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Reviewing tools and technologies for sustainable ports: Does research enable decision making in ports?

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ABSTRACT

Ports are experiencing increased pressure to reduce negative impacts on climate and environment, and their roles and functions in transport systems and economy make them a key factor in promoting sustainability. There is substantial research on strategies and measures for mitigating emissions and pollution. This paper reviews literature on tools and technologies for sustainable ports and presents a typology based on 70 publications published in peer-reviewed journals. The paper outlines 26 tools and technologies, across four main categories (i) port management and plans, (ii) power and fuels, (iii) sea activities and (iv) land activities. The paper further discusses to what extent existing research supports port decision makers in their effort towards sustainability. We suggest that the literature gives an insufficient foundation for decision making in ports. The main reason is that few papers are based on empirical findings. We therefore suggest several avenues for addressing port sustainability in future research to enable port decision makers to select and prioritize tools or technologies: increased use of empirical data, port engagement, and understanding actors and processes in port decision making.

1. Introduction

Transport is under increasing pressure to reduce impacts on climate and environment. Although maritime transport is typically viewed as an environmentally friendly transport mode, global emissions from the maritime sector is responsible for 10–15% of anthropogenic sulfur (SOx) and nitrogen oxide (NOx) emissions, as well as approximately 3% of the carbon dioxide (CO2) emissions (Lindstad and Eskeland, 2016). As a response, the International Maritime Organization (IMO) member states in 2018 set an absolute target of GHG emissions to 50% reduction by 2050 compared to 2008, referred to as the "Paris Agreement for shipping" (GreenPort, 2018). Meeting these reduction goals will require tremendous effort in terms of new technologies and other measures for adapting the maritime sector towards zero-emission. Ships spend most of their time outside the reach of national regulators, and as nodes in the multi-modal transport system linking maritime transport to other transport modes (Papaefthimiou et al., 2017), ports have a pivotal role in transitioning the maritime sector towards sustainability. At the same time, emission reduction efforts should not hamper economic growth and international trade. This could be a problematic balancing act since over 80% of international merchandise trade by volume is seaborne (Carpenter et al., 2018).

This paper gives an overview of available measures presented by scientific literature for transitioning ports towards sustainability, what we refer to as *tools and technologies for sustainable ports*. We apply a wide definition of sustainability when referring to tools and technologies for sustainable ports, by including any measure that reduces the climate or environmental impact of ports and their associated activities. This paper asks the following research questions: *What are the potential tools and technologies for transitioning ports towards sustainability? Does current research enable port decision makers to reach the ambitious emission reduction targets of the maritime sector?* In answering these questions, we start with conducting a literature review where we suggest a typology of tools and

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technologies for sustainable ports. In describing the entirety of potential tools and technologies for moving ports towards sustainability, categories are broad and reflect the variety of tools addressed in the literature. Second, we discuss to what extent the literature supports port decision makers in their effort towards sustainability.

There is a large body of research on ports, their roles and function in supply chains, economies and transport systems, and several publications review the literature on port sustainability (e.g. Davarzani et al., 2016; Lim et al., 2019; Sislian et al., 2016). Our review distinguishes itself from previous reviews, which typically address various sub-segments of the transitioning ports literature (e.g. Lim et al., 2019; Di Vaio and Varriale, 2018; Sislian et al., 2016), by applying a wide scope in terms of measures for transitioning ports towards sustainability. For instance, Di Vaio and Varriale (2018) emphasize managerial strategies for environmental sustainability, particularly discussing accounting instruments and training measures. The measures included in this review could be related to any aspect which might improve the sustainability of ports (e.g. managerial, technological, organizational, operational). Our review also distinguishes itself from previous reviews by (i) focusing on in-depth accounts of what the literature is concerned with, and (ii) focusing on whether the studies mention any real-life experiences. Current reviews do not discuss how and whether research provides sound foundation for port decision makers in choosing and implementing measures for transitioning ports, and we argue that in-depth accounts and empirical knowledge is important in this regard. Davarzani et al. (2016) use a broad approach in their bibliometric analysis of the literature on green ports and maritime logistics, but do not, however, provide an in-depth description of the identified seminal clusters.

Based on a detailed review of 70 publications between 2010 and 2018, this paper identifies 26 tools and technologies distributed across four main categories. The most prominent measure discussed in the literature is by far cold ironing. We argue that the current literature gives an insufficient foundation for decision making because few papers are based on empirical findings. We suggest several avenues for future research to help enable port decision makers to select and prioritize tools or technologies for transitioning ports towards sustainability: increase use of empirical data, port engagement, and understanding actors and processes in port decision making.

In next section, the scope of the literature review, included studies and procedure for identifying tools and technologies are described. The third section presents the 26 tools and technologies identified in the review and, if reported, experiences with these. The last section concludes on main findings in the literature and discusses implications for practice and research.

2. Methods

This literature review identifies empirical studies on tools and technologies for transitioning ports towards sustainability, and suggests a typology of measures for sustainable ports. Although the concept of sustainability is heavily debated (see Lim et al., 2019 for a discussion), definitions of port sustainability usually include the so-called Triple Bottom Line (TBL), suggesting that sustainability is achieved when environmental, economic and social dimensions intersect (Kuznetsov et al., 2015). The main objective of a sustainable port is to achieve a socially acceptable and safe port that is energy-efficient and environmentally friendly, while at the same maximizes economic profit (Lim et al., 2019). The following section presents the process of identifying, selecting and reviewing scientific publications addressing this issue.

2.1. Scope of review

The literature search was limited to scientific journal publications in English, published between 2010 and 2018. Relevant studies were identified and selected through searches in Web of Science and Google Scholar. Since technology develops rapidly, the time limitation was chosen to capture the most recent developments. The time period was also limited to include publications that best reflect the contemporary context of port sustainability, as contextual factors are continuously changing and influencing the priorities and focus of port decision makers. This limitation has been made possible by the exponential growth in publications on port sustainability in recent, as supported by Davarzani et al.'s (2016) bibliometric analysis. Although we recognize that contextual factors are likely to influence which measures are prominent in the scientific literature, it has not been our ambition to explore how research is influenced by these factors. Our policy recommendations follow this observation, recommending studies on decision makers and the decision-making process.

The search was divided into two main categories of search words. The first category identifies ports as the main interest, while the second category reflects our interest in any measure related to reducing the climate or environmental impacts of ports. This approach enables a broad approach in determining what the relevant tools and technologies for transitioning ports are. The following general search words were used:

	AND	Emission
		OR
		GHG
Port		**OR**
OR		Environment*
Seaport		**OR**
OR		Climat*
Harbor		**OR**
		energy
		OR
		Sustainab*

The search in Web of Science generated more than 6400 publications, falling under the following relevant categories:

Transport science technology	475
Energy fuels	1047
Environmental sciences	2726
Transportation	492
Environmental studies	414
Environmental engineering	390
Green sustainable science technology	253

Publications falling under each category were first reviewed by reading the titles, abstracts and introductions, before publications deemed relevant were included in a literature base. The search in Google Scholar generated more than a million hits, but the relevance for this review was substantially lower than in the Web of Science search. The first 300 hits in Google Scholar were also quickly reviewed by reading though the title, abstract and introduction. From that point, there were no, or few relevant hits not covered by the search in Web of Science and proceeding with this approach was expected to bring little additional value.

Studies were also identified through the personal knowledge and experience of the authors, and brainstorming with experts in the fields of sustainability in ports. In addition, relevant studies were identified through snowballing, i.e. identifying additional publications from the reference lists of publications already included in the review.

The most important delineating factor in selecting publications for detailed review, is the exclusion of publications from conferences and proceedings that are not published through journals. Although many conferences rely on peer-review to select publications to be presented and/or disseminated, the authors do not have sufficient knowledge of all relevant conferences within the very large field of port research to assess the scientific standard against which these publications have been held. Hence, all publications included in the review are journal publications. That implies that the vast amount of gray literature on sustainability issues in ports is also excluded from review.

After the quick review of titles and abstracts, 148 publications were included in the literature base intended for detailed review. After detailed review, 70 publications were considered to be within the scope of the study, which means that they address, discuss or refer to tools and technologies for sustainable ports.

Many publications investigate emissions from shipping and port operations without referring to specific measures for emission reduction (e.g. Villalba and Gemechu, 2011; Yu et al., 2017; Zamboni et al., 2013). These are therefore excluded from our review of tools and technologies. The same applies for publications addressing indicators for monitoring and controlling emissions, as these often do not refer to specific measures for port sustainability. In addition, there is an extensive literature on the causes of emissions and environmental problems in ports, such as diesel engines on cranes or other equipment. These studies are also excluded if they do to account for potential measures for solving these problems, such as replacing the diesel-run cranes with electric cranes.

It is also interesting to note that a subsegment of publications on port strategies in the face of climate change is not dedicated to understanding how ports can slow or mitigate climate change, but rather how ports should adapt to the consequences of climate change (e.g. Ng et al., 2018; Yang et al., 2018). These also fall outside the scope of this review.

2.2. Publications included in review

To get an overview of the perspectives of publications included in the review, the publications' listed key words were noted and sorted. As publications from two journals[1] did not include keywords, these were excluded from this overview of key words. Publications that address a particular tool or technology typically include these among their keywords. Setting these aside, reviewed publications revolve around emissions (23 publications), terminals (13 publications), shipping (13 publications) and energy (11 publications). Other prominent topics include management, sustainability and environment (all 9 publications).

As seen in Table 1, 60 publications are published 2014 or later. Whereas most publications address one or two particular tools or technologies, 10 publications refer to more than five tools and technologies (see Appendix B). Four publications further refer to more than 10 different tools and technologies and are therefore quite prominent in the review. In two publications from 2014, Acciaro et al. (2014a, 2014b) identify and describe initiatives in ports. They describe implemented and potential measures for increasing energy

[1] Maritime Policy and Management, Transport Research Record.

Table 1
Years of publication of publications in review.

2010	2011	2012	2013	2014	2015	2016	2017	2018
3	5	5	6	13	8	8	9	14

efficiency and facilitating energy management in two ports and compare and rank port objectives among port managers. In a recent study, Poulsen et al. (2018) describe the potential for implementing tools and technologies which improve environmental performance in five frontrunner ports. They assess adoption feasibility with reference to the tools' visibility and implementation complexity. Kang and Kim (2017) describe a number of potential sustainability practices in ports, and through consultation with ports stakeholders in major ports in Northeast Asia they define a conceptual model for incorporating sustainability practices in these ports.

The reviewed publications cover a number of different perspectives and confirm Di Vaio and Verriale's (2018) impression that scholars adopt a wide range of lenses. The 70 publications are published in 28 different journals. Fourteen publications are the only publication from a given journal, and more than half of the publications are published in the following journals:

- Transportation research part D: Transport and Environment (16)
- Maritime Policy and Management (7)
- Sustainability (6)
- Transportation research part E: Logistics and Transportation Review (5)
- Research in Transportation Business and Management (5)

This reflects findings by Davarzani et al. (2016), where both journals from Transportation Research as well as Maritime Policy and Management were prominent.

2.3. Developing a typology: structuring tools and technologies

Tools and technologies for sustainable ports are identified through the publications' reference to, mentioning or discussion of instruments and measures which can be or have been implemented in ports. Hence, the review includes both publications that refer to implemented tools, and publications with conceptual descriptions, models or estimations of tools.

We used conventional content analysis (Hsieh and Shannon, 2005) and data coding (e.g. Charmaz, 2006) to review the literature. First, results, discussions and conclusions were sorted through open coding. Through identifying tools and technologies included in each publication we conducted *explorative* mapping to get a comprehensive overview of the literature. The explorative mapping also included experiences with implementation and, if available, evaluations and assessments of the tool's effectiveness and implementation complexity. The explorative mapping provided an *outline* of tools and technologies in scientific publications and identifies prominent findings. Through axial coding, these findings were bundled and used to define preliminary *categories* of tools and technologies. The preliminary categories referred to specific tools and instruments and were later aggregated to bundles of tool and technologies with specific references to sub-categories (see Table 2, number of publications in brackets).

In their review of potential sustainability practices in greening ports, Kang and Kim (2017) refer to the following dimensions: environmental technologies, monitoring and upgrading, process and quality improvement, active participation, communication and cooperation. Lam and Notteboom (2014) however, provide four categories in describing port management tools; pricing, monitoring.

Table 2
Categories and subcategories of tools and technologies for sustainable ports.

Port management and policies (30)	Power and fuels (36)	Sea activities (19)	Land activities (19)
Port plans (6)	Wind energy (4)	Speed reduction (17)	Technological shift: trucks and drayage (8)
Management of environment and energy (10)	Solar energy (6)	Efficient vessel handling (7)	Modal shift (12)
Monitoring (10)	Wave and tidal energy (4)	Other (2)	Efficient truck operations (8)
Concession agreements (9)	Geothermal energy (1)		Efficient loading/unloading (3)
Modal split (12)	Electrification (30)		Automation and intelligence (6)
Port dues (10)	LNG (10)		Clean industrial activity (1)
Collaboration (7)	Biofuels (4)		
Other managerial policies (4)	Methanol and hydrogen (2)		
	Low sulfur fuels (4)		

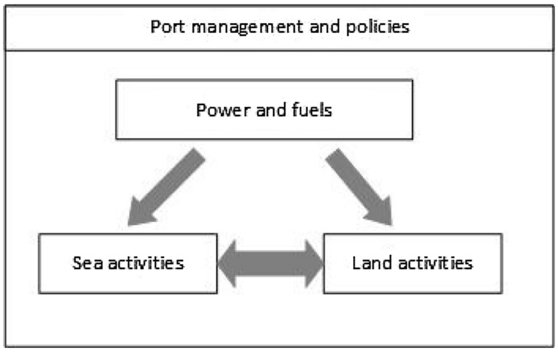

Fig. 1. Relations between categories of tools and technologies for sustainable ports.

Market access control and environmental standard regulation. Given that this paper aims to describe the entirety of potential tools and technologies for moving port towards sustainability, categories included here are broader than those applied elsewhere and reflect the variety of tools addressed in the literature.

The main categories in this review encompass the entirety of port systems, and their interrelations are depicted in Fig. 1. *Port management and policies* mainly include strategic and reflexive activities, and measures that enable long-term development, planning and learning to enhance port sustainability. Most importantly, they can be singlehandedly executed by the port owner and/or port authority, and implementation relies less on other actors, corresponding to Poulsen et al.'s (2018) reference to low implementation complexity. This category is also distinguished by its potential to encompass all other categories; any subcategory can be deliberately and explicitly used to manage and develop ports in a given direction, and thereby included in for instance port plans, concessions, port dues etc.

In contrast, measures related to *sea and land activities* influence everyday port operations, with different possibilities for incorporating innovations (i.e. power and fuels) and where decision-making addresses practical, operational and functional priorities in the imminent future.

The category *power and fuels* does not include measures that produce fundamental changes in operational activities in sea or at land, but rather refers to the application of niches and innovations in these operations. Innovations in power and fuels can influence sea and land activities alike, and, deriving from outside the port system, their emergence cannot be prompted through port management alone. This category includes both sources of power, as well as application of power and fuels in ports.

A full overview of subcategories are presented in Table 2. Subcategories are to some extent correlated and overlapping. For instance, nearly all subcategories *could* be placed under port management, as they constitute potentially explicit component in for instance monitoring or energy management. Measures are placed in several categories if the literature contains multifaceted approaches; i.e. as the literature addresses the management potential of modal shift, it is also considered a prominent managerial tool. However, as the literature, does not address the management potential of efficient truck operations, these are not included in both categories.

3. Results

The following section presents tools and technologies mentioned and discussed in reviewed literature, and to the extent they are available, descriptions of empirical experience follow for each tool or technology.

3.1. Port management and policies

This section presents the main findings and outputs in publications that address port management and policy as measures for increasing the sustainability of ports. An overview of publications referring to the different measures is provided by Table 3.

3.1.1. Port plans

A handful of publications refer to port plans as a potential tool for transitioning ports towards sustainability, and have different labels, such as ‘Port Energy Environmental Plan’ (Acciaro et al., 2014a), green port program (Acciaro et al., 2014b), plans for environmental protection, climate protection, climate initiative (Schipper et al., 2017), plan for prevention and reduction of pollution, green port plan (Anastasopoulos et al., 2011), clean air plans (Anastasopoulos et al., 2011; Gibbs et al., 2014). A recent review of the plans of ten ports around the world (Schipper et al., 2017) concludes that some port plans have no clear sustainability objectives, but that half of the ports are legally bound. On the international level, the World Port Climate Declaration, derived from the World Port Climate Initiative, declares specific objectives for ports to pursue: (i) reduce CO2 from deep sea vessels calling at ports, (ii) explore reduction of CO2 from port operation, (iii) explore how to reduce CO2 from inland shipping and other modes of transport, (iv) explore how to promote alternative energy sources, and (v) CO2 footprint calculation of ports (Fenton, 2017).

Table 3
Overview of publications addressing port management and policies.

Port plans	Management of environment and energy	Monitoring
Acciaro et al., 2014a, 2014b; Anastasopoulos et al., 2011; Fenton, 2017; Gibbs et al., 2014; Schipper et al., 2017	Acciaro et al., 2014a, 2014b; Boile et al., 2016; Chen and Pak, 2017; Kang and Kim, 2017; Lam and Notteboom, 2014; Le et al., 2014; Li et al., 2011; Poulsen et al., 2018; Puente-Rodríguez et al., 2016	Acciaro et al., 2014a, 2014b; Acciaro et al., 2018; Anastasopoulos et al., 2011; Gonzalez-Aregall et al., 2018; Chen and Pak, 2017; Fenton, 2017; Hall et al., 2013; Kang and Kim, 2017; Lam and Notteboom, 2014;
Concession agreements	**Modal split**	**Port dues**
Gonzalez-Aregall et al., 2018; De Langen et al., 2012; Ferrari et al., 2015; Lam and Notteboom, 2014; Notteboom, 2018; Notteboom and Verhoeven, 2010; Notteboom et al., 2012; Poulsen et al., 2018; Van den Berg and De Langen, 2014	Acciaro et al., 2014b; Gonzalez-Aregall et al., 2018; Bergqvist and Egels-Zandén, 2012; Bergqvist et al., 2015; Kang and Kim, 2017; Lam and Notteboom, 2014; Li et al2011; Notteboom, 2018; Notteboom and Verhoeven, 2010; Poulsen et al., 2018; Bergqvist et al., 2015; Van den Berg and De Langen, 2014	Acciaro et al., 2014a, 2014b; Gonzalez-Aregall et al., 2018; Bergqvist and Egels-Zandén, 2012; Bergqvist et al., 2015; Fenton, 2017; Gibbs et al., 2014; Kang and Kim, 2017; Lam and Notteboom, 2014; Poulsen et al., 2018
Collaboration	**Other managerial policies**	
Acciaro et al., 2014a, 2014b; Cerceau et al., 2014; Hentschel et al., 2018; Kang and Kim, 2017; Lu et al., 2016; Poulsen et al., 2018	Acciaro et al., 2014a; Bosman et al., 2018; Di Vaio and Varriale, 2018; Poulsen et al., 2018	

3.1.2. Management of environment and energy

Energy management appears to be a prominent feature of managerial tools for sustainable ports, and a large share of publications discussing energy management refer to *environmental management systems* (EMS). Some of these refer to management approaches in specific ports (Acciaro et al., 2014b, Lam and Notteboom, 2014; Li et al., 2011). Lam and Notteboom (2014:6) describe EMS as a "documented process that describes a structure for management of environmental impact processes and continuous improvement". While European ports are encouraged by the European Sea Port Organisation (ESPO) to develop environmental management plans, only half of European ports have adopted EMS (Boile et al., 2016). Ports can be expected to consider energy management a compelling measure because it has high symbolic value and is easy to implement (Poulsen et al., 2018). EMS is also a central aspect of ports' interaction with stakeholders. Puente-Rodriguez et al. (2016) conclude that ports' main challenges with developing appropriate EMS relate to (i) balancing economic and ecological objectives, (ii) institutionalizing knowledge-sharing and co-production, and (iii) including knowledge and involvement of external actors (Puente-Rodríguez et al. 2016:464). Some ports also define dedicated plans for *energy management,* which can be linked to EU policy (Boile et al., 2016) or city strategies that include measures directed at renewable energies, reducing energy consumption, promoting eco-friendly mobility, environmental protection and pollution abatement (Acciaro et al., 2014a).

3.1.3. Monitoring

Monitoring benefits ports in several respects, through (i) enabling responses to potentially unfounded claims of environmental damage, (ii) allowing ports to communicate how they manage environmental impacts, and (iii) allows ports to formulate or modify strategies and policies (Lam and Notteboom, 2014). Monitoring emissions can include both the terminal and the port as a whole (Acciaro et al., 2018), as well as hinterland transport (Gonzalez-Aregall et al., 2018). Monitoring relates to the development of environmental key performance indicators (Acciaro et al., 2014a; Chen and Pak, 2017), which enable footprint assessments (WPCD, Fenton, 2017), energy consumption studies (Anastasopoulos et al., 2011) and environmental risk management (Kang and Kim, 2017). The existing literature refers to explicit monitoring initiatives in ports aimed at establishing emission inventories (Acciaro et al., 2014a, Lam and Notteboom, 2014), estimating and setting emission targets (Hall et al., 2013), and defining emission reducing measures (Acciaro et al., 2014b).

3.1.4. Concessions

Within the landlord function[2] pursued by modern ports, concession agreements are central for upholding the operations and functions of the port. A vast literature is devoted to the use and potential of concession agreements (see for instance Ferrari et al., 2009; Notteboom, 2006; Theys et al., 2010) and a subsection of this field investigates their possible role in transitioning ports towards sustainability. Concessions allow the port authority to enter agreements with private actors who wish to establish an activity in a defined part of the port (Ferrari et al., 2015), and these agreements set the terms for these activities, which could be based on environmental criteria. Several publications refer to the inclusion of environmental criteria in concession grants (De Langen et al., 2012; Lam and Notteboom, 2014; Notteboom et al., 2012; Poulsen et al., 2018), which can include design standards and technology specifications, bans and limitations, use of tradeable emissions among port users, pollution charges and information reporting (Acciaro et al., 2018). The potential for influencing modal split is also examined in dedicated studies (Gonzalez-Aregall et al., 2018; Van den Berg and De Langen, 2014).

Four publications refer to empirical experience with environmental criteria in concessions. Notteboom and Verhoeven (2010)

[2] For overview of port governance models, see f.ex. Ferrari et al. (2015).

show that 85% of all terminal contracts include environmental clauses, and describe environmental management/reporting, maximum emission levels and technological requirements (i.e. cold ironing, electric yard equipment) to be most prominent. Although environmental governance through terminal concession agreements is quite common in European ports (Lam and Notteboom, 2014), scientific publications only account for experiences from a handful of ports worldwide, such as Los Angeles/Long Beach and Rotterdam (Lam and Notteboom, 2014; Poulsen et al., 2018). These ports use environmental criteria in assessing bids for concessions, and use concession agreements to promote clean truck operations, grant land to environmentally friendly terminal operators, and promote specific modal splits in hinterland transport.

3.1.5. Modal split

According to Gonzalez-Aregall et al. (2018), "the port's location as the transshipment hub in the transport chain puts them in a unique position to promote intermodality through a variety of mechanisms". The ports' focus on modal split can contribute to improved vehicle utilization (Kang and Kim, 2017) and incorporating environmental considerations in planning and executing hinterland transport strategies (Acciaro et al., 2014b). The latter is addressed in some publications (Gonzalez-Aregall et al., 2018; Notteboom and Lam, 2018; Van den Berg and De Langen, 2014), and modal split clauses seem to be present in 35% of concession contracts (Notteboom and Verhoeven, 2010).

The literature refers to a few empirical examples of modal split obligations in ports (Li et al., 2011; Van den Berg and De Langen, 2014) and find that such obligations can produce extra quay capacity for inland shipping, planning tools for handling barges/trains, and extra rail infrastructure at the terminal/dock. However, modal split quotas appear to be the least popular measure for improving environmental performance of hinterland transport, supposedly because they are considered constrictive and reduce the flexibility of port stakeholders (Bergqvist et al., 2015). Differentiated port dues can be used to internalize external costs of transport and to increase efficiency in hinterland transport, through encouraging modal shifts which distribute traffic across transport networks and allow more efficient use of infrastructure (Bergqvist and Egels-Zandén, 2012). Still, there does not seem to be any publication which presents empirical experience with use of green port dues for hinterland transport.

3.1.6. Port dues

Pricing could be used to boost a port's competitive position and to prevent marine pollution through reward or penalty pricing (Lam and Notteboom, 2014), which materialize itself as port dues. As seen above, port dues can be used to promote environmental performance of hinterland transport (Bergqvist and Egels-Zandén, 2012; Bergqvist et al., 2015; Gonzalez-Aregall et al., 2018), but the majority of publications refer to their potential influence on technology choices in maritime transport. Most link port dues to the environmental characteristics of vessels, e.g. the Environmental Ship Index (ESI), the Clean Shipping Index (CSI) or the Energy Efficiency Design Index (EEDI) (Fenton, 2017; Gibbs et al., 2014), which can be used to unify environmental requirements and award cargo- and/or vessel owners with the lowest environmental impacts. Poulsen et al. (2018) challenge the feasibility of port dues, arguing that the implementation involves many stakeholders, and the port dues' relatively small share of total operational cost reduces them to an awareness tool. Several publications refer to empirical experience with port dues aimed at sustainable operations on the land and sea sides of ports. The port of Shanghai applies penalty schemes for actors who do not comply with laws and regulations, while the experiences from other ports largely refer to positive incentives in Rotterdam, Antwerp, Hamburg, Vancouver, Los Angeles, Singapore and Gothenburg. Positive incentives mainly relate to reducing fees for high-performing vessels (Lam and Notteboom, 2014; Poulsen et al., 2018), i.e. vessels with low nitrogen or sulfur emissions (Acciaro et al., 2014b; Gibbs et al., 2014; Lam and Notteboom, 2014), but it might also apply for hinterland transport and port concession holders without own vessels (Lam and Notteboom, 2014).

3.1.7. Collaboration

A wide range of published literature, both within and outside the scope of this review, acknowledges the complexity of transitioning ports towards sustainability and the necessity of involving a broad set of stakeholders (e.g. Cheon, 2017; Denktas-Sakar and Karatas-Cetin, 2012; Lam et al., 2013). Collaboration and dialogue improve relationships between the port and its stakeholder (Kang and Kim, 2017), facilitate industrial ecology in port cities (Cerceau et al., 2014), and is associated with internal sustainability management in the port organization (Lu et al., 2016). Environmental criteria in concession agreements are one expression of bilateral collaboration for sustainability in ports (see above), as well as interaction between port authorities and stakeholders to encourage truck and train owners to use low emission technologies (Poulsen et al., 2018). There are also examples of multilateral collaboration. The port of Hamburg is prominent in this regard for initiating an international market consultation in developing a terminal area (Acciaro et al., 2014b), establishing a smartPORT energy project with federal authorities, as well as an eco-partnership with chambers of trade and commerce, the industry association and the city of Hamburg (Acciaro et al., 2014a). Further, in a hypothetical exploration of Renewable Energy Cooperatives (REC) in Rotterdam Hentschel et al. (2018) identify 14 specific aspects that can accelerate energy transitions through REC.

3.1.8. Other managerial instruments

The publications included in this review also refer to a number of other managerial policies which can assist ports in transitioning towards sustainability, related to energy efficiency awareness (Acciaro et al., 2014a), circular economy (Poulsen et al., 2018), support scheme for solar energy in terminals and on roof tops (Acciaro et al., 2014a), accounting and training instruments (Di Vaio and Varriale, 2018), and carbon capture and storage (2014a, Bosman et al., 2018).

Table 4
Overview of publications addressing power and fuels.

Wind energy Acciaro et al., 2014a, 2014b; Lam and Notteboom, 2014; Li et al., 2011	**Solar energy** Acciaro et al., 2014a, 2014b; Boile et al., 2016; Kang and Kim, 2017; Lam and Notteboom, 2014; Li et al., 2011	**Wave and tidal energy** Acciaro et al., 2014a; Hadadpour et al., 2014; Naty et al., 2016; Ramos et al., 2014
Geothermal energy Acciaro et al., 2014b	**Electrification** Acciaro et al., 2014a, 2014b; Acciaro et al., 2018; Adamo et al., 2014; Anastasopoulos et al., 2011; Arduino et al., 2013; Boile et al., 2016; Chang and Wang, 2012; Dragović et al., 2018; Fenton, 2017; Gibbs et al., 2014; Hall, 2010; Hall et al., 2013; Innes and monios, 2018; Kang and Kim, 2017; Kim et al., 2012; Lam and Notteboom, 2014; Kotrikla et al., 2017; Linder, 2010; López-Aparicio et al., 2017; Notteboom, 2018; Poulsen et al., 2018; Styhre et al., 2017; Tseng and Pilcher, 2015; Tzannatos, 2010; Winkel et al., 2016; Winnes et al., 2015; Yang, 2017; Yang and Chang, 2013; Zis et al., 2014	**LNG** Acciaro et al., 2014a; Boile et al., 2016; Bosman et al., 2018; Calderón et al., 2016; Gibbs et al., 2014; Kang and Kim, 2017; López-Aparicio et al., 2017; Poulsen et al., 2018; Schipper et al., 2017; Winnes et al., 2015
Biofuels Acciaro et al., 2014a; Bosman et al., 2018; Kang and Kim, 2017; Winnes et al., 2015	**Methanol and hydrogen** Boile et al., 2016; Winnes et al., 2015	**Low sulfur fuels** Acciaro et al., 2014a; Anastasopoulos et al., 2011; Gibbs et al., 2014; Lam and Notteboom, 2014

3.2. Power and fuels

The following section presents publications which mention, address or refer to the use of fuels or sources of power in the port or in port activities on sea and land. Publications addressing fuels and power are presented in Table 4. As such, this category is closely connected with sea and land activities but focuses primarily on replacing existing energy sources rather than the activities fueled by this energy.

This section gives an overview of alternative power sources referred to in the reviewed literature, before alternative fuels for vessels, vehicles and equipment are presented. Kang and Kim (2017) describe renewable and alternative energy source as potential sustainability practices for enhancing long-term viability of port operations, including wind energy, solar energy and tidal energy. These are therefore relevant indicators for improving green port performance (Anastasopoulos et al., 2011; Chen and Pak, 2017).

3.2.1. Wind energy

A few publications refer to practical experiences with wind energy in ports, which has been implemented in the ports of Rotterdam, Kitayjushu, Zeebruges, Hamburg (Acciaro et al., 2014a), and Venice (Li et al. 2011). The literature also addresses potential use of wind power in the ports of Rotterdam and Antwerp (Lam and Notteboom, 2014), and at an early stage a planned wind power plant in Port of Genoa was expected to reduce 6000 tons of CO^2 (Acciaro et al., 2014b). Processes with establishing wind power are costly, however, as they might require a full year of monitoring wind conditions on the selected site (Acciaro et al., 2014a).

3.2.2. Solar energy

The port of Hamburg has implemented a support scheme which allows port users to establish solar energy facilities, and solar energy is used to heat water in the port authority's offices (Acciaro et al., 2014a). Solar energy is also on the agenda in Antwerp (Lam and Notteboom, 2014), Rijeka (Boile et al., 2016), Genoa (Acciaro et al., 2014a, 2014b), Venice and Yantian (Li et al., 2011), Tokyo and San Diego (Acciaro et al., 2014a). These publications do not discuss how solar energy is used, but Kang and Kim (2017) suggest solar energy can be used to power cranes.

3.2.3. Wave and tidal energy

Acciaro et al. (2014a) refer to several ports who make use of tidal energy (Dover, Digby Nova Scotia) and wave energy (Kembla, Mutriku) to power their operations. In addition, three publications are feasibility studies for use of wave or tidal energy in specific ports in the southern Caspian sea (Hadadpour et al., 2014), the Mediterranean (Naty et al., 2016) and the Port of Ribadeo (Spain) (Ramos et al., 2014).

3.2.4. Geothermal energy

Geothermal energy is mentioned by Acciaro et al. (2014b), who refer to the port of Genoa's evaluation of the potential for more extensive use of heat plants, and the port of Hamburg's pilot project for heating rail switches with geothermal energy.

3.2.5. Electrification

This category includes publications which address the use of electricity in ports, mainly with regards to cold ironing, as well as technology shifts for yard vehicles and equipment. *Cold ironing* is the most prominent technology in the review, and 25 publications refer to cold ironing, on-shore power supply, shore side electricity, shore connection, quay electrification, quay side power etc. For

Table 5
Ports mentioned with reference to cold ironing.

Antwerp (Acciaro et al., 2014b; Gibbs et al., 2014; Poulsen et al., 2018; Schipper et al., 2017)	**Genoa** (Acciaro et al., 2014a, 2014b)	**Gothenburg** (Fenton, 2017; Styhre et al. 2017)	**Hamburg** (Acciaro et al., 2014a; Poulsen et al., 2018; Schipper et al., 2017)
Istanbul (Schipper et al., 2017)	**Kaohsiung** (Tseng and Pilcher, 2015)	**La Spezia** (Gibbs et al., 2014)	**Livorno** (Boile et al., 2016; Hall et al. 2013)
Lübeck (Gibbs et al., 2014)	**Oslo** (López-Aparicio et al. 2017)	**Rotterdam** (Poulsen et al., 2018; Schipper et al., 2017)	**San Pedro Bay (Los Angeles/Long Beach)** (Hall et al. 2013; Li et al. 2011; Poulsen et al., 2018; Schipper et al., 2017; Styhre et al. 2017)
Shanghai (Schipper et al., 2017)	**Vancouver** (Gibbs et al., 2014; Hall et al. 2013; Poulsen et al., 2018)	**Venice** (Boile et al., 2016; Gibbs et al., 2014; Li et al. 2011)	**Zeebruges** (Acciaro et al., 2014b)

simplicity, we will refer to this as cold ironing. Cold ironing allows vessels at berth to shut down auxiliary engines and rely on electricity for hotel and other operations at port. Most publications mention cold ironing in one way or another, some more generally (e.g. Anastasopoulos et al., 2011; Kang and Kim, 2017) or related to concession contracts (Notteboom and Lam, 2018). Most of the publications address the potential of cold ironing for reducing emissions in ports (Adamo et al., 2014; Chang and Wang, 2012; Dragović et al., 2018; Gibbs et al., 2014; Hall, 2010; Innes and Monios, 2018; Kotrikla et al., 2017; Linder, 2010; López-Aparicio et al., 2017; Styhre et al., 2017; Tseng and Pilcher, 2015; Tzannatos, 2010; Winkel et al., 2016; Winnes et al., 2015; Zis et al., 2014). Several of these also refer to planned or implemented cold ironing in specific ports, listed in Table 5. A 2010 survey by WCPI indicated that 32% of the 53 surveyed ports worldwide offer cold ironing, and that 85% are considering it (in Gibbs et al., 2014).

Cold ironing is considered for ferries (Gothenburg and Hamburg, Acciaro et al., 2014a, Fenton, 2017), cruise lines (Vancouver, Hall et al., 2013), passenger service vessels (Venice, Boile et al., 2016), barges (Antwerp, Acciaro et al., 2014b) and other cargo vessels (Acciaro et al., 2014a, Fenton, 2017). Cold ironing can further be applied at ship yards or ship repair docks (Acciaro et al., 2014a, 2014b), and in Antwerp it is already available for the port's tug and dredger fleet and floating cranes in addition to the dry docks (Acciaro et al., 2014b). However, empirical evidence from the implementation and operation of cold ironing is limited to one publication. Hall et al. (2013) find that the port authority's overlapping roles as terminal operators, funder and facilitators was a success factor in implementing cold ironing for cruise lines in Vancouver. Tseng and Pilcher (2015) underline the importance of the political and global economic climate for implementing cold ironing.

Arduino et al. (2013), however, discuss *anticipated* barriers and preconditions for implementing cold ironing in European ports: first, infrastructural issues related to dedicated infrastructure at marine terminals, electrical capacity, conduits and plugs applicable to visiting vessels, as this is more costly than conventional infrastructure. Second, institutional issues related to hard rules and requirements for emission reduction and the greening of ports (e.g. Emission Control Areas (ECAs) and standardization). Third, soft rules referring to the values and influences from economy and entrepreneurialism which shape interests and motivations for change among actors (e.g. high cost of electric energy and lack of interest among shipping companies). Finally, interaction issues referring to the lack of a common vision of future technological and social developments, while being influenced by strong lobbying groups.

The land side of ports includes a range of different motorized vehicles and equipment which can enable a *technological shift for yard vehicles and equipment* using alternative fuels or electricity. Some vehicles are owned by the port authority itself, but a substantial number also belongs to users and operators in the port. Poulsen et al. (2018) argue that port authorities are more successful in introducing low emission technologies in their own operations, and they can include electrification of yard equipment as an environmental criterion in concession agreements (Notteboom and Lam, 2018). The World Port Climate Declaration also targets the reduction of CO2 emission from port operations (Fenton, 2017), and the diversity of port operations implies potential initiatives in several areas, including cranes running on electricity and/or solar power (Kang and Kim, 2017; Yang, 2017; Yang and Chang, 2013), yard tractors (Kim et al., 2012), compressed natural gas engines on for instance straddle carriers (Acciaro et al., 2018) and battery electric AGVs (Acciaro et al., 2014b).

The review reveals limited accounts of empirical evidence from implementing tools that promote technological shifts in yard vehicles and equipment. Lam and Notteboom (2014) refer to the port of Rotterdam requiring cargo handling vehicles to meet sulfur fuel limits, and yard tractors at the port of Vancouver are required to reduce emission through complying with model year emissions standards, reducing speed or using emission reducing add-on devices (Hall et al., 2013). The port of Vancouver has also implemented a new rail locomotive which has the power to pull more cars and therefore reduce the number of trips needed to unload a shipment (ibid.).

3.2.6. Liquified natural gas (LNG)

Although ports are increasingly orienting towards liquified natural gas and the WPCI is promoting LNG in maritime transport (Gibbs et al., 2014), the adoption of LNG remains low (Poulsen et al., 2018). Providing LNG could be a natural development for ports where LNG trades already take place, but they still face challenges relating to distribution, infrastructure and optimization of bunkering locations (Acciaro et al., 2014a). LNG, often included in hybrid solutions, involves significant reductions of NOx, SO2 and PM, and Winnes et al. (2015) expect LNG to reduce CO2 emissions by 14%. Another study includes use of LNG in estimating an emission scenario for the port of Oslo (López-Aparicio et al., 2017).

Calderón et al. (2016) examine the potential for future growth of LNG and conclude that stricter environmental regulations progress LNG as an alternative, and that demand increases with the LNG fleet size. Although more ports are establishing LNG import facilities, only three publications include empirical references relating to LNG.

3.2.7. Biofuels

Biofuels (biogas, biodiesel) represent an opportunity for ports (Kang and Kim, 2017), both relating to ports handling raw materials and producing, storing and distributing biofuels (Acciaro et al., 2014a). They are not, however, a prominent issue in the publications and, besides descriptions of the Bio Port in Rotterdam (Bosman et al., 2018) there are hardly any accounts of experience with biofuels in ports. One reason could be the limited availability of biofuels to the transport sector (Winnes et al. 2015).

3.2.8. Methanol and hydrogen

Publications referring to the potential use of other fuels, such as methanol and hydrogen, are nearly non-existent. Winnes et al. (2015) describe methanol as a fuel similar to LNG, but with a less mature market position. Still, full scale tests are initiated in a Swedish ship company. They caution, however, that, in a life cycle perspective, the global warming potential is similar to marine fuel oil.

When it comes to hydrogen, Kang and Kim include hydrogen as a potential sustainability practice in port operations. Further, Boile et al. (2016) refer to a static hydrogen injection system for tugboat engines in the port of Marseille.

3.2.9. Low sulfur fuels

In addition to the handful of publications which address a particular alternative fuel, a few publications simply refer to the importance of converting to low sulfur fuels (e.g. Anastasopoulos et al., 2011). This could very well be marine fuel with a low sulfur content (Acciaro et al., 2014a; Gibbs et al., 2014; Lam and Notteboom, 2014).

3.3. Sea activities

This section present measures directed towards the day-to-day operations related to sea activities; vessel speed reduction, efficient vessel handling, and other measures. References to each subcategory are seen in Table 6.

3.3.1. Vessel speed reduction close to port

Tools for promoting vessel speed reduction appear to be the most prominent instrument for sustainability in sea activities. Speed reduction, or slow steaming, is expected to reduce the vessel's fuel consumption and hence its emissions (Anastasopoulos et al., 2011). A number of studies estimate or model potential emission reduction from slow steaming (Chang and Wang, 2012; Chang and Jhang, 2016; Linder, 2010; López-Aparicio et al., 2017; Styhre et al., 2017; Winnes et al., 2015; Zis et al., 2015). Cariou (2011) finds that speed reduction reduces overall CO_2 emissions, but with substantial differences between routes.

Several studies refer to the vessel speed reduction program in the ports of Los Angeles and Long Beach (e.g. Acciaro et al., 2014b; Gibbs et al., 2014; Li et al. 2011; Linder, 2018; Poulsen et al., 2018), where ocean vessels are requested to reduce speed within a certain distance from the port. Participating vessels are eligible for incentives such as pre-assigned berth labor for loading/unloading, a recognition program for shipping companies with high compliance and port fee reductions. Two studies (Jia et al., 2017; Johnson and Styhre, 2015) relate slow steaming to efficiency in port operations and investigate the possibility to reduce speed through decreasing vessels' time in port.

3.3.2. Efficient vessel handling

This subcategory overlaps with several subcategories falling under "Land activities" in that they focus on the interaction between efficiency in land activities and emission reduction in sea activities. Fig. 2 Moon and Woo (2014) depicts the impact of port time on energy efficiency at sea as well as in port.

Three publications refer to virtual arrival systems, which can be used to reduce a vessel's turnaround time in port (Poulsen et al., 2018). Emissions from ships at berth contribute to well over half of emissions in ports, and reduced turnaround time reduces emission from auxiliary engines, increases berth capacity and allows transport companies to reduce speed at sea (Styhre et al., 2017).

Systems for virtual arrival can ensure that vessels arrive when port services are available (Johnson and Styhre, 2015) and allow the vessel to avoid the hurry-up-and-wait approach and ensuring just-in time management with reduced fuel consumption and

Table 6
Overview of publications addressing tools and technologies relating to sea activities.

Vessel speed reduction	Efficient vessel handling	Other
Acciaro et al., 2014b; Anastasopoulos et al., 2011; Cariou, 2011; Chang and Jhang, 2016; Chang and Wang, 2012; Chen and Pak, 2017; Gibbs et al., 2014; Jia et al., 2017; Johnson and Styhre, 2015; Li et al., 2011; Linder, 2010; Linder, 2018; López-Aparicio et al., 2017; Poulsen et al., 2018; Styhre et al., 2017; Winnes et al., 2015; Zis et al., 2015	Gibbs et al., 2014; Jia et al., 2017; Johnson and Styhre, 2015; Lalla-Ruiz et al., 2018; Styhre et al., 2017; Poulsen et al., 2018; Moon and Woo, 2014	Gibbs et al., 2014; Winnes et al., 2015

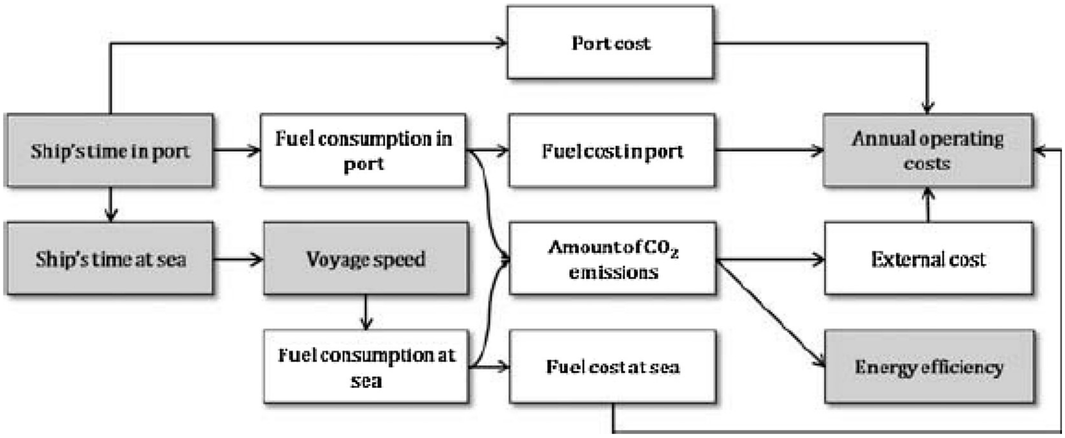

Fig. 2. The relation between time in port and energy efficiency.
Source: Moon and Woo (2014:447).

thereby emissions from the vessel (Gibbs et al., 2014; Jia et al., 2017).

One way of promoting timely arrival is through on-time incentive programs for liner vessels, as implemented in the port of Vancouver (Poulsen et al., 2018). Another instrument for reducing time in port is automated mooring, which allows engines to shut down approximately 30 min earlier and hence reduces emissions in the port area (Gibbs et al., 2014).

Further, Lalla-Ruiz et al. (2018) investigate using separate waterways for incoming and outgoing ships to reduce waiting time in the port of Shanghai. Winnes et al. (2015) expect that reduced lay time at berth and at anchor would reduce CO_2 emissions with 50% in the port of Gothenburg. Moon and Woo (2014) investigate similar issues using a simulation model, and confirm that improved port operations reduce operational costs, CO_2 emissions and external effects.

3.3.3. Other

A few publications also refer to tools and technologies not falling under any of the above sea categories. Gibbs et al. (2014) refer to use of sea water *scrubbers* to control exhaust gases from auxiliary engines, and expect them to reduce PM with 85%, SO_x with 50% and NO_x with three percent. Further, Winnes et al. (2015) refer to the potential in eco-driving during maneuvering in port.

3.4. Land activities

This section presents measures directed towards day-to-day operations related to land activities in ports, and references are presented in Table 7. Although the first subcategory "Technological shift in trucks and drayage" resembles technological shifts described under "Electrification" (Power and Fuels), technological shift here related to land transport over longer distances and is therefore less oriented towards electrification specifically.

3.4.1. Technological shift in trucks and drayage

Upgrading fleets for drayage and trucking is a prominent issue in the literature. One strategy for reducing emissions from the port is therefore to replace vehicles with newer vehicles with lower emissions (Acciaro et al., 2014b, Poulsen et al., 2018). The port authority can set environmental standards for trucks (and trains) operating at the port (Poulsen et al., 2018) and include limits or bans for certain types of vehicles as part of concession agreements (Notteboom and Lam, 2018). Hartman and Clott (2012) model what percentage of trucks the port can upgrade without adversely affecting the level of TEU throughput, whereas several studies refer to programs which encourage port users in North-America to replace their vehicles (Acciaro et al., 2014b; Hall et al., 2013; Li et al., 2011; Norsworthy and Craft, 2013). Gonzalez-Aregall et al. (2018) identify incentive programs for reducing externalities from hinterland transport from the port. Programs relating to sources of power or engine performance/emission standards are an instrument for influencing technology choices in trucks operating from the port.

Table 7
Overview of publications addressing tools and technologies relating to land activities.

Technological shift in trucks and drayage	Efficient truck operations	Efficient loading unloading
Acciaro et al., 2014b; Gonzalez-Aregall et al., 2018; Hall et al., 2013; Hartman and Clott, 2012; Li et al., 2011; Norsworthy and Craft, 2013; Notteboom, 2018; Poulsen et al., 2018	Acciaro et al., 2018; Chen et al., 2011; Chen et al., 2013; Hall et al., 2013; Li et al., 2018; Phan and Kim, 2015; Phan and Kim, 2016; Torkjazi et al., 2018	Johnson and Styhre, 2015; Moon and Woo, 2014; Styhre et al., 2017
Automation and intelligence	**Clean industrial activity**	
Acciaro et al., 2014b; Kang and Kim, 2017; Kavakeb et al., 2015; Li et al., 2011; Poulsen et al., 2018; Xin et al., 2014	Fenton, 2017	

3.4.2. Modal shift

In addition to promoting technological shift in port operations and transport to/from ports, encouraging modal shifts is a highly relevant tool relating to land activities. Publications addressing this issue are already reviewed in a previous section.

3.4.3. Efficient truck operations

Emission reduction from improved efficiency in truck operations at the port is also addressed, through for instance optimizing truck movements and arrivals (Chen et al., 2013; Phan and Kim, 2015) and using truck appointment systems (TAS) (Acciaro et al., 2018; Li et al., 2018; Phan and Kim, 2016; Torkjazi et al., 2018). These publications focus on coordinating the arrival of trucks with the arrival of vessels in order to reduce idling time at port, thereby reducing emissions and improving the system performance. Most of these studies, however, are based on mathematical modelling and calculations, and include limited empirical experiences with tools for efficient truck operations. One exception is the PierPASS program which, through a fixed traffic mitigation fee for containers moved in or out Monday through Friday between 3 AM and 6 PM, shifted 35–40% of container moves to the evening and the weekend (Hall et al., 2013).

3.4.4. Efficient loading/unloading

As described under “Sea activities”, efficient loading/unloading is an important aspect in reducing emissions from vessels at berth, both in reducing the vessel's time at berth and the vessel's waiting time before mooring (e.g. Johnson and Styhre, 2015; Moon and Woo, 2014; Styhre et al., 2017). As such, efficiency in these land activities mainly result in emission reductions from sea activities. These publications to a limited extent refer to other tools or technologies than efficient truck operations.

3.4.5. Automation and intelligence

An issue of growing importance is the prevalence of increasingly intelligent and cooperative technologies fostering automation. Although representing a highly potent opportunity, few publications refer to these developments in transitioning ports towards sustainability. Poulsen et al. (2018) refer to the use of intelligent traffic management, such as dynamic traffic signs; while Li et al. (2011) refer to a fully automated container quay in China, and Xin et al. (2014) conduct mathematical modelling on improved operational performance automated container terminals. Automated guided vehicles (AGVs) are operating in the port of Hamburg (Acciaro et al., 2014b) and could be a tool for optimizing vehicle routing and energy efficiency in port operations (Kang and Kim, 2017). Further, Kavakeb et al. (2015) refer to intelligent autonomous vehicles (IAVs) as “a new type of AGVs with better maneuverability and ability to pick up/drop off containers by themselves” (Kavakeb et al., 2015).

3.4.6. Clean industrial activity

Ports have historically been at the center of industrial activities, and as vital hubs in national, regional and global economies most ports continue to concede land to industry and production. Industrial activities can be influenced through environmental criteria in concession agreements. Although the promotion of clean industry at ports is included in the WPCI (Fenton, 2017), none of the publications included in this review investigate relevant tools others than concession agreements and collaboration with port stakeholders.

4. Discussion

The purpose of the literature review has been to give an overview of and suggest a typology for tools and technologies for sustainable ports as presented by scientific literature, and, based on the review, to discuss whether the current scientific literature help port decision makers.

4.1. Summarizing the tools and technologies for port sustainability

Based on detailed review of 70 publications between 2010 and 2018, the paper has identified 26 tools and technologies distributed across four categories. As seen in Table 8, the single most prominent issues addressed in the literature is undoubtedly cold ironing, which is mentioned in 25 publications. This makes “Power and fuels” the largest category of tools and technologies in the literature (36 publications). There are also substantial references to alternative fuels (12 publications), where LNG (10 publications) predominates. There is decisively less focus on other fuels and energy sources.

The second most prominent category of tools is “Port management and policies”, addressed by 30 publications. Within this

Table 8
Most prominent tools and technologies in review.

Tool/technology	Publications
Cold ironing	25
Speed reduction	17
Modal shift	12
Technological shift: yard vehicles and equipment	12
Alternative fuels	12

category, publications particularly relate to modal shift (12 publications), energy/environmental management, monitoring and port dues (all 10 publications).

Although the literature does not refer to many tools and technologies for improving sustainability in sea activities in ports, measures for speed reduction (17 publications) on approach are among the most prominent issues in the review. The use of alternative fuels also relates to sea activities.

Publications addressing tools and technologies relating to land activities largely focus on technological shifts in yard vehicles and equipment, trucks and drayage (total 16 publications). Trucks are also at the core of making port operations more efficient, which impacts sustainability related to both land activities (efficient truck operations) and sea activities (efficient vessel handling).

4.2. Port decision makers and the current literature on port sustainability

Given that few publications in this review are based on empirical findings and do not account for actual experiences from ports, we suggest that the current literature on measures for sustainable ports gives an insufficient foundation for decision making. A great share of the literature consists of hypothetical and/or conceptual considerations, as well modelling and calculations of anticipated effects. Although these are interesting and relevant approaches, more practical experience is needed to aid port decision makers in evaluating the transition potential of technologies.

To better support port decision makers in choosing and implementing sustainable tools and technologies, there is need for empirically based research on actual experiences, assessments and considerations in selecting tools and technologies, and challenges with implementation and experiences from operations. A key interest for most ports is knowledge about tools and technologies' potential for achieving goals concerning sustainability and emission reductions. What measures are most effective? What measures should be prioritized first? This inability of scientific research to support decision making among port authorities is also highlighted by Di Vaio et al. (2018), and the need for more knowledge on the effect of measures is supported by a series of papers on climate change adaptation (e.g. Becker et al., 2012, 2015). Becker et al. (2012) find that port decision makers consider themselves undereducated about climate risks, which highlights the need for more information from the scientific community to enable port decision makers to make qualified decisions. Port decision makers with more knowledge are more likely to act and implement measures (Ng et al., 2018). The recent Port Emission Tookit (GloMEEP, 2018) also identifies empirical findings (referred to as “quantifying results”) as an issue in need of direct and immediate action. This requires empirical data before and after implementation, allowing ex-ante evaluation of a measure's effectiveness.

Based on the findings in this review, we further argue that available research does not reflect the abundance and variety of actions taken in ports across the globe and that more effort should be made to investigating other ports than the frontrunners. The literature is largely constrained to a set of large, frontrunner ports, such as Los Angeles/Long Beach, Vancouver, Rotterdam, Amsterdam, Hamburg, Antwerp and Singapore. In including the full range of relevant tools and technologies, this review should have ensured the inclusion of all potentially effective measures for sustainability transitions, making it relevant for both small and large ports. This is important because it is likely that a host of different measures must be employed to achieve the ambitious emission reduction goals set for the maritime sector. However, the dominant position of frontrunner ports in the literature implies that the findings of this review are likely to be more relevant for large ports than small ones.

As such, there is an apparent gap between state of practice and state of research. Response rates in Becker et al.'s port survey (2012) illustrate challenges with including the diversity of ports in research, and even large, quantitative investigations struggle provide a representative empirical base. We therefore argue for a stronger focus on the variety within the practice field. There is a strong need for more research on small and medium sized ports - of which there are many – to increase transferability of learning points. It is also likely that the effectiveness of measures will be context-dependent (Moser, 2014), and capturing different contextual influences is therefore important to enable decision making.

5. Conclusion

Ports face increased demands for sustainability. Our literature review shows that the state of research can be characterized as a diverse research field, as research on port sustainability originates from many scholarly traditions, including business and management, mathematics, (environmental) engineering, social sciences, and humanities. Our broad approach to defining tools and technologies ensures that all potentially effective measures towards sustainability transitions in ports are included, and the review of 70 publications between 2010 and 2018 identifies 26 different tools and technologies across four main categories: port management and policies, power and fuels, sea activities, and land activities. The single most prominent issue addressed in the literature is undoubtedly cold ironing, making power and fuels the largest main category. Despite this large variety in tools and technologies, we argue that this literature overall is not likely to sufficiently support port decision makers in prioritizing different measures for emission reductions. The review reveals little empirical evidence on sustainability actions in port, and there are few accounts of actual experiences from ports.

Turning to the policy implications of our review, we would first like to challenge the research community and ask if the gap between research and practice relates to research's inability to engage ports. Most ports are businesses which are interested in maintaining business as usual and port decision makers are usually driven by short-term economic profits over long-term planning for sustainability (Becker and Caldwell, 2015). Research should therefore address strategies for engaging ports in research activities, especially smaller ports with smaller organizations and fewer resources. The disconnect between researchers on the one side and decision makers on the other, raises the question of how to bridge the divide between these two groups (Moser, 2014), a challenge that is common also in other research fields such as medicine and education. This literature could provide some important learning points.

Another policy implication relates to understanding policymakers themselves and the process of policymaking. In investigating how port decision makers perceive climate adaptation actions, Ng et al. (2018) find that decision makers are skeptical about the effectiveness and value of measures for mitigating climate change. This is critical since support from port stakeholders is necessary for successful implementation of management decisions (Becker and Caldwell, 2015). A highly interesting and relevant extension of this review is therefore investigation of port decision makers' knowledge, competence and confidence in selecting and implementing tools and technologies that transition ports towards sustainability. Following Ng et al. (2018) it could be argued that port decision makers may implement measures due to a “political duty” or as an opportunity to showcase technology. It would therefore be interesting to investigate further port decision makers' motivations in implementing measures for emission reduction.

Turning to the process of policymaking, a complicating factor is the complex nature of ports and the many different activities and stakeholders involved. Empirical investigations of port sustainability require explicit definitions of what and who the port is, hereunder what activities, processes and emissions that are relevant to include. Research shows that measures implemented on the landside of ports are less complicated to implement measures off-port (Becker and Caldwell, 2015). However, ports are increasingly being recognized an active part of the energy system and therefore challenged to play a more active role (Acciaro et al., 2014a). As such, improved understanding of decision making processes and how port complexity influences implementation of tools and technologies is an interesting avenue to progress research on sustainable ports.

Finally, there are two main limitations of the review. Firstly, the paper does not include publications prior to 2010. This implies that many earlier publications which are relevant to the topic, and reviewed by Davarzani et al. (2016) and Di Vaio and Varriale (2018), are excluded. However, given the fast progression of both technology development and pressures promoting sustainability in ports, this strict time delineation ensures continued relevance of the reviewed tools and technologies. Secondly, in only including journal publications, this paper excludes a substantial amount of gray literature and proceedings which are expected to include references to implemented practices and ongoing initiatives. As such, this paper does by no means claim to provide a full overview of tools and technologies and actual implementation activities. Rather, the paper focuses on identifying the state of research when it comes to considering and applying these tools and technologies.

Declaration of Competing Interest

None.

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Appendix A. Full table of tools and technologies

Port management and policies						
Port plans	**Management of environment and energy**	**Monitoring**	**Concession agreements**	**Modal shift**	**Port dues**	**Collaboration**
Acciaro et al., 2014a; Acciaro et al, 2014b; Anastasopoulos et al, 2011; Fenton, 2017; Gibbs et al, 2014; Schipper et al, 2017	Acciaro et al, 2014a; Acciaro et al, 2014b; Boile et al, 2016; Chen and Pak, 2017; Kang and Kim, 2017; Lam and Notteboom, 2014; Le et al., 2014; Li et al, 2011; Poulsen et al., 2018; Puente-Rodríguez et al., 2016	Acciaro et al, 2014a; Acciaro et al, 2014b; Acciaro et al, 2018; Anastasopoulos et al, 2011; Gonzalez-Aregall et al., 2018; Chen and Pak, 2017; Fenton, 2017; Hall et al, 2013; Kang and Kim, 2017; Lam and Notteboom, 2014	Gonzalez-Aregall et al., 2018; De Langen and Van Den Berg, 2012; Ferrari et al, 2015; Lam and Notteboom, 2014; Notteboom and Lam, 2018; Notteboom and Verhoeven, 2010; Notteboom et al., 2012; Poulsenet al, 2018; Van den Berg and De Langen, 2014	Acciaro et al, 2014b; Gonzalez-Aregall et al., 2018; Bergqvist and Egels-Zandén, 2012; Bergqvist et al, 2015; Kang and Kim, 2017; Lam and Notteboom, 2014; Li et al., 2011; Notteboom and Lam, 2018; Notteboom and Verhoeven, 2010; Poulsen et al., 2018; Bergqvist et al, 2015; Van den Berg and De Langen, 2014	Acciaro et al, 2014a; Acciaro et al, 2014b; Gonzalez-Aregall et al., 2018; Bergqvist and Egels-Zandén, 2012; Bergqvist et al, 2015; Fenton, 2017; Gibbs et al, 2014; Kang and Kim, 2017; Lam and Notteboom, 2014; Poulsen et al., 2018	Acciaro et al, 2014a; Acciaro et al, 2014b; Cerceau et al., 2014; Hentschel et al., 2018; Kang and Kim, 2017; Lu et al., 2016; Poulsen et al., 2018
Other managerial policies						
Acciaro et al., 2014a; Bosman et al., 2018; Di Vaio and Varriale, 2018; Poulsen et al., 2018						

Power and fuels

Wind energy
Acciaro et al., 2014a, 2014b; Lam and Notteboom, 2014; Li et al., 2011

Solar energy
Acciaro et al., 2014a, 2014b; Boile et al., 2016; Kang and Kim, 2017; Lam and Notteboom, 2014; Li et al., 2011

Wave and tidal energy
Acciaro et al., 2014a; Hadadpour et al., 2014; Naty et al., 2016; Ramos et al., 2014

Geothermal energy
Acciaro et al., 2014b

Electrification
Acciaro et al., 2014a, 2014b; Acciaro et al., 2018; Adamo et al., 2014; Anastasopoulos et al., 2011; Arduino et al., 2013; Boile et al., 2016; Chang and Wang, 2012; Dragović et al., 2018; Fenton, 2017; Gibbs et al., 2014; Hall, 2010; Hall et al., 2013; Innes and Monios, 2018; Kang and Kim, 2017; Kim et al., 2012; Lam and Notteboom, 2014; Kotrikla et al., 2017; Linder, 2010; López-Aparicio et al., 2017; Notteboom, 2018; Poulsen et al., 2018; Styhre et al., 2017; Tseng and Pilcher, 2015; Tzannatos, 2010; Winkel et al., 2016; Winnes et al., 2015; Yang, 2017; Yang and Chang, 2013; Zis et al., 2014

LNG
Acciaro et al., 2014a; Boile et al., 2016; Bosman et al., 2018; Calderón et al., 2016; Gibbs et al., 2014; Kang and Kim, 2017; López-Aparicio et al., 2017; Poulsen et al., 2018; Schipper et al., 2017; Winnes et al., 2015

Biofuels
Acciaro et al., 2014a; Bosman et al., 2018; Kang and Kim, 2017; Winnes et al., 2015

Methanol and hydrogen
Boile et al., 2016; Winnes et al., 2015

Low sulfur fuels
Acciaro et al., 2014a; Anastasopoulos et al., 2011; Gibbs et al., 2014; Lam and Notteboom, 2014

Sea activities

Speed reduction
Acciaro et al., 2014b; Anastasopoulos et al., 2011; Cariou, 2011; Chang and Jhang, 2016; Chang and Wang, 2012; Chen and Pak, 2017; Gibbs et al., 2014; Jia et al., 2017; Johnson and Styhre, 2015; Li et al., 2011; Linder, 2010; Linder, 2018; López-Aparicio et al., 2017; Poulsen et al., 2018; Styhre et al., 2017; Winnes et al., 2015; Zis et al., 2015

Efficient vessel handling
Gibbs et al., 2014; Jia et al., 2017; Johnson and Styhre, 2015; Lalla-Ruiz et al., 2018; Styhre et al., 2017; Poulsen et al., 2018; Moon and Woo, 2014

Other
Gibbs et al., 2014; Winnes et al., 2015

Land activities

Technological shift: Trucks and drayage
Acciaro et al., 2014b; Areagall et al., 2018; Hall et al., 2013; Hartman and Clott, 2012; Li et al., 2011;

Efficient truck operation
Acciaro et al., 2018; Chen et al., 2011; Chen et al., 2013; Hall et al., 2013; Li et al., 2018; Phan and Kim, 2015; Phan and

Efficient loading unloading
Johnson and Styhre, 2015; Moon and Woo, 2014; Styhre et al., 2017

Automation and intelligence
Acciaro et al., 2014b; Kang and Kim, 2017; Kavakeb et al., 2015; Li et al., 2011; Poulsen et al., 2018; Xin et al., 2014

Clean industrial activity
Fenton, 2017

Norsworthy and Craft, 2013; Notteboom, 2018; Poulsen et al., 2018	Kim, 2016; Torkjazi et al., 2018

Appendix B. Publications referring to more than five different tools and technolgies

Authors	Title	Tools/technologies
Acciaro et al., 2014b	Environmental sustainability in seaports: a framework for successful innovation	14
Acciaro et al., 2014a	Energy management in seaports: a new role for port authorities	13
Poulsen et al., 2018	Environmental upgrading in global value chains: the potential and limitations of ports in the greening of maritime transport	13
Kang and Kim, 2017	Conceptual Model Development of Sustainability practices: the case of port operations for collaboration and governance	11
Lam and Notteboom, 2014	The Greening of Ports: a comparison of port management tools used by leading ports in Asia and Europe	9
Gibbs et al., 2014	The role of sea ports in end-to-end maritime transport chain emissions	8
Li et al., 2011	An exploratory study on low-carbon ports development strategy in China	7
Anastasopoulos et al., 2011	How will Greek ports become green ports?	6
Fenton, 2017	The role of port cities and transnational municipal networks in efforts to reduce greenhouse gas emissions on land and at sea from shipping - an assessment of the World Ports Climate Initiative	6
Winnes et al., 2015	Reducing GHG emissions from ships in port areas	6

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