[7] A *t*-test comparing the means for retained and discarded ports indicated no significant differences in terms of port ownership or in specialization in container shipping but did reveal significant differences in other port characteristics: On average, the ports that we excluded from the sample were more often service or mixed ports than the ones we kept and on average more often located in medium–high or high population density areas.

[8] The total volume handled by the ports in the final sample is more than 13 billion tons. While there are no precise statistics on total global volumes handled in ports, UNCTAD (2019) reports a total volume of *loaded* cargo of over 11 billion. As ports report the sum of loaded and unloaded cargo, this suggests that the ports in our sample may account for as much as around 60% (13 billion out of a total of 22 billion) of the total volumes handled in all ports worldwide.

[9] For better comparison with dry and liquid bulk ports, we converted container shipments in TEU into cargo tons, assuming a 'rule of thumb' conversion factor of 10 tons per TEU. This conversion factor was chosen on the basis of data from ports that publish both TEU throughput volumes and corresponding throughput in metric tons.

[10] The 'Quality of Port Infrastructure' results from the 'Executive Opinion Survey' that captures the opinions of business leaders around the world on a broad range of topics. In particular, for the Quality of Port Infrastructure Index the question asked is: "In your country, how would you assess the quality of seaports?"

Previous studies (e.g., Vachon, 2010) have shown that the economic wealth of a country, as measured by per capita GDP, is positively related to sustainable development. We used data on GDP from the World Bank for the year 2017. Since the World Bank did not include data for Taiwan, we used GDP per capita (nominal) provided by the government website of Taiwan (www.taiwan.gov.tw).

For each port, observations on the environmental measures were coded in accordance with the coding scheme presented in Appendix B. Whenever the organizational reports and websites from a port mentioned the adoption of an air emissions reduction measure, the code 1 (present) was assigned. If not mentioned, we assumed that the port does not employ such measures and assigned the code 0 (absent). This coding is conservative in the sense that the data represents *minimum* observations of the adoption of air emissions abatement measures. For most variables, the codes were of a binary nature (present/absent). For the variable *Monitoring*, an ordinal scale was used to distinguish between three levels of emissions monitoring (0: No monitoring; 1: Partial monitoring; 2: Full monitoring). An ordinal scale was also used for the variables *LNG*, *Onshore Power* and *Batteries for vehicles*, distinguishing between 0 (not available), 1 (available today), and 2 (investments planned to be undertaken).

3.3. Modelling choices

The relatively small sample size (n = 93) affects our modelling choices. As the recommended minimum sample size for a logit (or an ordered logit) modelling framework is 200 observations (King and Zeng, 2001)[11], we used a Linear Probability Model (LPM) to model the binary and ordinal dependent variables. We are well aware of the consequences of this choice. LPM modelling implemented, in particular, with binary variables creates non-conforming predicted probabilities, i.e., values outside of the expected range between 0 and 1. Moreover, the error term produced by the LPM estimation is heteroscedastic and the LPM assumes also constant marginal effect of explanatory variables, which may be troubling for values that are not close to the averages (Wooldridge 2009, Cameron & Trivedi, 2009). Lastly, the residuals take only two possible values and thus cannot be normally distributed. Despite its shortcomings, "…the linear probability model is useful and often applied in economics (and) usually works well for values of the independent variables that are near the averages in the sample" (Woodridge, 2009, p. 249). The robust (or cluster) command in Stata was used to correct for heteroscedasticity. We also monitored the number of non-conforming predicted probabilities and implemented very conservative tests in which the outliers were dropped, our results remaining unchanged.

4. Analysis

This section first provides an overview of descriptive statistics and correlation matrix (please see Table 1) and then proceeds with a detailed view of adoption of measures across ports, using all the specific abatement measures as standalone, with and without country fixed effects respectively, thus alleviating the issue of unobserved country characteristics that are time invariant. Such a procedure is common in econometrics. Principal Component analysis was used to compute an indexed measure for determining the adoption of air emission reduction measures in ports.

4.1. Descriptive statistics and correlations

**** Insert Table 1 here ***

The descriptive statistics in Table 1 show that the number of ports that have adopted emission reduction measures is limited. While 20% of the ports in the sample use pricing for ships (0.20), only 3% use pricing for trucks (0.032). 5% of the ports provide standards for trucks, and a similar share of ports provide standards for ships. With the ordinal scale outlined in subsection 3.2, the mean of the monitoring variable (0.54) indicates that full monitoring of air emissions is still uncommon. The availability of cleaner energy for ships and trucks in ports is also still limited: 27% of the ports have LNG available for the ships calling at the port, but only 1% offers biofuel. 37% of the ports provide onshore power supply (at least at some berths) and 12% use batteries for port vehicles[12].

For the independent variables, the average port in the sample is located in a medium–low population density area (given by the respective means of 1.74). Their average throughput is 147 million tons, and with an average *container specialization* around 40%. Most ports have a landlord business model (mean of 1.63 with a large standard deviation of 0.85) and are government owned.

Our main analysis includes country fixed effects (GDP per capita and WEF score). The countries included in the sample have a mean GDP per capita of 27,756 million USD and the mean WEF score is 4.87 (on a scale from 1 to 7). In an additional analysis, we include country fixed effects, which should take care of unobserved heterogeneity among countries that could affect their propensity to adopt abatement measures (please see below).

Most of the dependent variables in Table 1 display significant and positive correlations with one another, especially within a group of similar measures (e.g., pricing). The correlations are weaker between groups of different measures (e.g., *Pricing* and *Moni-*

[11] We ran additional analysis for our 3-level dependent variables using the two alternative modelling frameworks, multinomial and ordered logit (Cameron and Trivedi, 2009). We have not included them, but they are available upon request. Our results remain unchanged.

[12] Since none of the ports in our sample had made methanol available, we did not include this measure in the analysis.

toring, or *Pricing* and *Standards*). The correlations between *Batteries* or *Biofuels for cars* with other dependent variables are not consistent in terms of coefficient signs, but they are also insignificant.

The port level independent variables (*Location, Size, Business model*, *Ownership*, and *Container specialization*) do not correlate strongly with the dependent variables. Only the *Business model* variable is correlated with *Monitoring*, indicating that mixed and/or service ports are less likely to adopt partial monitoring. Some of the port level independent variables are also positively correlated with each other (e.g., *Business model* and *Container specialization*, or *Business model* and *Ownership*).

At the country level, the GDP and WEF scores correlate positively with the dependent variables (some standard variables, and pricing and monitoring), and with each other. The correlation between *WEF* and *GDP* is high (68%), but this does not cause multicollinearity issues in further analysis. This was confirmed in post-estimation with a formal Variance Inflation Factor test, where the values obtained were under 10 (considered the threshold).

4.2. Modelling framework

We subsequently modelled the binary dependent variables in an LPM framework. The reasons for this choice were twofold: first, the relatively small size of the final sample (n = 93) could weaken the estimations with alternative frameworks (e.g., logit). The use of logit would prevent using country fixed effects and thus reduce the possibility to account for endogeneity. Second, there are only few possibilities to address endogeneity in our study, the preferred one being inclusion of country fixed effects to control for unobserved, time-invariant country characteristics. The use of LPM was thus preferred because it deals well even with a demanding specification and the use of fixed effects included as basis for the analysis. Endogeneity could affect our results in two ways: unobserved heterogeneity among ports could lead to the error term being correlated with the dependent as well as the independent variables, thus biasing the analysis. One set of such unobserved factors stems from the country in which a port is located. One could imagine that institutional incentives, policies or even succinct societal expectations would drive ports' sustainability strategies. Table 2 therefore presents the results of the first set of regressions with country-level controls (*GDP per capita* and the *WEF* score) included.

5. Findings

We introduce a full set of independent variables in combination with all our dependent variables (Table 2): in model 1 with *Monitoring,* in model 2 and 3 with *Pricing for ships and Pricing for trucks*, in model 4 to 6 with *Standards for ships*, *Standards for terminal equipment* and *Standards for trucks*, in model 7 with *Low emission fuels for port-owned vessels*, in model 8 with *Modal shift targets*, and in model 9 to 12 with *LNG, Biofuels, Onshore power* and *Batteries for port vehicles*. Mirroring the above structure, Table 3 presents our findings with country fixed effects.

**** Insert Table 2 and Table 3 here ***

Most of the independent variables display consistent signs across models, but significance levels vary.

In the main set of results reported in Table 2, *Location* seems to explain a lot of the variation in *Pricing for ships, Pricing for trucks, Port-owned vessels*, *LNG*, *Modal shift targets*, and *Batteries for vehicles*. Ports located in medium–low population density areas (for *Pricing for trucks*) and medium–high population density areas (for *Port-owned vessels*, *Modal shift targets*, *LNG*, and *Batteries for vehicles*) are more likely to adopt abatement measures than ports in low population density areas[13]. The magnitude of the effect of location on the adoption probability varies from roughly 8% (in the case of *Prizing for trucks*) to more than 36% in the case of *LNG*. These findings from Table 2 are consistent in signs with those in Table 3, although the significance levels are lower: *Location* significantly correlates with *Modal shift targets*.

Surprisingly, port *Size* only correlates with one of the dependent variables, namely *Pricing for ships* (in Table 3). The coefficient of this variable is positive, suggesting a positive relationship between the size of a port and the adoption of pricing strategies for ships calling at the port (e.g., lowering port dues or terminal handling charges for those ships that meet a certain air emission target) as an air emission abatement measure.

The coefficients in Table 2 for *Business Model* correlate negatively for service ports with the *Pricing for ships*, *Standards for trucks*, *LNG*, *Onshore power* and *Batteries for vehicles*. This suggests that service ports are less likely than landlord ports to adopt pricing measures. The magnitude of these effects is, respectively, 32% and 61%. Ports with mixed business models are roughly 20% less likely than landlord ports to adopt *Pricing for ships*.

The coefficient of *Government* (ownership) displays mostly a positive sign, but it is insignificant in both sets of analysis.

Ports specializing in handling container traffic are more likely to adopt *Pricing for ships* and *Standard for trucks.* The largest effect throughout these models is present for the model with *Pricing for ships* (25%). The coefficients of container specialization in Table 3 are additionally significant in models with *Port-owned vessels* and *LNG*.

[13] In a separate analysis (not included but available upon request), Table 2 and Table 3 were replicated with a variation of the *Location* variable collapsed to three levels only: low, medium and high. The results from this additional analysis were consistent and significant, supporting our finding on the relationship between port location and the adoption of abatement measures.

Table 2
LPM with individual dependent variables and country level controls.

VARIABLES	Model1 Monitoring	Model2 Pricing for ships	Model3 Pricing for trucks	Model4 Standard for ships	Model5 Standard for terminal equipment	Model6 Standard for trucks	Model7 Port-owned vessels	Model8 Modal shift targets	Model9 LNG	Model10 Biofuels	Model11 Onshore power	Model12 Batteries vehicles
Location = 1	−0.0558	0.140	0.0891*	−0.0273	0.00830	−0.0142	−0.0322	0.0558	−0.00588	−0.000581	−0.0669	0.00547
(medium–low)	(0.269)	(0.0981)	(0.0523)	(0.0355)	(0.0215)	(0.0435)	(0.0521)	(0.0756)	(0.160)	(0.0113)	(0.220)	(0.109)
Location = 2	0.0979	0.277***	−0.00924	0.0748	0.0140	0.0756	0.137*	0.324***	0.361*	0.0384	0.309	0.228*
(medium–high)	(0.283)	(0.0978)	(0.0231)	(0.0540)	(0.0181)	(0.0522)	(0.0789)	(0.114)	(0.194)	(0.0386)	(0.249)	(0.122)
Location = 3	0.244	0.230**	−0.00744	0.0438	0.0836	0.0280	0.0366	0.194*	0.104	−0.00242	0.0711	0.0522
(high)	(0.273)	(0.102)	(0.0253)	(0.0526)	(0.0660)	(0.0748)	(0.0741)	(0.111)	(0.163)	(0.0118)	(0.227)	(0.0865)
Size	−0.000198	0.000231	−5.87e-05	0.000258	−5.54e-05	−9.09e-05	−9.52e-05	4.36e-05	8.30e-05	0.000122	−0.000256	6.09e-05
	(0.000281)	(0.000179)	(5.38e-05)	(0.000206)	(7.04e-05)	(0.000101)	(0.000164)	(0.000214)	(0.000309)	(0.000124)	(0.000330)	(0.000298)
Business model = 2	−0.288	−0.304***	−0.0740	−0.0904	−0.0265	−0.133*	−0.131	−0.154	−0.359**	−0.0181	−0.547***	−0.261**
(service)	(0.304)	(0.106)	(0.0554)	(0.0556)	(0.0393)	(0.0693)	(0.0815)	(0.104)	(0.157)	(0.0194)	(0.190)	(0.124)
Business model = 3	−0.278	−0.153	−0.0268	−0.0361	0.0386	−0.0109	0.0360	0.0271	−0.0371	−0.0240	−0.117	−0.0143
(mixed)	(0.200)	(0.0946)	(0.0284)	(0.0621)	(0.0440)	(0.0547)	(0.0882)	(0.0879)	(0.165)	(0.0253)	(0.183)	(0.137)
Government	−0.0536	0.0315	−0.0117	0.113	0.0573	0.0883	0.0562	0.167	0.0536	0.0143	0.122	0.183
	(0.256)	(0.124)	(0.0355)	(0.0855)	(0.0818)	(0.0902)	(0.0986)	(0.149)	(0.203)	(0.0157)	(0.229)	(0.172)
Container	0.159	0.251**	0.0688	0.119	−0.0244	0.182*	0.184	0.102	0.213	0.0148	0.308	0.237
specialization	(0.233)	(0.107)	(0.0579)	(0.0743)	(0.0320)	(0.0985)	(0.114)	(0.119)	(0.193)	(0.0181)	(0.214)	(0.147)
WEF	0.0299	0.0903	0.0148	0.0400	−0.00194	−0.00410	0.0742	0.00676	0.0810	0.0217	0.188	0.0966
	(0.137)	(0.0572)	(0.0174)	(0.0300)	(0.0226)	(0.0277)	(0.0491)	(0.0782)	(0.0987)	(0.0217)	(0.117)	(0.0607)
GDP/capita	1.44e-05**	5.67e-06**	1.69e-06*	1.49e-06	1.35e-06	3.41e-06**	2.41e-06	6.49e-06**	9.49e-06**	−2.06e-07	7.09e-06	1.96e-06
	(5.96e-06)	(2.40e-06)	(9.70e-07)	(1.11e-06)	(1.13e-06)	(1.64e-06)	(1.60e-06)	(2.59e-06)	(3.92e-06)	(2.94e-07)	(5.47e-06)	(2.05e-06)
Constant	−0.000703	−0.640**	−0.112	−0.299*	−0.0341	−0.0979	−0.439**	−0.278	−0.548	−0.116	−0.817*	−0.565*
	(0.681)	(0.244)	(0.0877)	(0.161)	(0.0922)	(0.113)	(0.216)	(0.322)	(0.419)	(0.114)	(0.483)	(0.294)
Observations	93	93	93	93	93	93	93	93	93	93	93	93
R-squared	0.232	0.368	0.181	0.213	0.110	0.204	0.229	0.263	0.245	0.102	0.241	0.137

Robust standard errors in parentheses*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

Table 3
LPM with individual dependent variables and country fixed effects.

VARIABLES	Model1 Monitoring	Model2 Pricing for ships	Model3 Pricing for trucks	Model4 Standard for ships	Model5 Standard for terminal equipment	Model6 Standard for trucks	Model7 Port-owned vessels	Model8 Modal shift targets	Model9 LNG	Model10 Biofuels	Model11 Onshore power	Model12 Batteries vehicles
Location = 1	−0.0397	0.0231	0.0983	−0.0463	−0.0285	−0.0908	−0.0801	−0.0776	−0.124	−0.0129	−0.107	−0.00942
(medium–low)	(0.439)	(0.130)	(0.0943)	(0.0634)	(0.0456)	(0.0942)	(0.0838)	(0.142)	(0.143)	(0.0204)	(0.224)	(0.126)
Location = 2	0.139	0.0905	0.0231	0.0900	0.00585	0.125	0.0664	0.229*	0.0519	0.0196	0.267	−0.0114
(medium–high)	(0.404)	(0.117)	(0.0691)	(0.0744)	(0.0272)	(0.0821)	(0.0881)	(0.114)	(0.124)	(0.0238)	(0.224)	(0.130)
Location = 3	0.404	0.182	0.0248	0.00758	0.0993	0.0628	0.0515	0.167	0.138	−0.0473	0.0950	0.0853
(high)	(0.401)	(0.133)	(0.0646)	(0.0796)	(0.0710)	(0.0906)	(0.0781)	(0.126)	(0.160)	(0.0436)	(0.183)	(0.161)
Size	0.000481	0.000610**	−1.36e-05	0.000221	0.000103	0.000113	9.62e-05	2.17e-05	0.000419	0.000204	−0.000336	0.000513
	(0.000479)	(0.000287)	(0.000122)	(0.000177)	(0.000108)	(0.000177)	(0.000150)	(0.000277)	(0.000294)	(0.000185)	(0.000543)	(0.000451)
Business model = 2 (service)	−0.497	−0.287	−0.137	−0.171	−0.0561	−0.220	−0.132	−0.135	−0.244	−0.0444	−0.511	−0.232
	(0.461)	(0.203)	(0.152)	(0.132)	(0.107)	(0.165)	(0.163)	(0.229)	(0.247)	(0.0423)	(0.307)	(0.243)
Business model = 3 (mixed)	−0.108	−0.134	−0.0442	−0.0201	0.0407	−0.0375	0.0507	0.184	−0.0147	−0.0454	0.239	−0.0248
	(0.287)	(0.0947)	(0.0616)	(0.0767)	(0.0615)	(0.0803)	(0.104)	(0.174)	(0.163)	(0.0421)	(0.269)	(0.218)
Government ownership	0.111	0.214	0.0552	0.132	0.0410	0.173	0.104	0.271	0.0290	0.0482	0.183	0.169
	(0.374)	(0.166)	(0.0935)	(0.105)	(0.0708)	(0.155)	(0.143)	(0.263)	(0.220)	(0.0434)	(0.344)	(0.182)
Container specialization	0.227	0.411**	0.0713	0.156	0.00660	0.297**	0.278*	0.113	0.313*	0.0680	0.335	0.216
	(0.332)	(0.156)	(0.128)	(0.136)	(0.0551)	(0.130)	(0.157)	(0.197)	(0.181)	(0.0598)	(0.290)	(0.247)
Constant	0.979*	−0.140	−0.00252	−0.0539	−0.0301	−0.0245	−0.0303	−0.108	0.373	−0.0434	0.676	−0.127
	(0.535)	(0.0867)	(0.0320)	(0.0549)	(0.0380)	(0.0659)	(0.0589)	(0.136)	(0.293)	(0.0433)	(0.571)	(0.113)
Observations	93	93	93	93	93	93	93	93	93	93	93	93
R-squared	0.629	0.664	0.330	0.551	0.495	0.518	0.634	0.605	0.790	0.579	0.658	0.568

Robust standard errors in parentheses*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

The country-level variables *GDP per capita* and *WEF* score presented in Table 2 also correlate positively with the adoption of pricing measures. The overall goodness of fit in the specification with per capita GDP and WEF is lower than in the additional analysis reported in Table 3, which suggests that country-level, time invariant variables explain a large part of the variance in the adoption behaviour of ports.[14]

Our analysis provides some indications in support of the theoretical arguments outlined in the above section 2, in particular for three of the hypotheses. First, there is evidence in support of hypothesis 1 on increasing adoption rates for ports located in increasingly densely populated areas, as the related coefficients are significant and display the expected sign in several models reported. Second, the same is true for hypothesis 5 that landlord ports are more likely to adopt air emissions abatement measures. Lastly, container specialization in ports is clearly also driving the adoption of air emissions abatement measures as evident in the significant coefficients reported in Table 2. There is no evidence for hypothesis 4 on port ownership, and the evidence to support theory on the effects of port size on the adoption of air emissions abatement measures is weak.

As mentioned, the present analysis may suffer from endogeneity and we therefore implement fixed effects into the main analysis. However, some of the key independent variables could also be, at the basis, endogenous. More specifically, one could imagine that location and adoption of abatement measures are in spurious relations: at the time of a construction of a port, decision-makers could pre-empt the need and requirements of being green and therefore select in or out into specific locations (e.g., into lower population density areas to avoid community pressures). One way of dealing with such endogeneity would be to find an instrument and implement a two-stage regression model. Finding a good instrument proved to be difficult in the present case. Nonetheless, since the sampled ports are well-established entities, we believe that similar pre-emptive strategies should not be overwhelmingly at play at the time of port construction, which should have been driven by more pragmatic considerations.

5.1. Additional analysis: Principal component analysis

To gain further insights into how adoption of various abatement measures may play out for ports, we perform a factor analysis. From all the dependent variables loaded, three distinctive factors were retained, of which the first two display the highest difference and uniqueness (exact output suppressed for brevity). The first factor captures mostly *Pricing for ships*, *LNG* and *Onshore power*. The second factor is based mostly on *Standards for trucks* and the last one on *Standards for ships*. Such a clustering reflects a different, possibly orthogonal, nature of the abatement measures: while pricing is a monetary-based incentive (easier to implement and potentially more prone to be immediately used), introduction of standards may require a careful re-design of the business model and not only an analysis of the bottom line. The different factors also tease out the effect based on the audience targeted and the qualitative difference between standards for trucks and ships, as captured by two distinctive factors.

We additionally run a regression with the three factors in Table 4, respectively in Model 1, 2 and 3 and with the same specification as in our main set of regressions, including country-fixed effects.

**** Table 4 here ***

Container specialization is the only factor that explains some variance in both M1 and M2. The last factor has the lowest explanatory power of all, and no coefficients of interest are significant in M3. As mentioned, this non-result may be driven by an overall adoption rate for such measures.

The variables related to *Ownership*, *Size* and *Location* are insignificant across all models. The signs of several variables switch across the three models, such as in the case of medium–low population density locations (positive for the first factor and negative for the others), high population density locations (positive for factors 1 and 2, negative for factor 3), and mixed business model (negative for the first two factors and positive for the last one). This emphasizes again heterogeneous effects of these variables related to various abatement measures. However, there is no case of such sign changes in coefficients being simultaneously significant in two different models.

6. Conclusions

This paper adds to the developing literature on how different port characteristics impact on the adoption of air emission reduction measures. To the best of our knowledge, this has been the first systematic study into these impacts that takes a global perspective and considers all emitters. We show that ports have many potential measures that they could use to reduce air emissions, but also that many of these are not adopted by the majority of ports. Keeping in mind that our sample contains only the world's largest ports, and that other studies have established a positive relation between size of organizations and the introduction of sustainability measures, this suggests that no air emissions abatement measure has yet been widely adopted in the ports industry. This is relevant, as most of the identified measures are only effective when adopted by a large number of ports. This suggests a potential gap between the increasingly ambitious emissions reduction targets (e.g., as expressed by the IMO and IAPH) and the current adoption of

[14] Although not reported below, we also analysed data on two dimensions of national culture: Uncertainty Avoidance (UA) and Power Distance (PD) (Hofstede, 1984). The ports in the final sample are located in countries characterized by medium UA (41 of 93 with a low standard deviation) and high PD (46 of 93 with a large standard deviation). Both variables are correlated, and, when entered into the regression, display a negative sign. Their level of significance is rather low. With these variables included in the analysis, our main findings remain unchanged.

Table 4
PCA with country fixed effects.

	(1)	(2)	(3)
VARIABLES	Model1	Model2	Model3
Location = 1(medium–low)	0.0555	−0.475	−0.186
	(0.238)	(0.420)	(0.238)
Location = 2 (medium–high)	0.0936	0.544	0.226
	(0.222)	(0.377)	(0.260)
Location = 3 (high)	0.327	0.234	−0.148
	(0.211)	(0.388)	(0.372)
Size	0.000674	0.000330	0.000964
	(0.000425)	(0.000856)	(0.00119)
Business model = 2 (service)	−0.462	−0.864	−0.356
	(0.392)	(0.703)	(0.600)
Business model = 3 (mixed)	−0.0369	−0.187	0.0485
	(0.216)	(0.381)	(0.385)
Government ownership	0.173	0.708	0.427
	(0.301)	(0.676)	(0.429)
Container specialization	0.534**	1.232**	0.277
	(0.256)	(0.596)	(0.574)
Constant	−0.149	−0.210	−0.479
	(0.232)	(0.306)	(0.298)
Observations	93	93	93
R-squared	0.831	0.506	0.492

Robust standard errors in parentheses
*** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$

relevant measures: there is a long road ahead to live up to these aspirations. Further research is also required with regard to the potential role of regulations and institutions in shaping a coordinated path towards adoption of sustainability measures (see, e.g., Nursey-Bray, 2016).

Across all measures to reduce air emissions, we identified three key drivers: population density, a landlord business model, and a specialization in servicing container shipping. These findings are in line with predictions from the port literature. The size of the port does not seem to play a significant role, as otherwise predicted by the port literature. However, this result requires further research. We have studied a non-probabilistic sample of the world's largest ports, with an annual throughput ranging from about 10 million tons to over a billion tons. In this sample, size is not associated with the adoption of abatement measures. However, there are over 17,000 cargo-handling ports based on UN LOCODE data[15], of which most are much smaller than the ports in our sample. Thus, further research with a random sample from ports of all sizes would be required to further scrutinize the effect of size. The same applies for port ownership. This is an interesting result: while the theoretical logic for positing that government-owned port management bodies are more likely to take initiatives to reduce emissions than private port management bodies is compelling, our findings do not show such an effect.

For each of the abatement measures, we identified specific port characteristics that are associated with the extent of adoption. For instance, pricing strategies are more widely adopted by landlord ports and ports in densely populated areas. Likewise, monitoring is more likely adopted by ports in high population density areas. These are the measures that the ports actually use. So, why is that? Is it because monitoring and pricing are low-hanging fruits? Or is it simply because ports will require data on emissions levels in the first place, before they can embark on any air emissions abatement project? These are questions with relevance for further research.

Finally, we show that there are patterns in the adoption of air abatement measures in ports, in the sense that ports are more likely to implement specific bundles of measures. While the adoption of standards is not associated with the adoption of other measures, our analysis clearly shows that ports adopting pricing strategies also tend to adopt new energy sources. Especially, ports in lower population density areas are more likely to adopt a bundle of measures related to pricing and new energy sources. This is a relevant finding because, as argued previously, the effectiveness of air emissions abatement measures increases when adoption rates are high. These results suggest that ports should collaborate to coordinate abatement efforts and agree on a common direction to achieve effectiveness, choosing, e.g., performance standards, pricing, or a mix of measures.

Our analysis has relied on ports' own external communication regarding air emissions abatement and has in that sense been exploratory. In some cases, ports may fail to properly communicate about the measures they have implemented, while in other cases they may spend considerable resources on communication about implemented measures, which then turn out to have insignificant

15 See http://www.unece.org/cefact/codesfortrade/codes_index.html for the list of location with a UN LOCODE. However, one port management body may administer a port complex that consists of various codes.

effect on reducing air emissions. From the present analysis, we cannot make such distinctions, but we believe that a critical examination of the external communication of ports on air emission reduction efforts is an important avenue for future studies. It is important to assess the effectiveness of individual air emissions abatement initiatives, so as to identify those with the greatest potential. Some of the reporting on measures may turn out to be driven more by the aim to create an environmentally responsible public image than by impact on emissions, while others may hold significant potential to reduce air emissions of port operations globally.

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Appendix A. . Ports included in the final sample

	Among top 50 container ports	Among top 29 dry bulk ports	Among top 30 liquid bulk ports
Africa, India and the Middle East (n = 15)	Colombo	Ennore	Mumbai
	Durban	Paradip	New Mangalore
	Jawaharlal Nehru	Richards Bay	
	Jebel Ali	Saldanha Bay	
	Jeddah	Visakhapatnam	
	Khor Fakkan		
	Port Said		
	Salalah		
Asia (n = 31)	Busan	Gwangyang/Kwangyang	Chiba
	Dalian	Kaohsiung	Daesan
	Guangzhou	Nagoya	Hong Kong
	Hai Phong	Qinhuangdao	Incheon
	Hanshin Ports (Kobe-Osaka)	Taichung	Kaohsiung
	Ho Chi Minh		Nagoya
	Hong Kong		Ulsan
	Kaohsiung		Yokohama-Kawasaki-Tokyo
	Laem Chabang		
	Manila		
	Mundra		
	Nagoya		
	Ningbo-Zhoushan		
	Port Kelang		
	Qingdao		
	Shanghai		
	Shenzhen		
	Singapore		
	Tanjung Pelepas		
	Tanjung Perak		
	Surabaya		

	Tianjin		
	Xiamen		
	Yingkou		
	Yokohama-Kawasaki-Tokyo		
Australia, New Zealand and South Pacific (n = 5)		Dampier	
		Gladstone	
		Hay Point	
		Newcastle	
		Hedland	
Europe (n = 22)	Algeciras	Amsterdam	Alg
	Ambarli	Dunkirk	Am
	Antwerp	Narvik	Ant
	Bremen-Bremerhaven	Rotterdam	Ger
	Felixstowe	Vostochny	Le l
	Gioio Tauro		Mar
	Hamburg		Mil
			Hav
	Marsaxlokk		Rot
	Piraeus		Sou
	Rotterdam		Trie
	Valencia		Wil
			hel
North America (n = 12)	Long Beach	Duluth	Cor
	Los Angeles	Sept-Iles	Hou
	New York/ New Jersey	Vancouver	Lon
	Savannah	Virginia	Sou
			Lou
	Seattle-Tacoma		
	Vancouver		
South America (n = 8)	Colon	Itaqui	Ara
	Santos	Sepetiba	Car
		Tubarao	Sao

Appendix B. . Dependent variables

Category	Coding values to assign
Monitoring & measuring	**0:** No monitoring and measuring • This means that no data regarding air emissions or air quality are available in the most recent sustainability report, annual report or on the port website **1:** Partial monitoring of air emissions • Quantitative data are available on the port website or in the most recent sustainability or annual report for at least some of the following types of air emissions: CO2, NOx, SOx or PM. • It does not matter whether the data concerns air quality in the port or absolute emissions. **2:** Full monitoring of all types of air emissions • This means that quantitative data sets are available in the most recent sustainability or annual report or on the port website regarding all of the following types of air emissions: CO2, NOx, SOx, PM. • It does not matter whether the data set concerns air quality measurements in the port or absolute emissions. • It does not matter which emitters the data set originates from. A breakup of emissions by the different types of emitters (e.g., container terminals, trucks, ships) is not required.

Pricing	**0:** No use of pricing to promote reduction of air pollution • If neither the port's most recent sustainability report nor the port website make any specific mentions of "green" price incentives or penaltie assume that such is absent. **1:** Use of incentive or penalty pricing to promote reduction of or penalize air emissions • This means that the port offers some form of incentive or penalty pricing for: o Ships – this means that: ▪ The port offers port dues reductions to ships with LNG propulsion, cold-ironing or scrubbers; ▪ The port offers reduced port dues to ships with high scores in the Environmental Ship Index, Clean Shipping Index or Green Awar ▪ The port offers reduced port dues for vessels, which voluntarily reduce service speeds in the approach to the port (voluntary speec duction zone). ▪ The port offers reduced port dues to ships for on-time arrival in an effort to reduce air emissions from waiting time in port. o Trucks or trains – this means that: ▪ The port offers rebates or penalty prices to trucks or trains, depending on their emission levels o NB: Regarding terminal equipment, penalty or incentive pricing mechanisms are not used, because terminal leases have very long dura (several decades).
Environmental standards above regulatory standards	Environmental standards above current regulation, applied to:1. Specifications regarding ships' use of energy sources (cold ironing, LNG or low-s fuel)**0:** Not mentioned anywhere**1:** The port explicitly has requirements to ships regarding their fuel type (cold ironing, LNG or low-sulfur fuel). T quirements go beyond those specified in the MARPOL Convention. The most recent sustainability report or the port website explicitly state that t port's requirements exceed the requirements of the MARPOL convention.2. Specifications regarding terminal equipment**0:** Not mentioned anywh The most recent sustainability report or the port website specify minimum requirements to the equipment, which may be used in port terminals a which types of equipment may not be used. The port explicitly states that the requirements exceed those specified in national (or EU) regulation.3 Specifications regarding trucks (that operate in the port area)**0:** Not mentioned anywhere**1:** The port bans certain trucks from operating in the po area. The most recent sustainability report or the port website explicitly states that the requirements for trucks exceed those specified in national EU) regulation.
Low emission fuels for port-owned vessels	**0:** No use of clean energy sources (LNG, biofuels, methanol) in the port's own fleet of vessels (e.g., patrol vessels, tugs, survey vessels) • This means that the vessels in the port's fleet operate on traditional marine bunkers (Heavy Fuel or Marine Gas Oil). If the port sustainabilit port or the port website do not specifically mention other fuel types, we assume that those are not in use in the port fleet. **1:** Use of clean energy sources (LNG, biofuels, methanol, batteries or similar) for the port's own fleet of vessels • The port specifically states that at least one of its vessels uses a fuel type, which has lower air emissions than traditional marine bunkers (He Fuel and Marine Gas Oil). The relevant low-emissions fuel types are: LNG, biofuels, methanol, batteries and solar panels.

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