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Estimating the costs and external benefits of reducing shipping-induced air pollution: a case study of Xiamen Harbour, China

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Abstract

A cost–benefit analysis of air pollution reduction measures in maritime transport systems can support the sustainability commitments of the industry and validate the related economic incentives. However, a systematic cost–benefit analysis approach has not yet been framed, as data availability and resources are limited. This study explores an alternative cost–benefit estimate approach to reduce air pollution in shipping based on a broad review and applies it to a case study regarding the domestic emission controls of Xiamen shipping. The results show that switching to a fuel with a maximum allowable fuel sulphur content of 1.5% to 0.5% for cargo ships and other vessels leads to more than nine times the external benefits to costs, while switching to a fuel with less than 0.5% sulphur content may lead to below-cost external benefits; the benefits/cost ratio based on shore power is 3.14. The proposed approach contributes to estimating not only the input costs but also their external benefits to fit the externality of sustainability actions. In the future, more site-specific factors and parameters and more case studies are recommended to improve the research reliability and accuracy as well as enrich the knowledge base for shipping sustainability development.

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1 Introduction

1.1 Background

Air pollution caused by the emissions of sulphur oxides (SO_X), particulate matter (PM), and nitrogen oxides (NO_X) leads to ecosystem degradation and biodiversity loss and threatens sustainability goals (United Nations, 2020; United Nations Environment Programme, 2019). Burning fossil fuels has affected air quality, leading it to become the top environmental issue for the port and shipping sectors in recent decades (X. European Sea Ports Organization, 2021; Wu et al., 2018). Scientists have estimated that the number of premature deaths caused by ship emissions of particulate matter (PM), sulphur oxides (SO_X), and nitrogen oxides (NO_X) has increased from approximately 60,000 in 2002–250,000 in 2020 (H. Liu et al., 2019); furthermore, SO_X and NO_X emissions are converted to nitric or sulphuric acids by chemical reactions, increasing the vulnerability of marine organisms to ocean acidification (Abdulla, 2008).

In response to of institutional regulations, market and resource availability pressures, and public demands for a high-quality environment, various technical, operational, and economic sustainability actions have emerged to reduce air pollutant emissions (Sardain et al., 2019; Wang et al., 2021), and economic initiatives such as dues, grants, subsidies, trade with emission allowances, taxes, and penalties have shown much success in reducing these emissions (Christodoulou et al., 2019). To help understand the potential of abatement measures, evaluation methods such as impact assessments (Song et al., 2022), effectiveness evaluations (Zhang et al., 2022), feasibility evaluations (He et al., 2021), ecological evaluations based on emergy-ecological footprints (Xie et al., 2022), indicator-based eco-efficiency evaluations (Nunes et al., 2019), and cost–benefit analyses (Wu & Lin, 2021) were used. However, compared to other evaluation methods, a cost–benefit analysis has a direct link to economic issues and contributes to market-based air pollution reduction. With a cost–benefit analysis, stakeholders may deliver their sustainability commitments based on the recognition of financial cost input and social benefit output (Fung et al., 2014); governments and authorities can integrate the "market failure" as externalities into their economic incentives (Fung et al., 2014); and managers may assess whether candidate abatement measures are cost-effective, although these measures tend to look encouraging (International Maritime Organization, 2019).

1.2 State of the art

Due to globalization, vessel gigantism, and technology advancement (Russo & Musolino, 2020; Wu et al., 2019b), port generation has been transformed from only serving to connect the cities, to focusing on the industrial systems or latest maritime transport systems (Russo & Musolino, 2020; Russo et al., 2014, 2016). Port operation, which includes maritime shipping, loading and unloading, cargo handling, storage, and land traffic, is an important node within modern maritime logistics chains for promoting international trade (Russo & Musolino, 2021); this study, however, focuses on maritime shipping emissions, as there is a lack of shipping sustainability studies (Wu et al., 2018), and it can inform complicated and correlative capacity-building or decision-making.

A literature search was conducted using the keywords "shipping OR maritime OR marine transportation AND air pollution AND cost–benefit" from the Web of Science;

Table 1 The current research on cost–benefit analysis of shipping air pollution

Sources	Study scope	Costs estimation	Benefits estimation
Wang and Corbett (2007)	*Case area:* United States West Coast	Based on market prices for capital costs and operating costs	*Emissions estimation approach:* "top-down" based on the amount of fuel consumption
	Abatement measures: fuel switching and seawater scrubbers installing		*External benefits estimation approach:* "top-down" based on environmental costs from the United States Environmental Protection Agency
	Timeframe: 2005		
Browning et al. (2012)	*Case area:* Gulf of Mexico	Based on market prices for fuel costs and operational costs	*Emissions estimation approach:* "bottom-up" based on activity profiles and energy-based emission factors
	Abatement measures: fuel switching		
	Timeframe: 2005–2010		
Schinas and Stefanakos (2012)	*Case area:* international sulphur emission control areas	Based on market prices for fixed costs (covering capital costs, administrative costs, and other expenses) and variable costs (i.e. operating expenses)	None
	Abatement measures: Sulphur Emission Control Area (SECA) policy		
	Timeframe: for 15 years		
McArthur and Osland (2013)	*Case area:* Port of Bergen	None	*Emissions estimation approach:* "bottom-up" based on activity profiles and energy-based emission factors
	Abatement measures: alternative measures		*External benefits estimation approach:* "top-down" based on costs factors from academic research, the Coastal Administration, the CAFE, and the Benefits Table database (BeTa)
	Timeframe: 2010		
Doudnikoff and Lacoste (2014)	*Case area:* international sulphur emission control areas	Based on market prices for capital costs and operating costs	*Emissions estimation approach:* "bottom-up" based on activity profiles and energy-based emission factors
	Abatement measures: speed reduction		
	Timeframe: 2009–2013		
Sources	Study scope	Costs estimation	Benefits estimation
Jiang et al. (2014)	*Case area:* North Sea	Based on market prices for capital costs and operating & maintenance costs	*Emissions estimation approach:* "bottom-up" based on activity profiles and energy-based emission factors
	Abatement measures: fuel switching and seawater scrubbers installing		*External benefits estimation approach:* "top-down" based on costs factors from the CAFE and Developing Harmonised European Approaches for Transport Costing and Project Assessment (HEATCO) projects
	Timeframe: 2005–2013		

Table 1 (continued)

Sources	Study scope	Costs estimation	Benefits estimation
Song (2014)	*Case area:* Yangshan port	None	*Emissions estimation approach:* "bottom-up" based on activity profiles and energy-based emission factors
	Abatement measures: none		*External benefits estimation approach:* "top-down" based on costs factors from international studies and made adjustment by integrating China development level
	Timeframe: 2009		
Ballini and Bozzo (2015)	*Case area:* Copenhagen cruise port	None	Based on an EVA model, an advanced impact-pathway approach, to calculate the external benefits in Denmark
	Abatement measures: cold-ironing technology		
	Timeframe: 2012		
Maragkogianni and Papaefthimiou (2015)	*Case area:* Greek ports	None	*Emissions estimation approach:* "bottom-up" based on activity profiles and energy-based emission factors
	Abatement measures: none		*External benefits estimation approach:* "top-down" based on costs factors from the CAFE programme and NEEDS project
	Timeframe: 2013		
Antturi et al. (2016)	*Case area:* Baltic Sea	Based on market prices for investment costs and operating costs	Based on an impact-pathway approach by using the STEAM to output the ships' fuel consumption and the SILAM to model the emission concentration change
	Abatement measures: low-sulphur fuel standard		
	Timeframe: 2011–2015		
Sources	Study scope	Costs estimation	Benefits estimation
Åström et al. (2018)	*Case area:* Baltic and North Seas	Based on market prices for investments, operation & maintenance, and fuel penalty costs	Based on an impact-pathway approach, where the GAINS was used to estimate the emission pathways and the ARP were applied to value the health impact
	Abatement measures: Nitrogen Emission Control Area policy		
	Timeframe: 2011–2015		
Hu et al.(2018)	*Case area:* Ports	Based on market prices for investment costs and operating costs	None
	Abatement measures: shore-side power technology		
Innes and Monios (2018)	*Case area:* Port of Aberdeen	Based on market prices for capital costs and operating and maintenance costs	*Emissions estimation approach:* "top-down" based on the amount of fuel consumption

Table 1 (continued)

Sources	Study scope	Costs estimation	Benefits estimation
	Abatement measures: cold-ironing technology		*External benefits estimation approach:* "top-down" based on costs factors from the UK Government's Department for Environment, Food and Rural Affairs
	Timeframe: 2010–2016		
Tovar and Tichavska (2019)	*Case area:* Port of Las Palmas, Port of St. Petersburg, and Port of Hong Kong	None	*Emissions estimation approach:* "bottom-up" based on activity profiles and energy-based emission factors
	Abatement measures: SOx regulatory		*External benefits estimation approach:* "top-down" based on cost factors from the BeTa
	Timeframe: 2011–2012		
Vierth et al. (2019a, 2019b)	*Case area:* European areas	None	*Emissions estimation approach:* based on a internet-based NTM (Network for Transport Measures) calculation tool which relies on activity profiles and energy-based emission factors ("bottom-up")
	Abatement measures: modal shifting		*External benefits estimation approach:* "top-down" based on cost factors from the Swedish and European guidelines
	Timeframe: 2011–2012		
Sources	Study scope	Costs estimation	Benefits estimation
Lee et al. (2020)	*Case area:* South Korea	None	*External benefits estimation approach:* using a contingent valuation method (willingness to pay) to estimate economic benefits of LNG-fueled ships
	Abatement measures: using the LNG-fueled ships		
	Timeframe: 2018		
Nunes et al. (2021)	*Case area:* Iberian Peninsula	None	*Emissions estimation approach:* "bottom-up" based on a model of STEAM
	Abatement measures: none		*External benefits estimation approach:* "bottom-up" based on a EMEP model to show air pollutant concentrations; used the value of statistical life and the value of a life year which rely on the willingness to pay surveys
	Timeframe: 2015		
Spengler and Tovar (2021)	*Case area:* Spanish ports	None	*Emissions estimation approach:* "bottom-up" based on AIS-based activity profiles and energy-based emission factors
	Abatement measures: cold-ironing technology		*External benefits estimation approach:* "top-down" based on cost factors from BeTa
	Timeframe: 2016		
Wan et al. (2021)	*Case area:* Shekou Container Terminal	Based on government subsidy	*Emissions estimation approach:* "top-down" based on the amount of fuel consumption

Table 1 (continued)

Sources	Study scope	Costs estimation	Benefits estimation
	Abatement measures: low-sulphur fuel and shore power technology		*External benefits estimation approach:* "top-down" based on cost factors related to government subsidy
	Timeframe: 2018		
Wu and Lin (2021)	*Case area:* a shipping route from and to Hong Kong	Based on market capital costs and operating costs	*Emissions estimation approach:* "bottom-up" based on activity profiles and energy-based emission factors
	Abatement measures: low-sulphur policy		
	Timeframe: 2018		
Sources	Study scope	Costs estimation	Benefits estimation
Ytreberg et al. (2021)	*Case area:* Baltic Sea	None	Based on a DPSIR framework to assess the impacts of shipping activities, where the STEAM model has been used to estimate the emissions and models of ARP and GAINS has been used to estimate health-related damage costs
	Abatement measures: marine policy		
	Timeframe: 2018		
Gren et al. (2021)	*Case area:* Baltic Sea	None	*Emissions estimation approach:* "bottom-up" based on activity profiles and energy-based emission factors
	Abatement measures: NO$_X$ regulatory		*External benefits estimation approach:* "top-down" based on unit shadow costs determined by emission pathways and marginal abatement costs for emission targets
	Timeframe: 2018		

Table 1 shows the current studies on the cost and benefits of shipping air pollution. Beginning with the study of Wang and Corbett (2007), the number of relevant studies has increased in recent years, but most have focused on Europe and America (Antturi et al., 2016; Åström et al., 2018; Nunes et al., 2021; Song, 2014; Ytreberg et al., 2021; Gren et al., 2021). Technologies or policies such as fuel switching (Wang & Corbett, 2007), the use of scrubbers (Jiang et al., 2014), setting emission control areas (Åström et al., 2018), slow steaming (Doudnikoff & Lacoste, 2014), liquefied natural gas (LNG)-fueled ships (Lee et al., 2020), cold-ironing technology (Spengler & Tovar, 2021), and SO$_X$ and NO$_X$ regulators (Gren et al., 2021; Wu & Lin, 2021) have been explored, but only a few studies have compared the costs and benefits of alternative abatement measures (Jiang et al., 2014; Wan et al., 2021; Wang & Corbett, 2007). A systematic cost–benefit analysis approach has not yet been made.

With regard to current methodological approaches, it should be noted that the cost evaluation is based on the observable and available market prices for capital costs, investment costs, operating and maintenance costs, administration costs, fuel penalty costs, and other expenses (Antturi et al., 2016; Åström et al., 2018; Schinas & Stefanakos, 2012;

Wan et al., 2021; Wang & Corbett, 2007); the benefits estimation generally includes both the emissions calculation and external benefits evaluation (Antturi et al., 2016; Tovar & Tichavska, 2019). We can identify two general approaches characterized as "bottom-up" and "top-down" in emission estimation (Tichavska & Tovar, 2017). Specifically, bottom-up approaches are based on identifying the ships' activities profiles and rely on the power and emission factors of the ships' main engines, auxiliary engines, or boilers; top-down approaches directly multiply the change in fuel oil consumption and emission factors to output an estimation (Faber et al., 2021). As for impact valuation, the majority of the approaches rely on cost factor-based estimation approaches that directly multiply the unit damage costs with the amount of emission reduction to outcome external benefits (Spengler & Tovar, 2021; Tovar & Tichavska, 2019; Wan et al., 2021). Additionally, some studies have used impact pathway approaches to integrate the conditions of locations into the evaluation (Antturi et al., 2016; Nunes et al., 2021), where models of the GAINS (Greenhouse gas-Air pollution Interactions and Synergies), the EMEP (Cooperative Programme for Monitoring and Evaluation of the Long-range Transmission of Air Pollutants in Europe) (Holland et al., 2005a; European Commission, 2009), the STEAM (Ship Traffic Emission Assessment Model) the ARP (ALPHA-RiskPoll), the EVA (External Valuation of Air Pollution) (Ballini & Bozzo, 2015), and the SILAM (System for Integrated modeLling of Atmospheric coMposition) have been applied to help understand the emission pathways and quantify the impacts. A set of precalculated cost factors has been determined by using the impact pathways approach (United Kingdom Department for Environment Food & Rural Affairs 2019a). Although some scholars have been working to develop more evaluation approaches, such as the Drivers-Pressures-State-Impact-Response (DPSIR)-based impact assessment framework and unit shadow cost-based calculation, they are limited by the complexity of causality in interactions between shipping activities and natural ecosystems or emission pathway calculations (Gren et al., 2021; Ytreberg et al., 2021).

1.3 Research question and purpose

Located in southeastern China, Xiamen harbour has a pilot port, and Xiamen shipping plays an important role in the development of national shipping and the Maritime Silk Road (Wu et al., 2019a; Xiamen Port Authority, 2021). Numerous sustainable efforts, such as the use of shore power technology and low-sulphur fuel, have been made to reduce shipping emissions at harbours, but few studies have measured the costs and external benefits of reducing air pollution in shipping, especially when relevant data, funds, and time limitations exist (Wu et al., 2019a; Xiamen Port Authority, 2021).

Hence, this study aims to establish a systematic and repeatable estimation approach for exploring the costs and external benefits of measures designed to reduce air pollution from shipping; the approach is developed a comparison of the current cost–benefit analysis methods and considering Xiamen shipping as a case study. This case study, despite limited data availability and resources, explores the cost-effectiveness of the abatement measures, thereby supporting sustainability commitments and cooperation plans in modern port generation. In the next section, we provide the methods and approach, followed by a case study, discussion and conclusion.

2 Methodology

2.1 Methods

Based on the above review of the existing cost–benefit analyses of shipping-related air pollution, which are shown in Table 1, we can identify a variety of calculation methods for cost and external benefit estimation. A proper methodological estimation approach can be built by comparing the existing methods and combining the current data and resources. Since the ultimate sustainability goal is to perpetuate and enhance the natural environment and resources to maintain an ecological balance (X. Wu et al., 2019c), the estimation approach needs to consider not only healthy lives and human well-being but also marine and coastal ecosystem protections and conservation. Then, a case study can be carried out to verify this approach for its application to other ports.

2.2 Approach

2.2.1 Cost estimation approach

Based on the abovementioned broad review, the prior cost estimation approaches for shipping air pollution mostly considered market prices, except for the study of Wan et al. (2021), which integrated some political influences. This study similarly concerns the costs input that are financially incurred or received from the perspective of the participants, rather than that of the government; the costs inventory includes direct capital or investment costs and operating and maintenance costs, as other costs, such as non-compliance costs and manpower costs, are indirect or possess high uncertainties.

Correspondingly, regarding the use of shore power technology, the annual direct costs are comprised of investment costs and operation and maintenance costs, i.e.,

$$C_{Tt} = C_{Fpt} + C_{Fst} + C_{ot} \tag{1}$$

where C_{Tt} is the total cost of the shore power construction and operation in years $t = 1, 2, \ldots, n$, for which $t = 1$ represents the first year; C_{Fpt} and C_{Fst} are the invest costs of shore power construction for ports and ships, respectively, in year t; and C_{ot} is the operation cost for shore power in year t.

If taking time values of the capital into account, the total cost (C_T) for the shore power technology implementation can be calculated by

$$C_T = \sum_{t=1}^{t} C_{Tt} \times (1 + i)^t \tag{2}$$

where i expresses the discount rate on the annualized cost.

If taking a straight-line depreciation and a net residual value rate of j with an expected lifespan of N years for the shore power equipment, the total investment cost of shore power construction for ports (C_{FpT}) could be measured at an amortized cost through the equation

$$C_{FpT} = \sum_{t=1}^{t} C_{Fpt} \times (1 - j)/N \times (1 + i)^t \tag{3}$$

For fuel switching, fuel price differences account for the majority of the costs (Wang & Corbett, 2007). To calculate the fuel switching costs, a price gap approach is recommended in which the fuel price premium is multiplied by the amount of fuel consumption.

2.2.2 External benefit estimation approach

The market consistently fails to calculate the benefits resulting from the influences of natural resources or public health in the surrounding area, known as externalities (KENTON, 2020). To address sustainability concerns, the abovementioned studies used "top-down" and "bottom-up" approaches to estimate air pollution emissions, as well as the "top-down" or cost factor-based approach and impact pathway approach to value the social and ecological burden of air pollutant emissions.

First, for the emission estimation, in contrast with the "top-down" emission estimation approach, the "bottom-up" approach prioritizes a description of ship activities at a harbour rather than relying on possible energy consumption statistics. The "bottom-up" emission estimation method can also be based on a state-of-the-art automatic identification system (AIS) (Antturi et al., 2016) to acquire the static and dynamic data of ships and the quality parameters of fuel oil. In detail,

$$E = W \times EF \times Act \tag{4}$$

where E is the amount of a ship's air pollutant emissions; W is the actual power of the ship's main engine, auxiliary engine or boiler; EF is the emission factor of air pollutants (the amount of emissions per unit of power); and Act is the ship's operating time under different sailing conditions (Jian et al., 2020). Moreover,

$$W = MCR \times LF \tag{5}$$

$$EF = BEF \times LCF \times FCF \times CF \tag{6}$$

where MCR is the rated power of the ship's main engine, auxiliary engine, or boiler; LF expresses the load factor of the ship's main engine; BEF is the baseline of the ship's emission factor of air pollutants; LCF is the correction factor for a low main engine load; FCF is the correction factor for fuel oil based on the local sulphur content of fuel oil; and CF is the control factor of abatement technology (Jian et al., 2020).

However, if lacking activity data, the "top-down" method can be chosen by following the formula listed as follows:

$$E' = Q \times EF' \tag{7}$$

where E' is the amount of air pollutant emissions; Q is the amount of fuel consumption; and EF' is the emission factor of air pollutants (the amount of emissions per unit of energy consumed) (Xing, 2017).

Second, for external benefit estimation, the commonly used approaches are the cost factor-based approach and the impact pathway approach. The impact pathway approach identifies and traces the effects of air pollution reduction driven by measures intervention, uses atmospheric dispersion models to simulate regional concentration changes, conducts impact assessment based on concentration–response functions, and finally combines

resource and environmental value assessment techniques to monetize the impact (see Fig. 1) (Holland et al., 2005a; United Kingdom Department for Environment 2019). A significant advantage of this approach is the integration of location-specific elements (United Kingdom Department for Environment Food & Rural Affairs 2019b), though it can be extremely complicated to understand the emission pathways, atmospheric dispersion, and economic valuation, particularly due to the need for sufficient data, funds, and time.

In addition, the cost factor-based approach directly estimates the external benefits by multiplying the amount of emissions change with predetermined values per unit of emission by pollutants (see Fig. 2) (Spengler & Tovar, 2021). We can pick up precalculated cost factors from the United States Environmental Protection Agency's study (Wang & Corbett, 2007), the Coastal Administration of Norway (McArthur & Osland, 2013), the Clean Air For Europe (CAFE) program (Holland et al., 2005b; Jiang et al., 2014; Maragkogianni & Papaefthimiou, 2015; McArthur & Osland, 2013), the Benefits Table database (BeTa) (McArthur & Osland, 2013; Spengler & Tovar, 2021; Tovar & Tichavska, 2019), the Developing Harmonised European Approaches for Transport Costing and Project Assessment (HEATCO) projects (Jiang et al., 2014), the New Energy Externalities Development for Sustainability (NEEDS) programs (Maragkogianni & Papaefthimiou, 2015), the United King Government's Department for Environment, Food and Rural Affairs (Innes & Monios, 2018), the national government subsidy (Wan et al., 2021), and other studies (McArthur & Osland, 2013; S. Song, 2014). If it is not possible to follow the impact pathway approach due to intensive resources and time requirements, then the cost factor-based approach is recommended to calculate the impacts of emitted pollutants from shipping.

In-depth analyses include the several approaches. HEATCO's proposal is a harmonized assessment approach previously used as the basis of the CAFE programme. The NEEDS's cost factors are more focused on energy externalities. The BeTa is calculated by using the CAFE cost–benefit analysis methodology, and its cost factors are available to port and shipping industries (Holland et al., 2005a); furthermore, the cost factors for the United States, Norway, United King, and China as well as those from other academic studies are used to integrate regional characteristics. Therefore, this study suggests the cost factors from the BeTa and the study of S. Song (2014) for China region concerns (see Table 2).

After determining the cost factors, we must convert them to adjust to the relevant evaluation price year, taking inflation into the consideration. Then, we can calculate the external benefits of air pollution reduction by multiplying the adjusted cost factors and the emission reduction amount of air pollutants as follows:

$$B = R \times F \tag{8}$$

where B is the external benefits of the air pollutant emission reduction driven by the implementation of abatement measures; R is the amount of emissions abatement; and F is the cost factor for air pollution reduction.

2.2.3 Proposed cost–benefit analysis framework

Therefore, we can frame the costs and external benefits estimation approach for air pollution reduction in shipping, as shown in Fig. 3. This framework engages a market

price-based approach to estimate the costs of abatement measures, taking shore power technology and fuel switching as examples of potential solutions due to their wide use and actual application for Xiamen shipping. To fit sufficient or insufficient data situations, a combination of the "bottom-up" approach and "to-down" approach is given to calculate the air pollutant emissions. Moreover, cost factor-based estimate equations and impact pathway approaches are recommended to calculate the external benefits. We present and compare the benefit/cost ratios to verify the evaluation, giving consideration to some uncertainties in the estimation due to limited data availability and resources.

3 Case study and results

3.1 Case introduction

This study chooses the domestic shipping emission control area (DSECA) at the Xiamen harbour, as the study scope, which includes Dongdu, Haicang, Zhaoyin, Xiang'an, and Wutong port areas, as the study scope. The area boarding the sea is bounded by the red line in the bottom right corner (see Fig. 4). This area is located in a semi-enclosed bay with a typical semidiurnal tide, slight wave action, and a water depth of -46.5 m based on the Yellow Sea elevation (Wu et al., 2019a).

According to prior studies, the total amount of pollutant emissions from the Xiamen DSECA was estimated to be 17,683 tonnes in 2018, of which shipping emissions accounted for 92.8% (Jian et al., 2021). Of the pollutants, 10,544 tonnes came from NO_X emissions, followed by 2,816 tonnes of SO_2, 592 tonnes of PM_{10}, and 491 tonnes of $PM_{2.5}$ (Jian et al., 2021). Except for the SO_2 emissions in the Dongdu port area, which were less than the average in Xiamen city, the SO_2 emissions in the Haicang port area and the NO_2 and PM emissions in the Dongdu and Haicang port areas exceeded those in the urban area in 2018 (Jian et al., 2021).

To reduce the shipping emissions from the Xiamen harbour, measures have been put into practice, including the use of shore power technology and fuel switching for tugboats, cargo ships, and other vessels (Jian et al., 2021). By 2018, only 55 vessels used the shore power equipment in Haicang and Dongdu port areas, consuming 1,175,800 kW h of electricity. In addition, the sulphur content of fuel for tugboats was changed from 0.5 to 0.008%; the use of heavy fuel oil with 1.5% sulphur content was shifted to light diesel oil with 0.5% sulphur content for container ships and oil tankers during berthing time; and other vessels, including engineering vessels, fishing vessels, and working vessels, used light diesel oil with a 0. 5% sulphur content instead of heavy diesel oil with a 1.5% sulphur content throughout their whole voyages to reduce air pollutant emissions from Xiamen shipping (Jian et al., 2021).

3.2 Costs

In Table 3, Equations of (1), (2) and (3) are used to calculate the economic costs incurred in 2018 from implementing the Xiamen shipping abatement measures. In this
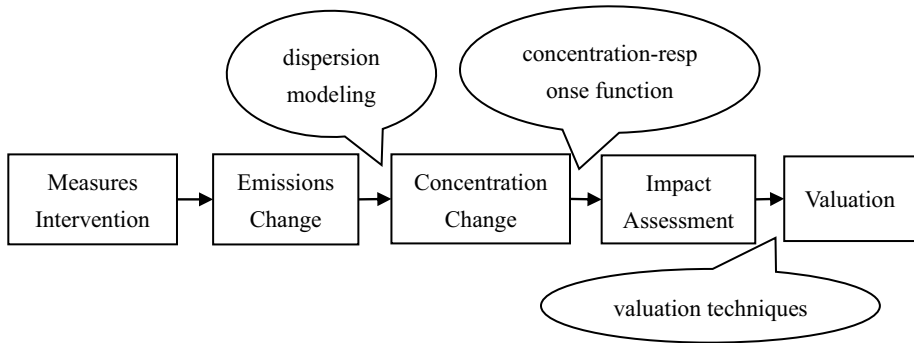
Fig. 1 The general impact pathway approach for external benefits assessment (adapted from United Kingdom Department for Environment Food & Rural Affairs 2019b
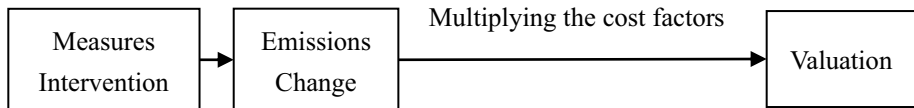

Fig. 2 The general cost factor-based approach for external benefits assessment (adapted from United Kingdom Department for Environment Food & Rural Affairs 2019b)

case study, the operation and construction costs for shore power technology were estimated only for 2016–2018 due to undesirable utilization rates prior to 2016. The investment costs of port shore power construction are 1750, 2826, 1750 yuan (RMB) for 2016, 2017, and 2018, respectively, as Jian et al. (2021) indicated. A net residual value rate of 5% with an expected lifespan of 30 years was given for the shore power technology (Hu et al., 2018; State Taxation Administration, 2004); 8% per annum for i was recommended by Hu et al. (2018). For the low auxiliary engine size in Xiamen shipping (Jian et al., 2020), the investment cost of retrofitting the electrical equipment on board C_{Fst} was 218 €/kW in 2005 with an equipment lifespan of 10 years, as reported by Entec UK Limited (2005). The operational cost C_{ot} included the electricity cost (approximately 0.6408 yuan/kW h for the electricity consumption with battery voltage less than 10 kVA and about 0.5202 yuan/kW h for the electricity consumption with battery voltage more than 220 kVA for industrial and commercial business in Xiamen area) and the maintenance cost (a general value of 1.6 €/running hour for engines and 1,100 €/ship saved for auxiliary engines in 2004 used by Entec UK Limited (2005)). For Xiamen shipping, 1.1758 million kWh of electricity was used for shore power in Dongdu and Haicang port areas until 2018, and 0.8999 million kWh of electricity was used for shore power with battery voltage less than 10 kVA thereafter according to Jian et al. (2021). In 2018, shore power running hours increased to 2025 h, with a total of 55 berthing times (Jian et al., 2021).

In addition, this study gives attention to fuel switching rather than installing scrubbers or other equipment to follow the actual measures taken by Xiamen shipping to reduce SO_X and

NO_X emissions (Jian et al., 2021). Using figures from Notteboom (2020), we find that the peak prices of ultralow-sulphur fuel oil and low-sulphur marine gas oil (maximum 0.1% sulphur) are approximately 680 \$/tonne and 700 \$/tonne, respectively, while that for intermediate fuel oil is approximately 470 \$/tonne. Before October 2020, the price of very low-sulphur fuel oil (above 0.10% but meeting a 0.50% sulphur limit) was approximately 570 \$/tonne at its highest (Notteboom, 2020). This study uses these values to measure fuel costs. If actual figures regarding fuel consumption are lacking, we derive the fuel volume from the emission reduction and emission factors. In other words, the amount of fuel consumption can be obtained as the emissions abatement (E') from Table 5 divided by EF' from Eq. (7). EF' can be measured by $1955 \times S\%$ (kg/t), where $S\%$ is the sulphur content in fuel; it can be expressed by the transformation rate of 97.75% for S according to Xing (2017).

The costs of shore power construction for ports and ships are 2,167.04 and 1,017.69 thousand yuan, respectively, and the operation cost is 2,180.92 thousand yuan. The added costs incurred from fuel switching for tugboats, cargo ships, and other vessels are estimated to be 114,027.94, 53,164.96, and 40,651.58 thousand yuan, respectively. Eventually, the total cost for shore power construction and operation and fuel switching in the Xiamen DSECA is 213,210.13 thousand yuan.

3.3 External benefits

By using the "bottom-up" Equations of (4), (5), and (6), the emissions reduction driven by intervention measures can be quantified. For Xiamen shipping, the study of Jian et al. (2021) provided the emission factors for air pollutants (see Table 4) and estimated

Table 2 Cost factors recommended for external benefits estimation

Sources	Prices year (unit)	Unit-price per emission component			
		SO_2	NO_X	PM_{10}	$PM_{2.5}$
BeTa:	2000 (€/tonne)				
Rural (EU-15 averages) (Holland & Watkiss, 2004)		5200	4200		14,000
Urban_for a city of (Holland & Watkiss, 2004):					
100,000 people		6000			33,000
500,000 people		30,000			165,000
1,000,000 people		45,000			247,500
Several million people		90,000			495,000
Shipping_for the area of (Holland & Watkiss, 2004):					
Eastern Atlantic		4500	4800		9100
Baltic Sea		1600	2100		2500
English Channel		5900	5400		12,000
Northern Mediterranean		4700	6200		10,000
North Sea		4300	3100		9600
Yangshan coastal region (Song, 2014)	2009 (\$/tonne)	10,687	12,329	76,867	85,771

According to the BeTa report, emissions in port use urban results for the city of the same size as the port city and add rural externality figure for the country in question; emissions close to shore use national rural results. Sources are indicated in the table

the amount of air pollution reduction based on a bottom-up approach in 2018 (shown in Table 5). This study employs the prior estimates rather than calculating them.

In consideration of data availability and resource restrictions, this case study adopts the cost factor-based approach to calculate the external benefits of the reduction in air pollution from Xiamen shipping in 2018; it uses Eq. (8), multiplying the unit price of air pollutant emissions from Table 2 and the figures from Table 5 to generate the final benefits (see Table 6). To integrate China's development level, this case study chooses the cost factors for Yangshan Port of Shanghai from S. Song (2014).

Finally, using shore power can obtain an external benefit of 16,842.93 thousand yuan and the external benefits of fuel switching for tugboats, cargo ships, and other vessels are 14,284.67, 467,607.66, and 373,809.28 thousand yuan, respectively. For the vessels' NO_X emission reduction driven by fuel quality improvements, the external benefit can be 27,376.04 thousand yuan. In total, the reduction in air pollution from Xiamen shipping in 2018 is estimated to be 899,920.58 thousand yuan.

3.4 Benefit–cost comparison

The results include the investment and operation costs of shore power and fuel switching and the external benefits of reduced air pollution in shipping in 2018. We also acquire a range of costs, benefits, and benefit/cost ratios (see Table 7). It can be found that fuel switching from heavy fuel oil with 1.5% sulphur content to light diesel oil with 0.5% sulphur content during berthing for cargo ships and other vessels has more external benefits than costs, but switching to lower 0.5% sulphur content fuel for tugboats has more costs than benefits. Using shore power can lead to external benefits that are 2.14 times higher than the costs.

4 Discussions

Based on a broad literature review, this study proposes a cost–benefit estimation approach to calculate the costs and external benefits driven by measures to reduce air pollution in shipping. Externality concerns can contribute to sustainability goals that not only ensure human health but also conserve marine and coastal ecosystems (Wu et al., 2019c). However, in contrast with market prices-based costs estimation, the external benefits calculation is still much debated, as there is considerable uncertainty and complexity in prices that determine "market failure" (Sheng et al., 2019). This study takes the externalities estimation approach due to its use of both emission calculations and monetary impacts valuation to determine their cause and effect relationships.

In emissions estimation, both the "bottom-up" and "top-down" approaches have been two commonly used; the IMO's fourth study on shipping greenhouse gas emissions generated the best comparison of them to date (Faber et al., 2021). This study combines the "bottom-up" approach and "top-down" approach to fit the activity data situation and takes the former as a priority for the Xiamen shipping activities at the DSECA. However, the knowledge base of shipping air pollutant impact valuation is deficient (Ytreberg et al., 2021), although two approaches, i.e., a cost factor-based approach and an impact pathway approach, have been provided (Holland et al., 2005a; United Kingdom Department for Environment 2019). Compared to the cost factor-based approach that directly multiplies the amount of reduced emissions by the precalculated cost factors to output the external
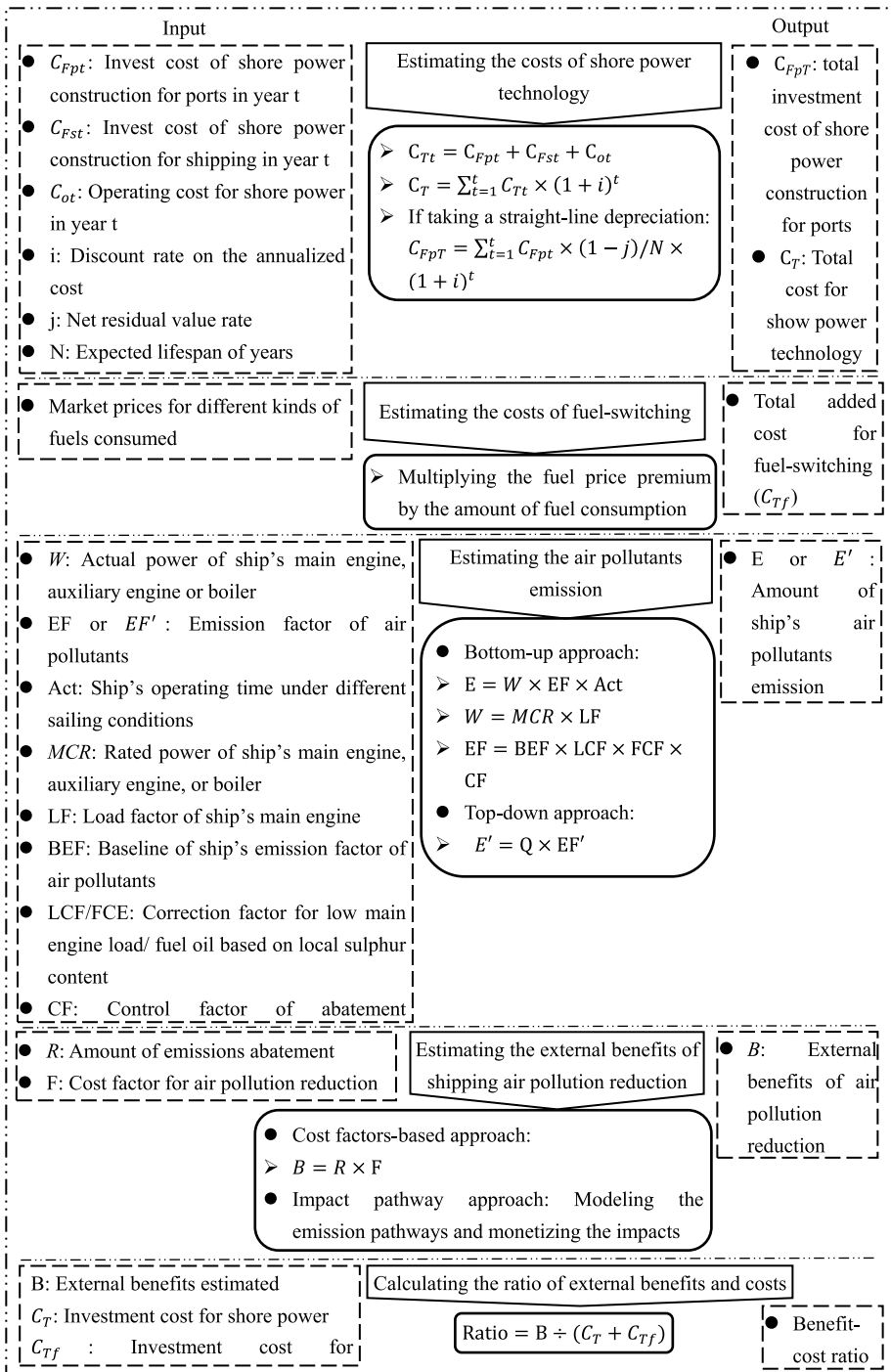
Input | **Output**

Estimating the costs of shore power technology

- C_{Fpt}: Invest cost of shore power construction for ports in year t
- C_{Fst}: Invest cost of shore power construction for shipping in year t
- C_{ot}: Operating cost for shore power in year t
- i: Discount rate on the annualized cost
- j: Net residual value rate
- N: Expected lifespan of years

➢ $C_{Tt} = C_{Fpt} + C_{Fst} + C_{ot}$
➢ $C_T = \sum_{t=1}^{t} C_{Tt} \times (1+i)^t$
➢ If taking a straight-line depreciation:
$C_{FpT} = \sum_{t=1}^{t} C_{Fpt} \times (1-j)/N \times (1+i)^t$

- C_{FpT}: total investment cost of shore power construction for ports
- C_T: Total cost for show power technology

Estimating the costs of fuel-switching

- Market prices for different kinds of fuels consumed

➢ Multiplying the fuel price premium by the amount of fuel consumption

- Total added cost for fuel-switching (C_{Tf})

Estimating the air pollutants emission

- W: Actual power of ship's main engine, auxiliary engine or boiler
- EF or EF': Emission factor of air pollutants
- Act: Ship's operating time under different sailing conditions
- MCR: Rated power of ship's main engine, auxiliary engine, or boiler
- LF: Load factor of ship's main engine
- BEF: Baseline of ship's emission factor of air pollutants
- LCF/FCE: Correction factor for low main engine load/ fuel oil based on local sulphur content
- CF: Control factor of abatement

- Bottom-up approach:
➢ $E = W \times EF \times Act$
➢ $W = MCR \times LF$
➢ $EF = BEF \times LCF \times FCF \times CF$
- Top-down approach:
➢ $E' = Q \times EF'$

- E or E': Amount of ship's air pollutants emission

Estimating the external benefits of shipping air pollution reduction

- R: Amount of emissions abatement
- F: Cost factor for air pollution reduction

- Cost factors-based approach:
➢ $B = R \times F$
- Impact pathway approach: Modeling the emission pathways and monetizing the impacts

- B: External benefits of air pollution reduction

Calculating the ratio of external benefits and costs

- B: External benefits estimated
- C_T: Investment cost for shore power
- C_{Tf}: Investment cost for

Ratio = B ÷ (C_T + C_{Tf})

- Benefit-cost ratio

Fig. 3 The costs and external benefits estimation approach for reducing air pollution in shipping
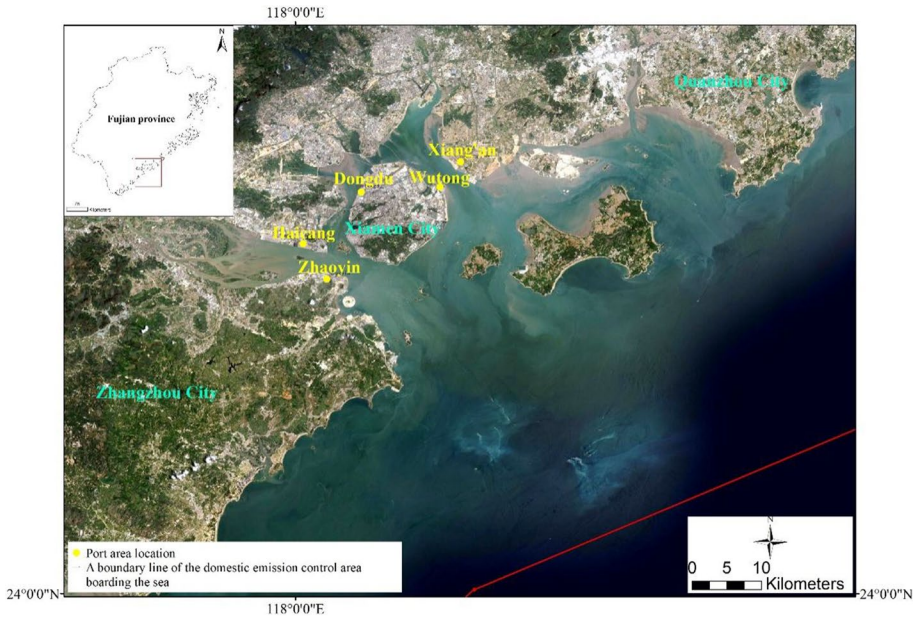
Fig. 4 The shipping emission control area at the Xiamen harbour

Table 3 The costs of the abatement measures for Xiamen shipping in 2018

Measures	Calculation and results
Shore power	Construction cost for ports: $1750 \times \frac{(1-5\%)}{30} \times (1 + 0.08)^2 + 2826 \times \frac{(1-5\%)}{30} \times (1 + 0.08) + 1750 \times \frac{(1-5\%)}{30}$ $= 2167.04 \times 10^3$ yuan
	Construction cost for ships: $218 \times 7.8024 \times (1 + 0.08)^{13} \times 1000 \times 0.22 = 1,017.69 \times 10^3$ yuan
	Operation cost: $0.6408 \times 0.8999 \times 10^6 + 0.5202 \times (1.1758 - 0.8999) \times 10^6 + 2025 \times 1.6 \times 7.8024$ $\times (1 + 0.08)^{14} + 55 \times 1,100 \times 7.8024 \times (1 + 0.08)^{14} = 2180.92 \times 10^3$ yuan
	Total cost: $5,365.65 \times 10^3$ yuan
Fuel switching	For tugboats: $(680 - 570) \times 6.6118 \times [26.5 \times 10^3 \div (1955 \times 0.008\%)] = 114027.94 \times 10^3$ yuan
	For cargo ships: $(570 - 470) \times 6.6118 \times [786 \times 10^3 \div (1955 \times 0.5\%)] = 53164.96 \times 10^3$ yuan
	For other vessels: $(570 - 470) \times 6.6118 \times [601 \times 10^3 \div (1955 \times 0.5\%)] = 40651.58 \times 10^3$ yuan
	Total cost: 207844.48×10^3 yuan
Total cost	213210.13×10^3 yuan

(1) The construction and operation costs of shore power are from (Entec UK Jian et al., 2020, 2021; Limited, 2005), and the discount rate is 0.08. (2) Based on the average exchange rate in 2018, 1 € is equal to 7.8024 yuan, and 1 $ can be converted to 6.6118 yuan. (3) The power of the auxiliary engine takes 1,000 kW as a minimum demand for container ships (Liu et al., 2011), and the general power ratio coefficient of the auxiliary engine and main engine for container vessels is 0.22 (Lisheng, 2020). (4) Due to the late year of shore power construction and its slow application processes, this study concerns the total amount of electricity consumption, running hours, and berthing times from 2016

Table 4 The air pollutant emission factors

Fuel type	Sulphur Content %	SO$_X$ (g/kW h)	NO$_X$ (g/kW h)	PM (g/kW h)
Heavy oil	1.5	0.56	1	0.82
Diesel oil	1.5	0.56	0.9	0.47
Light diesel	0.5	0.18	0.94	0.25
Light diesel	0.2	0.07	0.94	0.19
Light diesel	0.1	0.04	0.94	0.17

Source: Adapted from Jian et al. (2021)

monetary benefits, the impact pathway approach expresses site-specific evaluation by modeling the emission pathways and dispersion, concentration response, impact assessment, and monetary valuation. Recently, this impact pathway approach has been applied for the Copenhagen cruise port (Ballini & Bozzo, 2015), Baltic and North seas (Antturi et al., 2016; Åström et al., 2018; Ytreberg et al., 2021), and Iberian Peninsula (Nunes et al., 2021) by using models such as EVA, STEAM, SILAM, GAINS, ARP, or EMEP; however, we can see some uncertainties in dispersion modeling, recognition of potential impacts by exposure, and monetary valuation driven by model dependency, limited scientific knowledge, or subjective judgment, as well as intensive time and resources (United Kingdom Department for Environment 2019; Sheng et al., 2019). Given the limits of data availability and quality in Xiamen shipping, this case study adopts cost factor-based approaches to estimate the external benefits and uses the prevalued cost factors that integrate China's development level.

Limitations do exist in this study. For instance, the costs did not account for unknown expenses such as administration costs; the study only presents the calculation methods for shore power and fuel switching; and the determination of emission factors and cost factors needs more site-specific considerations. Nevertheless, compared to the benefit/cost ratios from previous publications (see Table 8), we find that the benefit/cost ratios estimated in this study have similar orders of magnitude, regardless of the specific method used. More specific measures, such as fuel switching in which fuel with 0.5% sulphur content replaces that with 1.5% sulphur content, show relatively high benefit/cost ratios; however, if the maximum allowable fuel sulphur content is less than 0.5%, the external benefits may be less than the costs. The use of shore power can lead to external benefits that are 2–4 times the costs; these costs may be affected by the low utilization rate of shore power.

Despite this, we are encouraged to conduct an investigation of other expenses for abatement measures and more evidential research on local emission factors and cost factors if time and budget permit. More case studies can also contribute to further meta-analyses on the costs and external benefits of reducing air pollution in shipping to better select sustainability solutions or even apply advanced techniques such as nanotechnology and nanostructures (Zinatloo-Ajabshir & Mousavi-Kamazani, 2021; Zinatloo-Ajabshir et al., 2020, 2021).

Table 5 The air pollution reduction from Xiamen shipping in 2018 (tonnes per year)

Air pollution reduction measures	SO_2	NO_X	PM_{10}	$PM_{2.5}$
The use of shore power	25.2	40.0	3.2	3.1
Fuel switching (maximum allowable fuel sulphur content changed from 0.5% to 0.0.008%) for tugboats	26.5	–	5.02	4.80
Fuel switching (changing the use of heavy fuel oil with 1.5% sulphur content to light diesel oil with 0.5% sulphur content during berthing time) for cargo ships	786	312	157	129
Fuel switching (changing the heavy diesel oil with 1.5% sulphur content to light diesel oil with 0. 5% sulphur content during the whole voyage) for other vessels	601	180	135	108
Additional NOx emission reduction	–	168	–	–
Total emission reduction	1438.7	700	300.22	244.9

The additional NOx emission reduction was driven by the improvement of fuel oil quality

Source: Adapted from Jian et al. (2021)

Table 6 The external benefits of reductions in Xiamen shipping air pollution in 2018

Measures	Calculation and results
The utilization of shore power	SO_2:$25.2 \times 10,687 \times 6.6118 \times (1+0.08)^9 = 3,559.51 \times 10^3$ yuan
	NO_X: $40.0 \times 12,329 \times 6.6118 \times (1+0.08)^9 = 6,518.10 \times 10^3$ yuan
	PM_{10}: $3.2 \times 76,867 \times 6.6118 \times (1+0.08)^9 = 3,251.05 \times 10^3$ yuan
	$PM_{2.5}$: $3.1 \times 85,771 \times 6.6118 \times (1+0.08)^9 = 3,514.27 \times 10^3$ yuan
	Total benefit:$16,842.93 \times 10^3$ yuan
Fuel switching for tugboats	SO_2:$26.5 \times 10,687 \times 6.6118 \times (1+0.08)^9 = 3,743.13 \times 10^3$ yuan
	PM_{10}:$5.02 \times 76,867 \times 6.6118 \times (1+0.08)^9 = 5,100.08 \times 10^3$ yuan
	$PM_{2.5}$: $4.80 \times 85,771 \times 6.6118 \times (1+0.08)^9 = 5,441.46 \times 10^3$ yuan
	Total benefit:$14,284.67 \times 10^3$ yuan
Fuel switching for cargo ships	SO_2:$786 \times 10,687 \times 6.6118 \times (1+0.08)^9 = 111,022.72 \times 10^3$ yuan
	NO_X: $312 \times 12,329 \times 6.6118 \times (1+0.08)^9 = 50,841.22 \times 10^3$ yuan
	PM_{10}: $157 \times 76,867 \times 6.6118 \times (1+0.08)^9 = 159,504.56 \times 10^3$ yuan
	$PM_{2.5}$: $129 \times 85,771 \times 6.6118 \times (1+0.08)^9 = 146,239.16 \times 10^3$ yuan
	Total benefit:$467,607.66 \times 10^3$ yuan
Fuel switching for other vessels	SO_2:$601 \times 10,687 \times 6.6118 \times (1+0.08)^9 = 84,891.42 \times 10^3$ yuan
	NO_X:$180 \times 12,329 \times 6.6118 \times (1+0.08)^9 = 29,331.47 \times 10^3$ yuan
	PM_{10}:$135 \times 76,867 \times 6.6118 \times (1+0.08)^9 = 137,153.60 \times 10^3$ yuan
	$PM_{2.5}$:$108 \times 85,771 \times 6.6118 \times (1+0.08)^9 = 122,432.79 \times 10^3$ yuan
	Total benefit:$373,809.28 \times 10^3$ yuan
Additional NOx emissions	NO_X:$168 \times 12,329 \times 6.6118 \times (1+0.08)^9 = 27,376.04 \times 10^3$ yuan
Total benefit	$899,920.58 \times 10^3$ yuan

(1) This study chooses the cost factors from the Yangshan coastal region by Song (2014) to indicate China's local features and the annual discount rate is 0.08. (2) Based on the average exchange rate in 2018, $1 can be converted to 6.6118 yuan. (3) The vessels' NO_X emission reduction in a single row in the table is driven by improving the fuel quality for cargo ships (Jian et al., 2021)

Source: Own elaboration

Table 7 The costs and external benefits of the reductions in air pollution in Xiamen shipping

Abatement measures	Costs (10^3 yuan)	External benefits (10^3 yuan)	Benefit/cost ratio
The utilization of shore power	5,365.65	16,842.93	3.14
Fuel switching (maximum allowable fuel sulphur content changed from 0.5% to 0.0.008%) for tugboats	114,027.94	14,284.67	0.13
Fuel switching (changing the use of heavy fuel oil with 1.5% sulphur content to light diesel oil with 0.5% sulphur content during berthing time) for cargo ships	53,164.96	494,983.70	9.31
Fuel switching (changing the heavy diesel oil with 1.5% sulphur content to light diesel oil with 0. 5% sulphur content during the whole voyage) for other vessels	40,651.58	373,809.28	9.20

This estimation ignores the additional external benefits driven by the improvement of fuel quality to compare the effects of the air pollution reduction measures

Source: Own elaboration

5 Conclusions

A cost–benefit analysis that helps uncover the costs and external benefits of air pollutant reduction measures supports the complicated and uncertain decision-making processes endemic to modern ports, which are vital nodes of maritime transport systems; these systems require significant cooperation and coordination. This study provides a systematic and repeatable cost–benefit estimation methodology based on a broad review of the current fragmented cost–benefit analysis for reducing air pollution in shipping and uses this approach to estimate the costs and benefits of implementing air pollution reduction measures for Xiamen shipping in its domestic emission control area. This approach aims to calculate not only the input costs but also their external benefits to fit the externality of sustainability actions and support the stakeholders' and governments' sustainability commitments and economic incentives.

After a case application of the established estimation approach, we can realize that switching the maximum allowable sulphur content of fuel to 0.5% shows great cost-effectiveness, while switching to less than 0.5% sulphur content could be negative; additionally, the use of shore power technology can yield a benefit/cost ratio of 3.17. This case study focuses only on recognizable investment costs and operation and maintenance costs; for data availability and resources restrictions; it combines a "bottom-up" emission estimation approach and a cost factor-based approach, rather than using the complex, high data demand, and site-specific impact pathway approach. However, its results are comparable to those from previous studies.

Nonetheless, more detailed surveys on the cost input, shipping activities, energy consumption, and site-specific cost factors are needed to improve the reliability and accuracy of the results. We also suggest conducting an impact pathway approach-based external benefits estimation for reducing air pollution in shipping for the sake of comparison. More

Table 8 The existing benefit/cost ratios for shipping air pollution reduction from previous studies

Abatement measures	Benefit/cost ratios	Sources
Using low-sulphur fuel (sulphur content not exceeding 1.5% (0.5%)) on the United States West Coast	1.80 (2.57)	Wang & Corbett, (2007)
Sulphur scrubbers for new build ships (retrofitted ships) in the North Sea	6.26 (3.61) per year, without capital's time value	Jiang et al. (2014)
Sulphur reduction policy, dropping the maximum allowable fuel sulphur content from 1% to 0.1%, in the Baltic Sea SECA	0.23, only considering the disability adjusted life-years saving	Antturi et al. (2016)
Implementing a nitrogen emission control area by 2021 in the Baltic and North seas	1.5–12 for 2030 scenario, if transport demand and ships' age distribution would be not affected	Åström et al. (2018)
Shore power technology for Port of Aberdeen	2.36, if with expected lifespan of 30 years and without capital's time value	Innes & Monios, (2018)

case studies would expand the base knowledge on which decision-makers rely for implementing sustainability-oriented measures.

Data availability All data generated or analysed during this study are included in this published article.

Declarations

Conflict of interest The author declares no conflicts of interest.

References

Abdulla, A. (2008). Maritime traffic effects on biodiversity in the Mediterranean Sea. https://portals.iucn.org/library/sites/library/files/documents/2008-042-1.pdf. Accessed 2 September, 2021.

Antturi, J., Hänninen, O., Jalkanen, J. P., Johansson, L., Prank, M., Sofiev, M., et al. (2016). Costs and benefits of low-sulphur fuel standard for Baltic Sea shipping. *Journal of Environmental Management, 184*, 431–440. https://doi.org/10.1016/j.jenvman.2016.09.064

Åström, S., Yaramenka, K., Winnes, H., Fridell, E., & Holland, M. (2018). The costs and benefits of a nitrogen emission control area in the Baltic and North Seas. *Transportation Research Part d: Transport and Environment, 59*, 223–236. https://doi.org/10.1016/j.trd.2017.12.014

Ballini, F., & Bozzo, R. (2015). Air pollution from ships in ports: The socio-economic benefit of cold-ironing technology. *Research in Transportation Business and Management, 17*, 92–98. https://doi.org/10.1016/j.rtbm.2015.10.007

Browning, L., Hartley, S., Bandemehr, A., Gathright, K., & Miller, W. (2012). Demonstration of fuel switching on oceangoing vessels in the Gulf of Mexico. *Journal of the Air and Waste Management Association, 62*(9), 1093–1101. https://doi.org/10.1080/10962247.2012.697974

Christodoulou, A., Gonzalez-Aregall, M., Linde, T., Vierth, I., & Cullinane, K. (2019). Targeting the reduction of shipping emissions to air: A global review and taxonomy of policies, incentives and measures. *Maritime Business Review, 4*(1), 16–30. https://doi.org/10.1108/MABR-08-2018-0030

Doudnikoff, M., & Lacoste, R. (2014). Effect of a speed reduction of containerships in response to higher energy costs in Sulphur Emission Control Areas. *Transportation Research Part d: Transport and Environment, 28*, 51–61. https://doi.org/10.1016/j.trd.2014.03.002

Entec UK Limited (2005). Service Contract on Ship Emissions: Assignment, Abatement and Market-based Instruments. Task 2a—Shore-Side Electricity. https://ec.europa.eu/environment/air/pdf/task2_shoreside.pdf. Accessed April 3, 2022.

European Commission (2009). New energy externalities developments for sustainability (NEEDS). http://www.needs-project.org/. Accessed 3 March 2020.

European Sea Ports Organization (2021). ESPO Green Guide 2021. https://www.espo.be/media/ESPO%20Green%20Guide%202021%20-%20FINAL.pdf. Accessed 30 July 2022.

Faber, J., Hanayama, S., Zhang, S., Pereda, P., Comer, B., Hauerhof, E., et al. (2021). Fourth IMO GHG Study 2020. https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth%20IMO%20GHG%20Study%202020%20-%20Full%20report%20and%20annexes.pdf. Accessed 30 July 2022.

Fung, F., Zhu, Z., Becque, R., Finamore, B., & Natural Resources Defense Council (2014). Prevention and Control of Shipping and Port Air Emissions in China. (pp. 7–41). Beijing, China: Natural Resources Defense Council.

Gren, I. M., Brutemark, A., & Jagerbrand, A. (2021). Air pollutants from shipping: Costs of NOx emissions to the Baltic Sea. *Journal of Environmental Management*. https://doi.org/10.1016/j.jenvman.2021.113824

He, L., Wang, J. J., Liu, Y. M., Zhang, Y., He, C., Yu, Q., et al. (2021). *Selection of onshore sites based on monitoring possibility evaluation of exhausts from individual ships for Yantian Port*. China: Atmospheric Environment. https://doi.org/10.1016/j.atmosenv.2021.118187

Holland, M., & Watkiss, P. (2004). Benefits Table database: Estimates of the marginal external costs of air pollution in Europe. https://ec.europa.eu/environment/enveco/air/pdf/betaec02a.pdf. Accessed 3 March 2020.

Holland, M., Hunt, A., Hurley, F., Navrud, S., & Watkiss, P. (2005a). Methodology for the Cost-Benefit analysis for CAFE: Volume 1: Overview of Methodology https://ec.europa.eu/environment/archives/cafe/pdf/cba_methodology_vol1.pdf. Accessed 3 March 2020.

Holland, M., Pye, S., Watkiss, P., Droste-Franke, B., & Bickel, P. (2005b). Damages per tonne emission of $PM_{2.5}$, NH_3, SO_2, NO_x and VOCs from each EU25 Member State (excluding Cyprus) and surrounding seas. https://ec.europa.eu/environment/archives/cafe/activities/pdf/cafe_cba_externalities.pdf. Accessed December 20, 2021.

Hu, X., Wang, B., Huang, J., Ruan, W., Kong, Y., & Zhou, Z. (2018). Cost-benefit optimization analysis of participants in shore-side power construction and operation and characteristic comparison among river, lake and ocean shore-side power. *Dianli Zidonghua Shebei/electric Power Automation Equipment, 38*(9), 169–178. https://doi.org/10.16081/j.issn.1006-6047.2018.09.025

Innes, A., & Monios, J. (2018). Identifying the unique challenges of installing cold ironing at small and medium ports – The case of aberdeen. *Transportation Research Part d: Transport and Environment, 62*, 298–313. https://doi.org/10.1016/j.trd.2018.02.004

International Maritime Organization (2019). Procedure for assessing impacts on States of candidate measures. https://wwwcdn.imo.org/localresources/en/MediaCentre/HotTopics/Documents/MEPC.1-Circ.885%20-%20Procedure%20For%20Assessing%20Impacts%20On%20States%20Of%20Candidate%20Measures%20(Secretariat).pdf. Accessed 17 May 2021.

Jian, W., Zhi, H., Sen-yang, C., & Yan-ying, L. (2021). Assessment of the effectiveness of air pollutant reduction in the Xiamen Shipping Control Zone (Green Port). *Straits Science, 1*, 22–28.

Jian, W., Zhi, H., Yan-ying, L., Sen-yang, C., Yan-cong, W., Yue-yun, H., et al. (2020). Vessels' air pollutant emissions inventory and emission characteristics in the Xiamen emission control area. *Environmental Science, 41*(08), 3572–3580.

Jiang, L., Kronbak, J., & Christensen, L. P. (2014). The costs and benefits of sulphur reduction measures: Sulphur scrubbers versus marine gas oil. *Transportation Research Part d: Transport and Environment, 28*, 19–27. https://doi.org/10.1016/j.trd.2013.12.005

KENTON, W. (2020). Externality. https://www.investopedia.com/terms/e/externality.asp. Accessed 10 September 2021.

Lee, H. J., Yoo, S. H., & Huh, S. Y. (2020). Economic benefits of introducing LNG-fuelled ships for imported flour in South Korea. *Transportation Research Part d: Transport and Environment*. https://doi.org/10.1016/j.trd.2019.102220

Lisheng, L. (2020). *Environmental and Economic Benefits Assessment of Ship Shore Power in Dalian Port*. Dalian Maritime University.

Liu, H. B., Dong, Z. Q., & Lin, J. Q. (2011). On the technology of on-shore power supply for vessels. *Port & Waterway Engineering., 9*, 181–184.

Liu, H., Meng, Z.-H., Lv, Z.-F., Wang, X.-T., Deng, F.-Y., Liu, Y., et al. (2019). Emissions and health impacts from global shipping embodied in US–China bilateral trade. *Nature Sustainability, 2*(11), 1027–1033. https://doi.org/10.1038/s41893-019-0414-z

Maragkogianni, A., & Papaefthimiou, S. (2015). Evaluating the social cost of cruise ships air emissions in major ports of Greece. *Transportation Research Part d: Transport and Environment, 36*, 10–17. https://doi.org/10.1016/j.trd.2015.02.014

McArthur, D. P., & Osland, L. (2013). Ships in a city harbour: An economic valuation of atmospheric emissions. *Transportation Research Part d: Transport and Environment, 21*, 47–52. https://doi.org/10.1016/j.trd.2013.02.004

Notteboom, T. (2020). Roro shipping vs trucking: revisiting the impact of low-sulphur marine fuel use on cost competitiveness of routing options in north Europe. *WMU Journal of Maritime Affairs, 19*(4), 399–426. https://doi.org/10.1007/s13437-020-00221-z

Nunes, R. A. O., Alvim-Ferraz, M. C. M., Martins, F. G., Peñuelas, A. L., Durán-Grados, V., Moreno-Gutiérrez, J., et al. (2021). Estimating the health and economic burden of shipping related air pollution in the Iberian Peninsula. *Environment International*. https://doi.org/10.1016/j.envint.2021.106763

Nunes, R. A. O., Alvim-Ferraz, M. C. M., Martins, F. G., & Sousa, S. I. V. (2019). Environmental and social valuation of shipping emissions on four ports of Portugal. *Journal of Environmental Management, 235*, 62–69. https://doi.org/10.1016/j.jenvman.2019.01.039

Russo, F., Musolino, G., & Assumma, V. (2014). An integrated procedure to estimate demand flows of maritime container transport at international scale. *International Journal of Shipping and Transport Logistics., 6*(2), 112–132.

Russo, F., & Musolino, G. Case Studies and Theoretical Approaches in Port Competition and Cooperation. In O. Gervasi, B. Murgante, S. Misra, C. Garau, I. Blečić, D. Taniar, et al. (Eds.), *Computational Science and Its Applications—ICCSA 2021, Cham, 2021// 2021* (pp. 198–212): Springer International Publishing

Russo, F., & Musolino, G. (2020). Quantitative characteristics for port generations: The Italian case study. *International Journal of Transport Development and Integration, 4*(2), 103–112.

Russo, F., Musolino, G., & Assumma, V. (2016). Competition between ro–ro and lo–lo services in short sea shipping market: The case of Mediterranean countries. *Research in Transportation Business & Management, 19*, 27–33. https://doi.org/10.1016/j.rtbm.2016.03.002

Sardain, A., Sardain, E., & Leung, B. (2019). Global forecasts of shipping traffic and biological invasions to 2050. *Nature Sustainability, 2*(4), 274–282. https://doi.org/10.1038/s41893-019-0245-y

Schinas, O., & Stefanakos, C. (2012). Cost assessment of environmental regulation and options for marine operators. *Transportation Research Part c: Emerging Technologies, 25*, 81–99. https://doi.org/10.1016/j.trc.2012.05.002

Sheng, H., Xu, H., Zhang, L., & Chen, W. (2019). Ecosystem intrinsic value and its application in decision-making for sustainable development. *Journal for Nature Conservation, 49*, 27–36. https://doi.org/10.1016/j.jnc.2019.01.008

Song, S. K., Shon, Z. H., Moon, S. H., Lee, T. H., Kim, H. S., Kang, S. H., et al. (2022). Impact of international Maritime Organization 2020 sulfur content regulations on port air quality at international hub port. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2022.131298

Song, S. (2014). Ship emissions inventory, social cost and eco-efficiency in Shanghai Yangshan port. *Atmospheric Environment, 82*, 288–297. https://doi.org/10.1016/j.atmosenv.2013.10.006

Spengler, T., & Tovar, B. (2021). Potential of cold-ironing for the reduction of externalities from in-port shipping emissions: The state-owned Spanish port system case. *Journal of Environmental Management*. https://doi.org/10.1016/j.jenvman.2020.111807

State Taxation Administration (2004). Circular of the State Administration of Taxation on the Follow-up Management of the Cancelled Enterprise Income Tax Approval Items. http://www.chinatax.gov.cn/n810341/n810765/n812193/n812993/c1202792/content.html. Accessed April 2, 2022.

Tichavska, M., & Tovar, B. (2017). External costs from vessel emissions at port: A review of the methodological and empirical state of the art. *Transport Reviews, 37*(3), 383–402. https://doi.org/10.1080/01441647.2017.1279694

Tovar, B., & Tichavska, M. (2019). Environmental cost and eco-efficiency from vessel emissions under diverse SOx regulatory frameworks: A special focus on passenger port hubs. *Transportation Research Part d: Transport and Environment, 69*, 1–12. https://doi.org/10.1016/j.trd.2019.01.019

United Kingdom Department for Environment, F. R. A. (2019). Air quality: economic analysis. https://www.gov.uk/guidance/air-quality-economic-analysis. Accessed 3 March 2020.

United Nations Environment Programme (2019). Global Environment Outlook—GEO-6: Healthy Planet, Healthy People. https://wedocs.unep.org/bitstream/handle/20.500.11822/27539/GEO6_2019.pdf?sequence=1&isAllowed=y. Accessed 26 December 2019.

United Kingdom Department for Environment Food & Rural Affairs (2019a). Air quality damage cost guidance. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/770576/air-quality-damage-cost-guidance.pdf. Accessed 3 March 2020.

United Kingdom Department for Environment Food & Rural Affairs (2019b). Impact pathways approach: Guidance for air quality appraisal. https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/770649/impact-pathway-approach-guidance.pdf. Accessed 3 March 2020.

United Nations (2020). Summary of the second World Ocean Assessment. https://www.un.org/regularprocess/content/second-cycle-regular-process.

Vierth, I., Sowa, V., & Cullinane, K. (2019a). Evaluating the external costs of a modal shift from rail to sea: An application to Sweden's east coast container movements. *European Journal of Transport and Infrastructure Research, 19*(1), 60–76.

Vierth, I., Sowa, V., & Cullinane, K. (2019b). Evaluating the external costs of trailer transport: A comparison of sea and road. *Maritime Economics and Logistics, 21*(1), 61–78. https://doi.org/10.1057/s41278-018-0099-7

Wan, Z., Zhang, T., Sha, M., Guo, W., Jin, Y., Guo, J., et al. (2021). Evaluation of emission reduction strategies for berthing containerships: A case study of the Shekou Container Terminal. *Journal of Cleaner Production*. https://doi.org/10.1016/j.jclepro.2021.126820

Wang, C., & Corbett, J. J. (2007). The costs and benefits of reducing SO2 emissions from ships in the US West Coastal waters. *Transportation Research Part d: Transport and Environment, 12*(8), 577–588. https://doi.org/10.1016/j.trd.2007.08.003

Wang, X.-T., Liu, H., Lv, Z.-F., Deng, F.-Y., Xu, H.-L., Qi, L.-J., et al. (2021). Trade-linked shipping CO2 emissions. *Nature Climate Change, 11*(11), 945–951. https://doi.org/10.1038/s41558-021-01176-6

Wu, X., Zhang, L., & Dong, Y. W. (2019a). Towards sustainability in Xiamen Harbor, China. *Regional Studies in Marine*. *Science, 27*, 100552. https://doi.org/10.1016/j.rsma.2019.100552

Wu, P. C., & Lin, C. Y. (2020). Cost-benefit evaluation on promising strategies in compliance with low sulfur policy of IMO. *Journal of Marine Science and Engineering., 9*(1), 3.

Wu, X., Zhang, L., & Feng, H. (2019b). Green strategic planning approach for international shipping activities. *Sustainability, 12*(1), 41.

Wu, X., Zhang, L., & Luo, M. (2018). Current strategic planning for sustainability in international shipping. *Environment Development and Sustainability, 22*(3), 1729–1747. https://doi.org/10.1007/s10668-018-00303-2

Wu, X., Zhang, L., & Luo, M. (2019c). Discerning sustainability approaches in shipping. *Environment Development and Sustainability, 22*(6), 5169–5184. https://doi.org/10.1007/s10668-019-00419-z

Xiamen Port Authority (2021). Xiamen Port Authority continues to guide the green development of ports. http://port.xm.gov.cn/gkzx/gkxw/202112/t20211224_2611322.html. Accessed January 10, 2022.

Xie, B., Zhang, X., Lu, J., Liu, F., & Fan, Y. (2022). Research on ecological evaluation of Shanghai port logistics based on emergy ecological footprint models. *Ecological Indicators, 139*, 108916. https://doi.org/10.1016/j.ecolind.2022.108916

Xing, H. (2017). *Study on Quantification of Extaust Emissions from ships*. Doctoral thesis, Dalian Maritime University, Dalian.

Ytreberg, E., Astrom, S., & Fridell, E. (2021). Valuating environmental impacts from ship emissions—The marine perspective. *Journal of Environmental Management*. https://doi.org/10.1016/j.jenvman.2021.111958

Zhang, Q., Liu, H., & Wan, Z. (2022). Evaluation on the effectiveness of ship emission control area policy: Heterogeneity detection with the regression discontinuity method. *Environmental Impact Assessment Review, 94*, 106747. https://doi.org/10.1016/j.eiar.2022.106747

Zinatloo-Ajabshir, S., Ghasemian, N., Mousavi-Kamazani, M., & Salavati-Niasari, M. (2021). Effect of zirconia on improving NOx reduction efficiency of Nd2Zr2O7 nanostructure fabricated by a new, facile and green sonochemical approach. *Ultrasonics Sonochemistry, 71*, 105376. https://doi.org/10.1016/j.ultsonch.2020.105376

Zinatloo-Ajabshir, S., Ghasemian, N., & Salavati-Niasari, M. (2020). Green synthesis of Ln2Zr2O7 (Ln = Nd, Pr) ceramic nanostructures using extract of green tea via a facile route and their efficient application on propane-selective catalytic reduction of NOx process. *Ceramics International, 46*(1), 66–73. https://doi.org/10.1016/j.ceramint.2019.08.231

Zinatloo-Ajabshir, S., & Mousavi-Kamazani, M. (2021). Recent advances in nanostructured Sn−Ln mixed-metal oxides as sunlight-activated nanophotocatalyst for high-efficient removal of environmental pollutants. *Ceramics International, 47*(17), 23702–23724. https://doi.org/10.1016/j.ceramint.2021.05.155