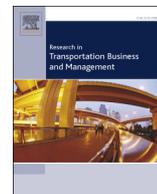




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Reducing GHG emissions from ships in port areas

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ABSTRACT

Climate change has recently received more attention in the shipping sector. This is mainly due to a growing demand for reduced global emissions and the fact that shipping is one of the fastest growing sectors in terms of greenhouse gas (GHG) emissions. In parallel, ports have started to introduce programmes and policies to address these emissions.

This study aims at quantifying potential reductions of ships' emissions of GHG from efforts implemented by ports. Building on a model that calculates GHG emissions from ships in various scenarios for individual ports, different kinds of measures for emission reductions are investigated for diverse types of vessels and parts of the port area. A case study of the ship traffic to the Port of Gothenburg is performed. Projections of ship emissions in the port area for 2030 are made, and three scenarios, '1. Alternative fuel', '2. Ship design' and '3. Operation', are analysed. These scenarios are related to a business as usual development. GHG emissions from ships in the port are projected to increase by 40% to 2030 in a business as usual (BAU) scenario. The highest reductions were seen in the 'Operation' scenario where GHG emissions were 10% lower than the BAU level.

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1. Introduction

International shipping contributes with approximately 2.4% of global anthropogenic greenhouse gas (GHG) emissions, and its share is expected to increase in the future (International Maritime Organization, 2014). GHGs from shipping include mainly carbon dioxide (CO₂), methane (CH₄) and dinitrogen oxide (N₂O), of which CO₂ dominates the global warming potential. In addition, ships emit also other gases with climate impact such as black carbon which has a warming potential and sulphate particles which have a cooling effect. The goal to keep the increase in global mean temperature below 2 °C, as agreed upon in the Copenhagen Accord (UNFCCC, 2009), is becoming more and more difficult to reach since global action has been slow and all greenhouse gas emitting sectors would need to decarbonise to a high degree within a few decades. Energy efficiency measures are important to implement in order to decrease fuel use, but significant reduction in GHG emissions can be achieved only by the replacement of fossil fuels with renewable fuels. Energy efficiency can be defined by the relationship between the benefit or performance of a service and the energy input. By this definition, there are measures that reduce the GHG emissions of a service that do not necessarily increase energy efficiency. Changing from a fossil fuel to a renewable fuel is one example of this, as the amount of energy input does not necessarily change at a fuel shift. Fossil fuels store carbon from the atmosphere for long-term time horizons. The hydrocarbons in fuels from renewable

sources, biogenic fuels, store carbon for short-term time horizons and CO₂ originating from these sources will not influence the long-term build-up of CO₂ in the atmosphere. In this paper, the term GHG reduction measure is used to describe both energy efficient measures and measures where fossil CO₂ is replaced by biogenic CO₂.

Environmental impact from international shipping has traditionally not focussed on climate change. The reasons are, according to Gilbert and Bows (2012), more obvious local pollutants such as nitrogen and sulphur oxides; the omission of shipping from national inventories under the Kyoto Protocol; its importance in globalisation; and its reputation as the most energy efficient mode of transportation. Main topics for discussions have instead been, for example, the usage of toxins in antifouling paints, release of non-indigenous species with ballast water and fouling, noise, and emissions of combustion gases and particles to air. However, the problem of climate change has received increased attention in the shipping sector (Gibbs, Rigot-Muller, Mangan, & Lalwani, 2014). One important reason for this is that the global community has recognised the need to reduce global emissions and the fact that shipping is expected to become one of the fastest growing sectors in terms of greenhouse emissions, along with the aviation sector (Gilbert, Bows, & Starkey, 2010).

There has in recent years been a focus on slower speed at sea in order to reduce fuel consumption, and there has indeed been a significant reduction in CO₂ emissions per transport work as a consequence of slow steaming. However, the average speed of the world fleet depends foremost on freight rates and on the bunker price (Faber, Nelissen, Hon, Wang, & Tsimplis, 2012; Smith, 2012). There is thus a risk that ships will speed up again and that emissions will increase when freight

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rates rise in times of prosperity. There has also been a focus on improved ship design, for example the development of the energy efficiency design index (EEDI) at the International Maritime Organization (IMO).

Only relatively recently, ports have started to introduce specific programmes and policies to address greenhouse gas emissions (Gibbs et al., 2014). These programmes are important since a significant share of CO₂ emissions from shipping are derived from the time the ships stay in ports. Emissions from ships at berth have been estimated to approximately ten times greater than those from the ports' own operations and there is a greater potential to reduce GHG emissions from ships in port than from port activities on the landside (Habibi & Rehmatulla, 2009). Villalba and Gemechu (2011) calculated emissions in the port of Barcelona and found that the emissions of GHG from the port area originated in equal amounts from the ships and from land-based activities. Gibbs et al. (2014) also consider the impact of the hinterland traffic, and found that its emissions are substantially less than from shipping, but higher than emissions from the port operations.

There are several arguments for ports to address CO₂-emission reductions for visiting ships. The main reason is the expected benefits from reducing climate impact by CO₂ emissions. Positive side effects of using less fuel during a ship call are reductions in emissions of nitrogen oxides, sulphur dioxide and particles, which all cause health risks and can have significant effect on the air quality in the port city. These arguments are, to a large extent, driven by the port cities' political goals on environmental standards. A city's efforts to reach political climate goals can be allocated to different activities within the city's jurisdiction, as is done in the City of Gothenburg. Private ports might not be driven to the same extent by political goals. Important for all ports, however, are the aspects of potential marketing benefits as a proactive green port.

Port authorities can influence GHG emissions from ships by supporting systems and technologies and implementation of incentive programmes that facilitate fuel savings within the port area (Acciaro, Ghiara, & Cusano, 2014). Ports can, for example, manage and administer the supply of alternative fuels and onshore power connections, and use environmentally differentiated harbour dues for ships. There are several examples of port initiatives with incentives for shipping companies to operate their ships with lower GHG emissions, e.g. the vessel speed reduction programme of Port of Long Beach and Port of Los Angeles, the EcoAction Programme and Blue Circle Award in Port of Vancouver, and reduced port fees within the scope of the World Port Climate Initiative.

This study aims at quantifying potential reductions of ships' emissions to air of greenhouse gases. Only reductions of emissions within the port area are considered. A model for calculating emissions from ships in ports and the effects of potential abatement measures has been developed. The model is suitable for scenario analyses of how to reduce GHG emissions from ships in specified ports. In this work the Port of Gothenburg on the Swedish West Coast has been used as a case study. The data used for the analysis include port call statistics and technical data for individual ships. The model differentiates between ship types and ship sizes, as well as between five operational modes. The measures included in the calculations are transition from fuel oil to other fuels such as natural gas and methanol; increased possibility to use on-shore power supply (OPS) for vessels at berth; rejuvenation of the fleet and various measures for more fuel efficient ship operation. The measures are sorted into three categories: alternative fuels, ship design and operation. The model requires an assessment of the likelihood of implementation of a certain measure for different ship types and ship sizes. Scenarios consist of combinations of measures with different degrees of implementations for different sections of the fleet.

A number of studies have looked at emissions of green-house gases in ports. Goldsworthy and Goldsworthy (2015) have produce a model using AIS data to describe ship movements and operating modes capable of providing a comprehensive analysis of ship engine exhaust emissions in a wide region which contains numerous ports, and have applied it to the Australian coast and Australian ports. Tichavska and

Tovar (2015) used AIS data and the STEAM emission model (see e.g. Jalkanen et al., 2009) to calculate emissions from cruise ships and ferries in Las Palmas Port. Chang, Song, and Roh (2013) calculated the emissions from ships in the port of Incheon, Korea, and compared a bottom-up approach with a top down approach and found large discrepancies. Different policy options to influence GHG emissions in ports are discussed by Linder (2010) and Merk (2014).

2. Potential GHG reduction measures

Maritime transport is often pointed out as a highly energy efficient mode of transportation. Incentives for further improvements are constantly adopted by the industry, even though empirical studies suggest that there are cost-effective measures available that are not always implemented due to existence of barriers to energy efficiency (e.g. Johnson, Johansson, & Andersson, 2014; Rehmatulla & Smith, 2015). These barriers are mechanisms that prevent investment in technologies that are both energy efficient and economically efficient (Sorrell, O'Malley, Schleich, & Scott, 2004). Examples of barriers are related to the types of charter contracts that hinder an implementation, lack of reliable information on cost and saving, and lack of direct control over operations (Rehmatulla & Smith, 2015). Short planning horizons, financial risks by investing in new technology and work methods, a second-hand value of the vessel that does not reflect investments in energy efficient equipment, lack of life cycle approach when constructing vessels, and transaction costs are all further examples of barriers (Styhre & Winnes, 2013).

2.1. Alternative fuels

Fuel shifts from fossil to bio fuels are far from realised in the transport sector. In shipping, an increased use of liquefied natural gas (LNG) and methanol provides potential bridges in order to reach low carbon ship transports (Bengtsson, Fridell, & Andersson, 2012). Liquefied natural gas is increasingly adopted as a marine fuel also for ships other than LNG carriers. The technical solution often includes a dual-fuel engine that can run on either LNG or fuel oil, and which always uses a minor amount of fuel oil for ignition when using LNG. Liner service ships and ships in regions with an established infrastructure for LNG will more easily adopt LNG as fuel. A shift from marine fuel oils to LNG leads to significantly reduced emissions of NO_x, SO₂ and particulate matter. The CO₂ emissions are about 25% lower compared with fuel oils but the total emissions of CO₂-equivalents are not necessarily in favour of LNG as a marine fuel since a few percent of the fuel methane slip through the combustion process unburnt (Bengtsson, Andersson, & Fridell, 2011). Methane is a potent GHG; 72 times more powerful than CO₂ in a 20 year perspective and 25 times as powerful from a 100 year perspective (Forster et al., 2007). The differences for the two time horizons are due to differences in residence times and reactivity of CH₄ and CO₂ in the atmosphere.

Methanol is another fuel that similarly to LNG can be used in marine dual fuel engines. Methanol is in an earlier state of market introduction but full scale tests have been started: the Swedish ship owner Stena Line gradually replaces all conventional engines on board the RoPax ferry Stena Germanica to methanol engines. Methanol is easier to store and distribute than LNG since it is a liquid at room temperature. The production and combustion of methanol cause lower emissions of CO₂-equivalents (per energy unit of the fuel) than LNG fuel in a time horizon of 100 year but it performs worse than LNG in a 20 year time horizon. The total global-warming potential per combusted energy unit of methanol is very similar to that of conventional marine fuel oils from a life cycle perspective (Brynnolf, Fridell, & Andersson, 2014).

Major reductions of emissions of GHGs from marine engines can be achieved by replacing fossil fuels with renewable ones. The availability of biofuels for the transport sector is however limited. According to statistics from the International Energy Agency, total world production

of bio-gases and liquid biofuels for industrial purposes were approximately 72 million tonnes oil equivalents (MTOE) in 2012 (International Energy Agency, 2014). Of these, 3.4% were used as fuels in the transport sector. The same year the oil consumption by international shipping was estimated to 257 million tonnes (International Maritime Organization, 2014). Introduction of biofuels on the market is also possible through blending with fossil fuels.

Connecting to on-shore power supply for ships at berth is an option that can give significant reductions in the emissions of local air pollutants from auxiliary engines in port. The potential to also reduce emissions of GHGs is high but depends on the source of electricity. The use of, e.g., wind or hydro generated electricity will give large reductions in the GHG emissions, while the use of coal power may give even higher emissions than electricity generated on board the ship. Ports and ship owner/operators jointly decide on investments in OPS solutions. This is mainly due to high capital costs for both sides. Ship owners with ships in liner service might still experience long-term financial benefits from these investments depending on electricity versus fuel prices and on potential negotiated port due rebates.

2.2. Design related measures

The ship design process consists of constant trade-offs between different requirements on design parameters. A high environmental performance is often associated with additional costs and new green technologies are often opted out. Emissions of climate gases are not necessarily part of the same trade-offs between environment and cost. Saving fuel is an efficient measure to reduce both operational costs and emissions of GHGs. Ship designers have long aimed at delivering energy efficient designs and in times with high oil prices, the economic incentives become even more evident. The ability to reduce ship emissions of carbon dioxide through design measures has been estimated at up to 50% (International Maritime Organization, 2009). This large potential can be realised only if the vessels are designed for a relatively low speed, and then operate according to design specifications (International Maritime Organization, 2009).

Port incentive programmes that favour and attract ships with modern and GHG efficient designs could have some effect. However, no programmes targeting ship design improvement are known to the authors and large effects are more likely a result from international regulations than from individual port programmes. A new international regulation on energy efficient designs entered into force in 2011. According to the decision of the IMO marine environmental protection committee, all new ships from 1 January 2013 and onward are obliged to report an 'Energy Efficiency Design Index' (EEDI). The index gives a

ship's estimated emissions of CO₂ per unit of traffic work (i.e. g CO₂/dwt*NM). The index is calculated with a function including installed engine power and the expected power at design speed as parameters. For each ship type a reference line has been calculated that approximately corresponds to a fit to the EEDI for existing ships in 2009 as a function of ship size. No new built ships are allowed to have an EEDI higher than the reference line. The regulations are tightened in three steps, a first time in 2015 a second in 2020 and a third in 2025. Recent studies show that designs have improved significantly between 2009 and 2015 and often outperform the EEDI reference values for several ship types and sizes (Faber, Hoen, Koopman, Nelissen, & Ahdour, 2015). The operational efficiency is, however, not the same as the design efficiency. This can be expected, primarily since the EEDI does not consider fill rate and is a function of dwt rather than the cargo capacity; it is a measure of ship design rather than transport work. Furthermore, there may be differences in the assumed engine work used to calculate EEDI and the actual engine work during operations, in large related to ship speed. Since the average age of ships is approximately 22 years (UNCTAD, 2014), the actual effects of the EEDI regulation on emissions will only happen gradually and slowly.

Small vessels today have a higher potential to be optimised with respect to fuel consumption than large vessels, as less resources have been invested in the optimization of small vessels historically (International Maritime Organization, 2009). Optimization of hull shape and superstructure can be assumed to reduce fuel consumption by 15% for all types of vessels of over 5000 gross tons. The corresponding figure for vessels less than 5000 gross tons is 20% (International Maritime Organization, 2009). These reduction potentials are only valid for emissions of individual ships. In absolute amounts a 15% reduction of CO₂ on a large ship may well be bigger than a reduction by 20% on emissions from a smaller vessel. Improvements to the propulsion machinery, auxiliary machinery and peripheral systems on ships are generally assumed to be optimised so that CO₂ emissions are reduced by 15%. This means that potential reductions beyond EEDI requirements in principle only apply to small ships.

The significant economies of scale in shipping mean that the marginal cost decreases with increased transport volumes. As a result, there is a trend towards bigger ships in both ocean shipping and in the short- and medium distance trades (UNCTAD, 2014). Large ships are also more energy efficient, calculated as fuel consumption per transported load unit, than smaller ships within a specific ship category (Smith, Prakash, Aldous, & Krammer, 2015). In order to reduce emissions in ports, the benefits of accommodating large ships over smaller sized ships are less apparent, partly due to longer times at berth for loading and unloading operations.

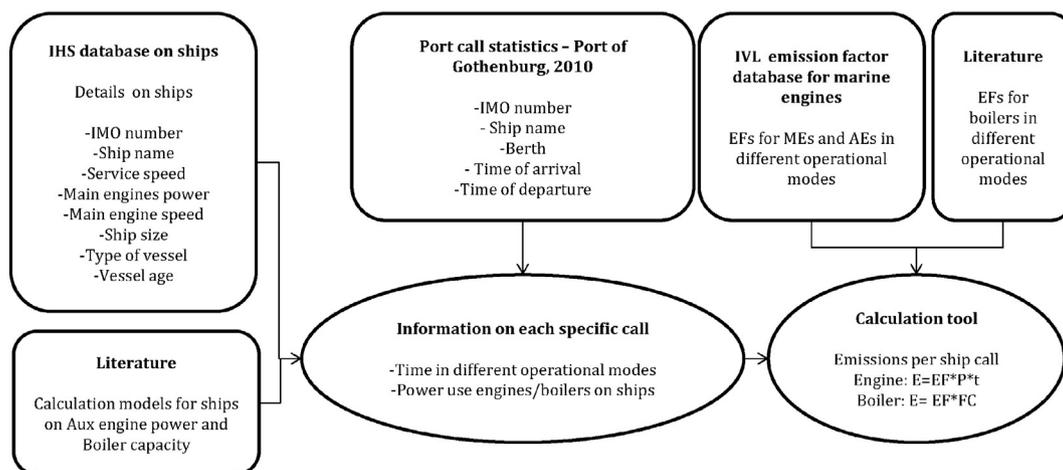


Fig. 1. Overview of data sources for the calculations of emissions. The emissions, for each ship call, are calculated for five different operational modes. For each operational mode, the emissions are the product of an emission factor (EF), engine power (P) and time (t). Main engine is abbreviated (ME) and auxiliary engine (AE). For boilers the emissions are calculated as the product of emission factor (EF) and Fuel consumption (FC).

2.3. Operations related measures

Operational measures generally have low investment cost and can be applied to all ships, and can give substantial effects on the fleet's fuel consumption in a short time (Eide, Longva, Hoffmann, Endresen, & Dalsøren, 2011). Operational measures to reduce GHG emissions rely on both efficient port and ship operations, and are often considered to entail larger GHG reductions than measures of other characters. This depends, to a large extent, on the potential of slow steaming. However, within the port area other operational measures than slow steaming may gain in relative importance.

A vessel's fuel consumption is strongly dependent on ship speed. Simplified, the fuel consumption per unit of time can be described by a third-degree function of the vessel's speed, so that a speed reduction by 10% reduces the consumption by 27% (Faber et al., 2012). The relationship between ship speed and fuel consumption per unit of time is thus close to cubic, and a small decrease in speed entails a relatively large impact on the fuel consumption. However, ships are built to operate at a certain design speed, and the fuel saving potential related to slow steaming depends in practise largely on the ship's design speed and present service speed. Further, if the ship is already going slow, further speed reduction might damage the engines or even increase the fuel consumption (Johnson & Styhre, 2015).

Turnaround time in port is mainly depending on terminal opening hours, stevedore operations, availability of berths and access to and efficiency of loading and unloading equipment. Speed reduction at sea due to shorter time in port is one of the measures deemed to contribute to large reductions in emissions at limited costs (Eide et al., 2011). Faber et al. (2009) have estimated that up to 10% GHG emission reduction is possible, and Bazari and Longva (2011) determined that the potential ranged from approximately 10–20% depending on the vessel type and size. Johnson and Styhre (2015) showed that a conservative estimate of one to four hours of reduced time per port call would lead to a reduction in fuel use of 2–8% for two bulk ships operating in the tramp market.

It is however not evident how the shipping company in practise can make use of the time saved by shorter turnaround time. Depending on market conditions, slow steaming is not always the most profitable option. In times of prosperity, it can be more beneficial for the shipping company to keep speed high and instead increase the transport work performed. Thus, this effect is mainly dependent on the economic climate and the demand for shipping services (Lindstad, Asbjørnslett, & Strømman, 2011).

Another potential operational measure is eco-driving which means that officers on board are educated on how to navigate more economically, e.g. by avoiding sharp load increases on the engine. For trucks a long term maximum potential for fuel savings is estimated at 5%, the corresponding value for ships remains unclear.

3. Method

This study starts with an inventory of the GHG emissions from the ships in Port of Gothenburg for the year 2010. Emissions from five operational modes are summed in order to account for ship operations in the traffic area: "in fairway channel"; "at anchor"; "in port basin"; "manoeuvring"; and "at berth".

Port call statistics were received from the port, including IMO number, ship name, berth number and time spent at berth for each ship call. The IMO numbers were used to match each port call to ship specifications from the IHS database Sea-web (online ship details register of all ships of 100 GT and above), including information about main engines, size and type of the vessel, and vessel age. An overview of the method is presented in Fig. 1.

For each ship call, engine emissions are calculated as the product of an emission factor, the utilised engine power and time. Emissions of the GHGs CO₂, CH₄ and N₂O are included in the calculations and calculated

Table 1

Alternatives to conventional marine fuels for propulsion and on board electricity included in the analysis.

Measure	Calculated as:
Conventional fuel to LNG (liquefied natural gas)	Difference between emissions of CO ₂ equivalent from a time horizon of 100 years and 20 years, respectively, from ships using heavy fuel/marine gasoil and emissions from ships using liquefied natural gas. Only emissions from combustion, i.e. no emissions from upstream processes, are included.
Conventional fuel to LBG (liquefied bio gas)	Difference between emissions of CO ₂ equivalents from a time horizon of 100 years and 20 years, respectively, from ships using heavy fuel/marine gasoil and emissions from ships using liquefied biogas. Only emissions from combustion, i.e. no emissions from upstream processes, are included.
Conventional fuel to methanol (MeOH) from fossil sources	Difference between emissions of CO ₂ equivalents, from ships using heavy fuel/marine gasoil and emissions from ships using methanol produced from LNG. Only emissions from combustion, i.e. no emissions from upstream processes, are included.
Conventional fuel to methanol (MeOH) from renewable sources	Difference between emissions of CO ₂ equivalents, from ships using heavy fuel/marine gasoil and emissions from ships using methanol produced from renewable sources. Only emissions from combustion, i.e. no emissions from upstream processes, are included.
Connection to on-shore power supply	Ships connect to shore side electricity when at berth. In total 40 min are used for handling the connection and disconnection for each call. During this time, auxiliary engines are running.

as CO₂ equivalents (CO₂-e). CO₂ is in general the dominating GHG from marine engines, CH₄ and N₂O represent only around 1–2% of CO₂-e emissions. A detailed description of emission calculations for marine engines can be found in Cooper and Gustafsson (2004). The emission factor for methane slip from LNG combustion is from Brynolf (2014). For ships where data are missing in the Sea-web database, algorithms estimating engine power from information on ship types and ship sizes are used. These algorithms are adjustment functions of large statistical selections, as described in Sjöbris, Gustafsson, and Jivén (2005). Boiler emissions are calculated from generic figures on fuel consumptions for different ship types and sizes according to data from the Port of Los Angeles (2011). Any measures already in use in the port are accounted for in the calculations. This includes the relatively extensive use of on-shore power supply (OPS) in Port of Gothenburg.

The projections of future emissions depend on a number of assumptions. Global total emissions are expected to increase due to a higher demand for shipping services. The International Maritime Organization (IMO) estimates that 810 Mtonnes CO₂ emitted globally per year in 2012 will become between 910 and 1200 Mtonnes in 2030 (International Maritime Organization, 2014). On a local scale, projections cannot be based solely on assumption on future global scenarios. Projections for the CO₂ emissions from ships in the Port of Gothenburg are based on increases in ship traffic fuel consumption in the port of 1.45% per year between 2010 and 2030. This is an average value between forecasts for global and regional shipping (HELCOM, 2009;

Table 2

Design related measures for reduced emissions of GHG included in the model.

Measure	Calculated as:
Increased share of modern ships	Ships perform according to EEDI 3 levels.
Ship design improvements above EEDI 3 levels	Small ships have potential to surpass the EEDI requirements. Maximum reductions of CO ₂ are estimated to be up to 35% for the smallest vessel sizes (GT < 5000).

Table 3
Operational measures for reduction of GHG included in the model.

Measure	Calculated as:
Reduced speed	Speed reduction from stated design speed to 10 knots in the fairway channel. Ships with design speeds of 10 knots or less are not expected to change speed
Reduced lay time at berth	Reduced time at berth by 10%. No assumption is made on speed reductions associated with this measure.
Reduced lay time at anchor	Reduced time at anchor by 10%. No assumption is made on speed reductions associated with this measure.
Eco-driving during manoeuvring	A reduction of emissions of CO ₂ by 5% during the manoeuvring phase of the ship call.
Faster connection to OPS	Speeding up connection/disconnection to the electricity grid to 20 min/call instead of the normal duration 40 min/call, for ships using on-shore power supply.

International Maritime Organization, 2009; McDaniel & Kyster-Hansen, 2011; and Swedish Transport Agency, 2011) and the increase in Swedish consumer price index for transport the last ten years. In the business as usual (BAU) scenario, no GHG reductions additional to those from the energy efficiency design index (EEDI) regulations are assumed for visiting ships. After the inventory and the forecast in the BAU scenario, the GHG reduction potential is assessed by applying a number of measures in a series of scenarios. The studied measures are divided into the categories 'alternative fuels', 'design measures', and 'operational measures'.

An overview of the studied alternative fuel options and a brief explanation of the calculations are given in Table 1.

The measures related to design that are included in the model consider potential improvements from increased traffic of modern ships and also higher performance of small ships, see Table 2.

Five options that aim at improvements of ship and port operation have been considered in the analysis. An overview of the options and a brief explanation of calculations for each one of them are given in Table 3.

4. Scenarios for Port of Gothenburg

Based on the projection of traffic increase in the region to year 2030, four main scenarios have been analysed for the Port of Gothenburg. A business-as-usual (BAU) scenario is used as a baseline to which the remaining scenarios are related. Each scenario is intended to represent a strategy of the port to either promote fuel shifts, design measures or operational measures. It is apparent that ports' potential to influence the implementation rates of measures in the different scenarios varies greatly.

4.1. Port description

The Port of Gothenburg receives between 10,000 and 12,000 calls per year, including bunker ship traffic, and additionally between 1000 and 2000 ships pass to and from ports upstream the river Göta Älv. It annually handles approximately 900,000 containers, 20 million tonnes of petroleum, half a million RoRo units and 1.5 million passengers. This makes the port the largest cargo port in Scandinavia. The port has since 1998 rewarded ship operators with high environmental performance through a system with environmentally differentiated port dues. The port offers connections to the on-shore power grid at six

RoRo berths and has installed a windmill that supports the grid with electricity corresponding to the ships' power needs.

4.2. Inventory of GHG emissions—year 2010

The number of ship movements per ship category and size is presented in Table 4. The first row of the table indicates total number of ship calls including passing ships of different ship types based on ship call statistics from the Port of Gothenburg for year 2010. The second row in Table 4 presents calculated amounts of GHG emissions from ships calling the port. These calculations are carried out on a 'per call' basis according to the description in the method chapter. The port receives ships of all size classes and the following rows in Table 4 present how the CO₂-equivalent emissions are divided between different classes of ships in terms of their gross tonnage.

The call frequency of individual ships is of high relevance to the potential implementation of different measures. Ships that visit the port 10 times or less per year contribute to 37% of all emissions of CO₂-e. In Fig. 2 the contribution of CO₂ from different ship types are split into categories based on frequency of calls.

Another important aspect is where emissions occur in the port, i.e. "in fairway channel"; "at anchor"; "in port basin"; "manoeuvring"; or "at berth", since emissions from different operational modes are targeted by different measures. Fig. 3 shows how the CO₂-e emissions are divided into the different operational modes. A majority of CO₂-e emissions, 53%, in the Port of Gothenburg inventory, originate from the "at berth" mode. Emissions from ships in the fairway channel account for 23% of total CO₂-e emissions, while emissions from anchored ships, ships in the port basin, and ships manoeuvring to and from quay-side position account for 10%, 9% and 5% respectively.

In the category ">100 calls", a relatively large share of the emissions can be attributed to ships in the fairway channel. This is in part due to that there are many ferries and RoRo vessels in Port of Gothenburg with large main engines within the category ">100 calls". This has resulted in a high level of emissions in fairway channel for this category. There is also a supply of on-shore power to approximately 2300 calls per year of the ships in this category of high frequent visitors. This reduces emissions from these ships at berth. The total CO₂ emissions in the port divided between ship operational modes and frequency of calls is presented in Fig. 4.

For ships in the category "1–10 calls", the emissions from ships at berth and at anchor dominate total emissions.

4.3. Projections for the future

The scenario building needs to consider the specific composition of ship types in a port. Another important aspect is the port's respective shares of liner services and tramp shipping. Ships in liner service are more likely to use on-shore power supply and fuels without widely established supply infrastructure than ships in tramp shipping. Port incentives that favour energy efficient ship designs can also be assumed to have a higher impact on ships with frequent visits to the port. The size of an economic incentive is directly correlated to the number of visits, while a cost for an innovative design feature is a one-time expenditure. Incentives targeting operational measures are more likely to have a high impact throughout the fleet since such incentives are less dependent of

Table 4
Number of ship movements of different ship categories and their CO₂-e emissions in Port of Gothenburg 2010.

	Ferry/RoRo	Container	Dry and liquid bulk	Cruise	General cargo	Bunker ships	Other	Total
Number of ship calls including passing ships	4297	1211	3007	41	1343	3600	177	13,676
Emissions of CO ₂ -equivalents (tonnes), 2010	85,800	30,200	79,800	1450	4360	9330	3600	210,000
CO ₂ -eqv emissions from ships <5000 GT, (%)	0	2%	16%	1%	69%	100%	30%	12%
CO ₂ -eqv emissions from ships 5000–30,000 GT, (%)	65%	54%	53%	23%	31%	0	27%	55%
CO ₂ -eqv emissions from ships >30,000 GT, (%)	35%	45%	31%	76%	0	0	43%	33%

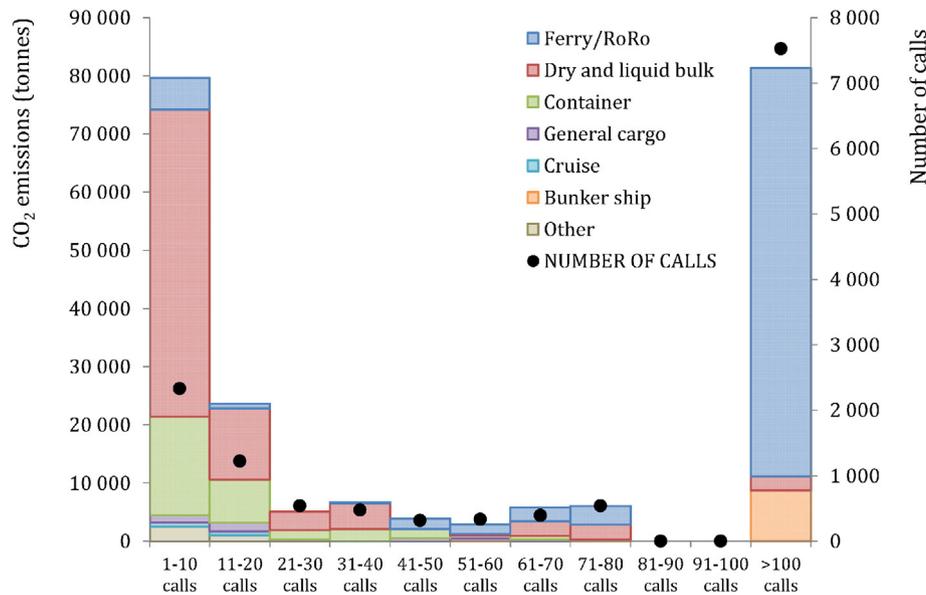


Fig. 2. CO₂-e emissions in categories based on frequencies of calls and passing ships in Port of Gothenburg 2010. The number of calls in the different categories is indicated.

ship type and trade. Further, ships in tramp service often have more time waiting in the port area, e.g. for berth availabilities and pilots. Waiting times can be directly influenced by ports.

In the BAU scenario, the age distribution of ships in 2010 is assumed not to change to year 2030, and the potential GHG reductions according to EEDI regulations are assumed to correspond to actual operational improvements. Thus, operational effects from design improvements are included in the BAU scenario. An introduction of LNG as a fuel for ships in the port corresponding to 2% of fuel used is assumed based on current LNG fuelled ships on order and a relatively high demand for the technology in the Sulphur Emission Control Area (SECA) where Port of Gothenburg is located. In total, emissions of CO₂-e by 2030 in a business as usual scenario are approximately 255,000 tonnes.

Three additional scenarios are studied. These scenarios are based on assumptions of technical feasibility, regulatory aspects and potential influential power of the port. The scenario setup is intended to provide a picture of an ambitious attitude towards reduction in GHG emissions up to 2030 within realistic boundaries. The scenarios are however based on theoretical assumptions and should not be coupled to Port of Gothenburg specifically. Each scenario includes potential emission reductions from a specific category of measures. The first scenario, “Fuel”, considers reductions in emissions through potential fuel shifts. The second, “Design”, considers emission reduction potentials through attracting more modern ships to the port. The third scenario, “Operation”, considers operational measures. The explicit assumptions of scenarios 1 to 3 are given in Table 5.

Scenario 1, “Fuel”, estimates potential results on GHG emissions if a port decides to facilitate increased use of alternative fuels. A 15% transition to LNG/LBG is assumed based on the 3rd IMO GHG report (International Maritime Organization, 2014). A relatively high share of LNG is motivated by SECA rules and the benefits of LNG as a low sulphur and cost efficient fuel choice. A 1% biogas corresponds to a blend-in in LNG of approximately 7%. The blend-in ratio is highly uncertain, and will have a potentially large effect on the overall emissions of CO₂-e. Methanol is introduced as marine fuel in 2015 on one ferry in frequent traffic to the port. In scenario 1 it is assumed that methanol fuel is used by two ships in 2030 corresponding to 2% of the total fuel consumption of ferries in the port. A blend in of bio-methanol of 10% is assumed. The price premiums for bio-alternatives over fossil LNG and methanol are high and they cannot be considered viable options for full implementation in 2030.

On-shore power supply today corresponds to a 10% reduction in CO₂-e emissions from the Ferry/RoRo category. This ship type category is still the most suitable for further installations of the technology if considering frequent visits as a primary decision parameter. OPS installations for Ferry/RoRo ships are assumed to have doubled by 2030, leading to further reductions in CO₂-e corresponding to approximately 6000 tonnes. Ships in frequent traffic to the port are considered most likely to adopt the OPS technology due to the higher potential of return on investment costs. The only other ship category in liner traffic and with frequent visits to the port is container ships. Calls to the Port of Gothenburg by individual container ships are however fewer than for the Ferry/RoRo ships using OPS. It is assumed that the potential emission reductions from OPS are lower for container ships than for Ferry/RoRo ships. We have assumed a 5% reduction of GHG emissions from implementation of OPS for container ships by 2030. The assumption is considered realistic since many container ships have explicit liner character and a potential for standardised solutions in series of sister ships, another common feature of container shipping. For cruise ships there is increased pressure from authorities and customers for lowering the climate impact and use of OPS will have a relatively large impact on this category due to the high electricity demand also at berth.

Scenario 2, “Design”, occurs when the port makes efforts to attract modern ships with more energy efficient designs. In practise, this is a complex task as many factors influence how a ship operator distributes the company fleet. It is assumed that it is difficult for a port to

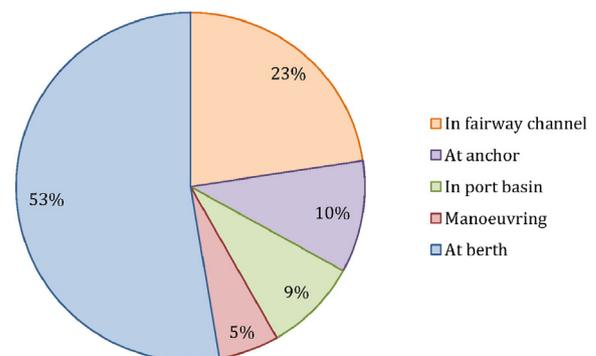


Fig. 3. Emissions of CO₂-e, divided in five different operational modes, from ships to and from Port of Gothenburg in 2010.

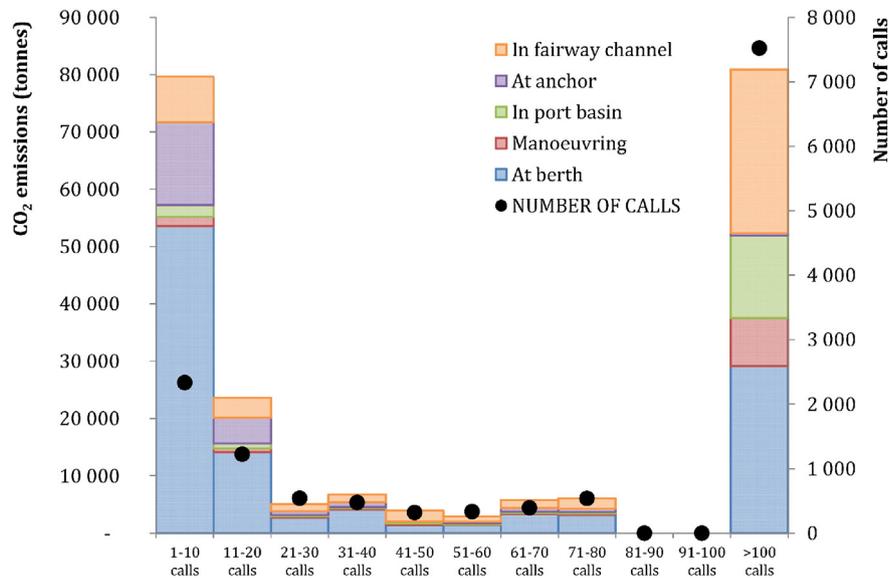


Fig. 4. Shares of CO₂-e emissions from different operational modes in the Port of Gothenburg 2010. The number of calls in the different categories is indicated.

accomplish significant adoption of this measure among visiting ships. Successful implementation is most likely relying on regional efforts. A CO₂-e emission reduction of 5% throughout the fleet is assumed in this study for Port of Gothenburg.

Small ships are expected to improve designs more rapidly than the average fleet based on the assumption that there have been fewer improvements historically, and the potential to progress is therefore higher. A potential reduction of 25% from small ships is assumed.

In Scenario 3, “Operation” CO₂-e emission reductions from speed reductions to 10 knots in the fairway channel, a total travelling distance of 8.7 NM, are assumed for 80% of the visiting ships. Only the Ferry/RoRo ships are expected to have a lower compliance to low speed adjustments due to passenger requirements on fast transportation. For example, the high-frequent RoPax services between Gothenburg and Denmark and the continent need to go around 20 knots in order to be a viable transport option to passengers. The “Operation” scenario also includes assumptions on reduced lay time at berth by ten percent with an overall implementation of 50% by all ship type categories except cruise ships. It is assumed that the cruise industry depends on offering their customers a reasonable time ashore in the visited port cities. A reduction of GHG-emissions from shorter times at berth for cruise ships is therefore not considered applicable in this scenario. Similar assumptions on implementation rates are made for time at anchor for

relevant ship types. The scenario further includes assumptions on full implementation of eco-driving, with economic navigation during the brief manoeuvring period, and faster connections to OPS for relevant ship types.

5. Scenario findings

The business as usual scenario assumes a yearly increase in traffic of 1.45% for all ship types and ship sizes. With this increase, the CO₂-e emissions in total are calculated to be 255,000 tonnes in 2030 in the Port of Gothenburg.

A 3% reduction in CO₂-e results from Scenario 1 “Fuel” when considering the global warming potential with a 100 year time horizon. If viewed in a 20 year time horizon, the CO₂-e emissions instead increase by 3%. The fuel shift to LNG has the highest relative importance on the changes, and the small introduction of LBG assumed for 2030 contributes to 17% of the total global warming potential reductions in Scenario 1 “Fuel”, when considering effects from a 100-year perspective.

Design efforts accomplish 1% reduction in total CO₂-e emissions. Within the time horizon of this study, significant improvement beyond the baseline is unlikely. The two measures included in scenario 2, “Design”, contribute equally to the emission reductions.

Table 5

Presentation of the assumed implementation by 2030 of CO₂-e reductions from measures in the studied scenarios.

	Ferry/RoRo	Container	Dry and liquid bulk	Cruise	General cargo ^a	Other
<i>Scenario 1 “Fuel”</i>						
Liquefied natural gas	14%	14%	14%	14%	14%	14%
Liquefied bio gas	1%	1%	1%	1%	1%	1%
Methanol	2%	0%	0%	0%	0%	0%
Bio methanol	0.2%	0%	0%	0%	0%	0%
On-shore power supply (OPS) – “green electricity”	10%	5%	0%	10%	0%	0%
<i>Scenario 2 “Design”</i>						
Only modern ships	5%	5%	5%	5%	5%	5%
Ship design improvements (only small ships)	25%	25%	25%	25%	25%	25%
<i>Scenario 3 “Operation”</i>						
Reduced speed	50%	80%	80%	80%	80%	80%
Reduced lay time at berth	50%	50%	50%	n.a.	50%	50%
Reduced lay time at anchor	n.a.	n.a.	50%	n.a.	50%	n.a.
Eco-driving during manoeuvring	100%	100%	100%	100%	100%	100%
Faster connection to OPS	100%	100%	n.a.	100%	n.a.	n.a.

^a General cargo ships are mainly passing the port area for transport to or from ports upstream on the river Göta Älv or the lake Vänern.

Table 6
Total emissions of CO₂-e divided between ship type categories in the different scenarios, Port of Gothenburg 2030.

	Ferry/RoRo	Container	Dry and liquid bulk	Cruise	General cargo	Other	Total
Scenario “BAU”	103,000	35,400	104,000	1810	5860	4880	255,000
Scenario 1 “Fuel”—100 year time horizon	99,300	33,700	102,000	1710	5750	4780	247,000
Scenario 1 “Fuel”—20 year time horizon	106,000	35,900	108,000	1820	6100	4980	262,000
Scenario 2 “Design”	102,000	35,000	103,000	1780	5590	4880	252,000
Scenario 3 “Operation”	89,400	30,600	98,000	1490	5260	4610	229,000

Measures targeting operation result in relatively large reductions, in total 10% compared to the BAU scenario. Reduced speed has the largest relative importance in scenario 3, “Operation”. Approximately two thirds of the total reductions of CO₂ emissions are achieved by reduced speed down to 10 knots in the fairway channel.

In Table 6, the total modelled emissions in 2030 from each ship type category is presented for the different scenarios. The category “Dry and liquid bulk” contributes the most to emissions in all scenarios. Largest emission reductions from this category occur in Scenario 3, “Operation”. This scenario results in significantly higher reductions for each individual ship type than the other scenarios. The “Dry and liquid bulk” ships also have a relatively high influence on the total reductions in Scenario 2, “Design”, due to a higher share of small ships than “Ferry/RoRo” and “Container”—the other two ship type categories with high emission levels.

The operational measures that contribute most to the emission reductions in the ‘Operation’ scenario are reduced speed and reduced lay time at berth. The remaining measures in the scenario ‘Operation’ contribute less than some of the measures modelled in the scenarios ‘Fuel’ and ‘Design’. The latter measures include the shift to LNG-fuel (100 year time horizon) and LBG fuel (100- and 20 year time horizon), the introduction of OPS, and the design related measures. The contributions of individual measures are presented in Fig. 5.

The scenario ‘Operation’ includes reduced speed in the fairway channel for all ships, which is the largest contributing measure to CO₂-e emission reductions. Ships with significant power installed in main engines, typically ships in the ‘Ferry/RoRo’- and ‘Container’ categories, will contribute more to emission reductions than ships with smaller engines, which in general also have lower design speed. The emission

reductions from ‘At berth’ in the scenario ‘Operation’ can mainly be attributed to the ship categories ‘Ferry/RoRo’, ‘Container’ and ‘Dry and liquid bulk’, in approximately equal amounts. The reductions from ‘At berth’ depend on fuel consumption in auxiliary engines and boilers, and time at berth.

The total emission reductions divided between operational modes in the different scenarios are shown in Fig. 6. The modelled measures result in larger absolute emission reductions in the operational modes ‘fairway channel’ and ‘at berth’ than in the other operational modes. As discussed above, emission reductions in the fairway entails the largest emission reductions in the modelled scenarios. Emissions from ships at berth are most efficiently targeted with the modelled reductions in time at berth in the scenario ‘Operation’. It is especially difficult for a port to incentivise reductions of emissions at berth from low frequent visitors by other means than reducing the time at berth. Measures with high potential to reduce the emissions from ships at berth include OPS and the use of alternative fuels, preferably with bio-origin. The potential for a large impact from these measures, on low frequent visitors are highly dependent on ports’ potential as administrator of the unconventional marine fuels. Further, it depends on investment incentives for both ports and ship owners. For ship owners such incentives are often proportional to the number of visits to ports that offers the fuel of choice or OPS.

Some of the measures are highly dependent on a regional approach in order for successful implementation and adoption by ship operators. Joint efforts between several ports in a region to offer similar incentives and facilities will increase the incentives for ship owners to invest in new technologies for CO₂ reductions on their ships. A high density of supply points for alternative fuels in a region will increase bunkering

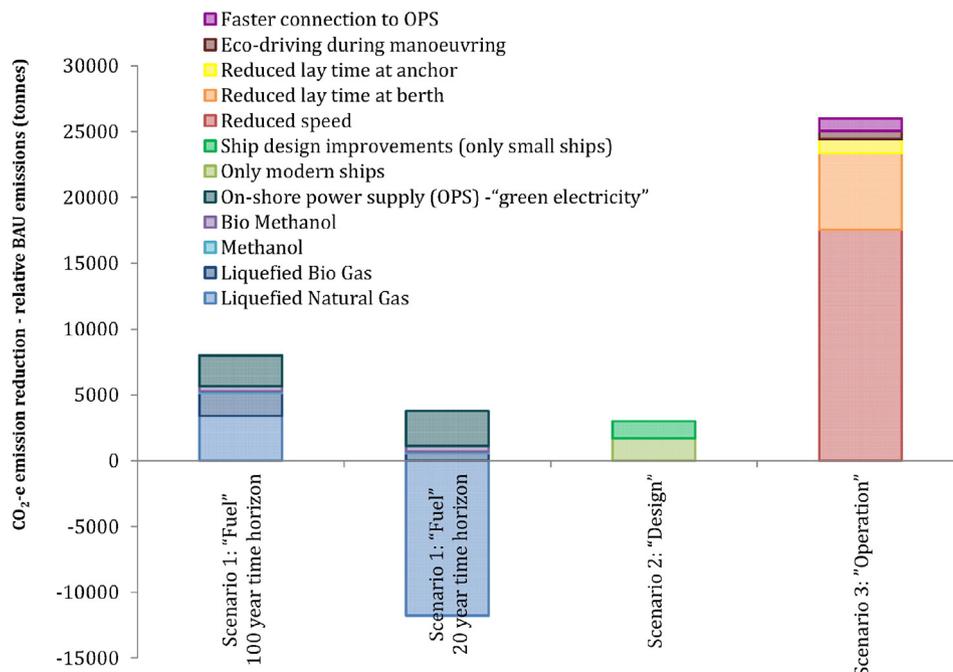


Fig. 5. CO₂-e emission reductions in the different scenarios and the respective reduction contributions of different measures—Port of Gothenburg 2030.

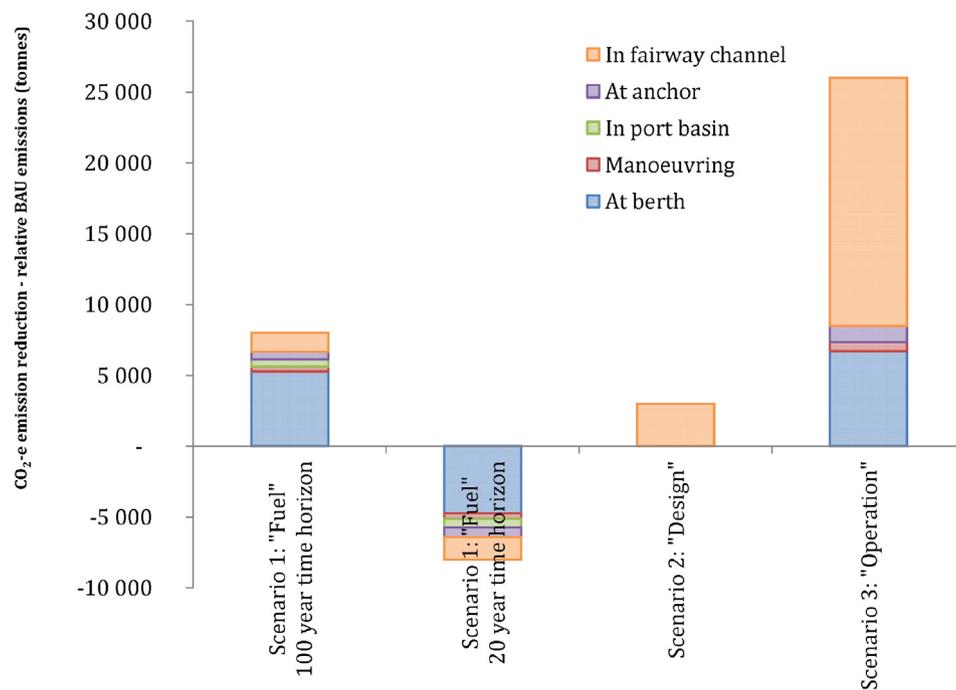


Fig. 6. Importance of different operational modes on total CO₂-e reductions in the scenarios, Port of Gothenburg 2030.

possibilities for ships in both liner- and tramp service that uses e.g. LNG for fuel.

6. Concluding remarks

The scenario analysis identifies difficulties to reach significant reductions of GHG emissions in the studied port by 2030. Close to half of the greenhouse gas emissions from ships can be attributed to ships with less than ten visits per year. This decreases the port's potential to offer significant incentives for fuel shifts, onshore power supply and design improvements, since these measures often are connected with high investment costs. These low frequent visitors can be assumed to be most easily directed by incentives for operational measures that often result in fuel savings instead of additional costs. The biggest challenge for ports with a high share of calls from ships in tramp service is reductions of emissions from these ships when at berth.

In order to reach sustainability objectives for the shipping sector and decrease the CO₂-emissions significantly, steps towards more strict policies and regulations related to alternative fuels and ship design need to be taken on an international level, rather than on a local port level. However, the port can still facilitate the process by using environmentally differentiated port dues and by offering alternative fuel supply in port.

The potentially adverse effect of LNG fuel on global warming potential shall be considered in relation to the reductions in local air pollutants that the fuel shift entails. Since the share of total GHG emissions in port areas are low compared to emissions during voyage, a port city might be more benefited from prioritising local issues before global. The renewable alternatives to LNG and fossil based methanol can significantly reduce emissions of GHG by ships in ports and their effect is visible even at low blend in rates. Similarly, providing OPS from renewable sources to ships can be a highly effective measure to reduce GHG emissions. Using renewable fuels can improve the local as well as the global environmental situation and are well in line with goals on sustainability.

The Port of Gothenburg is a port with possibilities and capacity to receive liquid and dry bulk, general cargo, containers, ro-ro units and passengers. This indicates that the presented method can be used by ports handling various types of cargo flows. As the method is based on ship call statistics, inventories can be completed for any port as long as statistics can be provided on ship identification and times at berth. The simple

statistic data on ships' calls and ship details, used as input to the analyses, is judged to be of high enough quality when addressing a limited geographical area. Enlarging the geographical scopes in CO₂ inventories requires the use of more precise data on, e.g., ship speed where AIS data preferably should be used.

The presented scenario building model is developed in order to study and compare results of combinations of measures for GHG reductions from ships in port areas. This study includes three scenarios based on our best assumptions on implementation rates of different measures. Involvement of stakeholders for scenario building will improve the usability of the model for port administrations by tailoring sets of suitable measures for individual ports.

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