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Energy efficient port calls

A study of Swedish shipping with international outlooks

Linda Styhre, Hulda Winnes

Author: Linda Styhre and Hulda Winnes, IVL Swedish Environmental Research Institute
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IVL Swedish Environmental Research Institute Ltd.
P.O Box 210 60, S-100 31 Stockholm, Sweden
Phone +46-(0)10-7886500 // +46-(0)10-7886590 // www.ivl.se

Preface

Hulda Winnes and Linda Styhre have carried out the research presented in this report. The project Energy efficiency of ship calls (Energieffektivitet vid fartygsanlöp) was funded by the Swedish Energy Agency (Nr 38881-1). Case studies have been carried out in three Swedish ports that have participated in the project: Port of Gothenburg, Ports of Stockholm and Port of Halland. Further, the research scope was expanded to include an international comparative study of three additional ports at different continents: Port of Sydney in Australia, Port of Osaka in Japan and Port of Long Beach in the USA.

A necessary contribution to this project have been data and information received from the port authorities. The Gothenburg Port Authority, the Stockholm Port Authority, the Halland Port Authority, the Port Authority of New South Wales, Port & Harbor Bureau in City of Osaka, and the Ports of Los Angeles and Long Beach are thankfully acknowledged for their support.

The work has resulted in two scientific papers:

1. Winnes, H., Styhre, L. and Fridell, E. (2015) Reducing GHG emissions from ships in a port area, Research in Transport Business and Management, Volume 17, pages 73-82.

2. Styhre, L. Winnes, H. Black, J., Lee, J. and Le-Griffin, H. (2016) Greenhouse gases from ships in port cities – a comparative study of four ports in Australia, Europe, Japan and USA. Proceeding of the World Conference on Transport Research, Shanghai, 10-15 July, 2016.

The last paper was selected for publication in a journal and has been submitted to the Journal of Transport Research: Part D for a review.

Further, the Swedish Maritime Administration has kindly contributed statistics of Swedish ship calls for a full year and assisted us with additional information when asked for.

Summary

The purposes of this study are to calculate the fuel consumption and carbon dioxide emissions for Swedish shipping and for ships in a selection of national and foreign ports. Further, abatement potentials from different measures are analysed and discussed for the different ports and shipping types.

The calculation of the total fuel consumption of Swedish shipping in 2014 resulted in approximately 1 500 000 tonnes of fuel. Significantly more fuel is used at sea than in the port areas. In Sweden, the high-frequency shipping services contribute to a significant amount of the total fuel consumption: the ships that call more than 100 times/year stand for about 19% of the total consumption while ships with less than 10 calls contributed to 38%.

Fuel consumption and CO_2-equivalent emissions for ships in three Swedish ports and three foreign ports are presented and discussed, see table below. Comparisons between the ports can be made only in a context of ship traffic characteristics, e.g. ship types, ship sizes and call frequency. Further, the geographical boundaries of the inventory affect the result. The average CO_2-equivalents per port call reveal great differences between the ports. Port of Long Beach and Port of Sydney have a high ratio of large ships, which partly explain the high average values. Large ships have larger installed main engines and auxiliary engines, and stay a longer time at berth for the loading and unloading of cargo. More than half of the emissions from ships in ports originate from the time at berth.

Ports	Number of ship calls (one year)	Fuel used in port (tonne)	Emissions of CO_2-e (tonne)	Average CO_2-e emission per port call
Gothenburg	5999	46 000	150 000	25
Halland	1728	3 400	11 000	6
Long Beach	2806	74 000	240 000	69
Osaka	12399	30 000	97 000	8
Stockholm	8381	30 000	97 000	12
Sydney	1370	29 000	95 000	70

International shipping contributes to approximately 2.4% of greenhouse gas (GHG) emissions, and its share is expected to increase in the future. This stands in contrast to ambitions to reduce the use of fossil fuels. In order to reach sustainability objectives international steps towards more strict policies and regulations are necessary for the shipping sector. National efforts are in many ways limited to voluntary incentive schemes, and local port initiatives cannot significantly influence overall energy needs and emission levels. However, it is argued that an individual port can still facilitate a transfer to more energy efficient shipping and a reduction of emissions from ships in the port areas. For example, ports can implement environmentally differentiated port dues and give rebates to ship owners that perform well, manage and administer the supply of alternative fuels and on-shore power connections, and work for a reduction of ship speed in the fairway channel. The call frequency of individual ships to the same port is of high relevance to the improvement potential. The diverse conditions between ports suggest that emission abatement measures need to be customer-tailored for specific ports.

Sammanfattning

Syftet med denna studie är att beräkna bränsleförbrukningen och CO_2-utsläppen för svensk sjöfart och för fartyg i ett urval av nationella och utländska hamnar. Vidare analyseras och diskuteras potentiella åtgärder för olika hamnar och sjöfartstyper.

Beräkningar av den totala bränsleförbrukningen för svensk sjöfart år 2014 resulterade i cirka 1 500 000 ton bränsle. Betydligt mer bränsle används till sjöss än i hamnområdena. De fartyg som anlöper samma hamn ofta står tillsammans för en mycket stor del av den totala bränsleförbrukningen i Sverige: fartyg som anlöpte fler än 100 gånger/år stod för cirka 19 % av den totala förbrukningen medan fartyg med färre än 10 anlöp stod för 38 %.

Bränsleförbrukning och koldioxidekvivalenter för sjöfarten i tre svenska hamnar och tre utländska hamnar redovisas och diskuteras i rapporten, se tabell nedan. Jämförelser mellan hamnarna kan endast göras med hänsyn till hamnens trafik och förutsättningar, t.ex. fartygstyper, fartygsstorlekar och anlöpsfrekvens. Vidare påverkas resultatet av den geografiska avgränsningen för emissionsinventeringen. De genomsnittliga emissionerna av CO_2-e per anlöp visar på stora skillnader mellan hamnarna. Hamnarna i Long Beach och Sydney har en hög andel av stora fartyg vilket delvis förklarar de höga genomsnittliga värdena per anlöp. Stora fartyg har stora installerade huvudmotorer och hjälpmotorer samt ligger en längre tid vid kaj för lastning och lossning av gods. Mer än hälften av utsläppen från fartyg i hamn härrör från tiden vid kaj.

Hamnar	Antal anlöp under ett år	Bränsleanvändning (ton)	Emissioner CO_2-e (ton)	Genomsnittlig CO_2-e emissioner per anlöp
Göteborg	5999	46 000	150 000	25
Halland	1728	3400	11 000	6
Long Beach	2806	74 000	240 000	69
Osaka	12 399	30 000	97 000	8
Stockholm	8381	30 000	97 000	12
Sydney	1370	29 000	95 000	70

Internationell sjöfart bidrar med cirka 2,4 % av de globala växthusgaserna och dess andel förväntas öka i framtiden. Detta står i motsatsförhållande till ambitionerna att minska användningen av fossila bränslen. För att sjöfarten skall kunna vara med och bidra till globalt uppsatta klimatmål, krävs skärpta internationella riktlinjer och regler. Nationella insatser är oftast begränsade till frivilliga incitament och lokala initiativ som har liten möjlighet att påverka sjöfartens totala energibehov och utsläppsnivåer. Den enskilda hamnen kan dock fortfarande underlätta en övergång till mer energieffektiv sjöfart och till att minska emissioner från fartyg i hamnområdet. Till exempel kan hamnen implementera miljödifferentierade hamnavgifter, erbjuda alternativa bränslen och elanslutning, samt arbeta för en minskning av farten i farleden. Antal anlöp som enskilda fartyg gör per år till samma hamn är en viktig parameter som avgör lämpliga åtgärder. De olika förhållandena i hamnarna tyder på att åtgärderna måste vara anpassade för den enskilda hamnens förutsättningar.

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1 Introduction

International shipping contributes 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 (CO_2), methane (CH_4) and dinitrogen oxide (N_2O), of which CO_2 dominates the global warming potential. In addition, ships emit, depending on the fuel burnt, other gases with climate impact such as black carbon which has a warming potential and sulphate particles which have a cooling effect (Lee et al., 2006; Eyring et al. 2007; Lauer et al., 2007; IMO, 2009; Eyring et al., 2009).

Efforts to reduce the environmental impact from international shipping have traditionally not focussed on climate change. The reasons are, according to Gilbert and Bows (2012): more obvious local pollutants such as nitrogen oxides and sulphur oxides dominate environmental risks; the omission of shipping from national inventories under the Kyoto Protocol; and shipping's importance in globalisation and its reputation as the most energy efficient mode of transportation. Main topics for environmental impacts have instead been for example: the usage of toxins in antifouling paints; the release on non-indigenous species with ballast water and fouling; the emission of noise and combustion particles and pollutants into the air. However, the problem of climate change has recently received increased attention in the shipping sector (Gibbs et al., 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 et al., 2010).

Approximately 6% of all marine fuel in European shipping has been estimated to be used in port areas (Entec, 2002). Ships are the single largest source of port-related pollution, and approximately ten times greater than those from the ports' own operations (Habibi and Rehmatulla, 2009; Stripple et al., 2015).

There are several arguments for ports to address CO_2 emission reductions for visiting ships. The main reason is the expected benefits from a reduced climate impact. 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 climate goals can be allocated to different activities, such as port operations, within the city's jurisdiction. Private ports might not be driven to the same extent by political goals. But important for all ports, are the aspects of potential marketing benefits as being a proactive green port.

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

This report contains several different studies. Some of them are presented and published in detail in scientific journals and summarised below. Others are not previously presented. The next chapter of this report gives a brief overview of Swedish shipping and the purpose of the study. This is followed by an analysis of national ship call statistics including a calculation of total energy needs of Swedish shipping. The results of case studies of six different ports are presented in the next chapter. The purpose of the detailed analysis of these case studies are to quantify ships' emissions to air of greenhouse gases in port areas and to discuss the potential GHG emission reductions in relation to port and port traffic characteristics. A model for calculating emissions from ships in ports, developed by IVL Swedish Environmental Research Institute has been used. Improvement potentials are discussed in the following chapter, with a focus on four important abatement measures: reduced speed in fairway channels; reduced turnaround time at berth; connection to on-shore power supply and alternative fuels (LNG, LBG and MeOH). Finally, the concluding remarks summarise findings and reflections, and point towards future research.

2 Background

2.1 Swedish shipping and ports

It is not an easy task to grasp the definition of Swedish shipping, because several considerations should be made in order to account for a single nation's shipping activities. Swedish shipping is many different things and no definition is straightforward. Ships flying the Swedish flag or ships under Swedish control are two options. Sweden had a national ship register with 319 ships, corresponding to 3.1 million gross tons, by the end of 2015. Of these, 125 were cargo ships and 194 were passenger ferries. Overall, this is the lowest number of ships in the Swedish registry since 1970. Swedish ship owners however dispose of more tonnage than the ships that fly the Swedish flag (Trafikanalys, 2016). Most of the tonnage controlled by Swedish ship owners are used in service between foreign ports. In parallel, a majority of goods and passengers in transport to and from Sweden are transported by ships of foreign flags. Other definitions of the term Swedish shipping are Swedish domestic shipping or possibly all shipping within the territorial waters or exclusive economic zone (EEZ).

From an energy perspective, it might be relevant to instead consider only the marine fuel distributed in Swedish port areas. This is the method used for official international reporting. However, this fuel can be used by ships with foreign flags in traffic between foreign ports. In 2015, 2.1 million m^3 marine fuel were sold in Sweden. Of this, 96% was for ships in foreign traffic, and for ships in traffic between Sweden and other countries. The amount varies from year to year. The main parts of the fuel sold are heavy fractions of oil (Energimyndigheten, 2016).

Most of the ship traffic to and from Sweden occurs on international waters and the possibility to limit energy use from ship traffic cannot be regulated by any single country. Regulations for shipping most often originate from international conventions agreed upon in committees of the International Maritime Organization (IMO). Also the potential to regulate energy use in territorial waters or the EEZ are limited due to the internationally agreed conventions. Further, regulating only ships within the Swedish registry would have little effect in total and would potentially cause ship owners to transfer their ships to other registers. Still, traffic to and from Swedish ports carried 83% of our exported goods and 84% of our imports in 2014 (Trafikanalys, 2014). In addition, passenger ferries provide extensive services for tourism and travel. In 2015, 170 million tonnes of goods passed Swedish quays and 26 million passengers travelled to or from Sweden with ferries.

Efficient energy use of these transports is a vital contribution to a more sustainable society in the future.

Port authorities and actors such as pilots, marine fuel suppliers, terminal operators, and charterers that operate from ports, have a coordinating function and a potential to influence ships' energy use. Increased efficiency during loading and unloading operations, efficient communications between ports and calling ships are examples of measures used to facilitate that the ship voyage planning can be enhanced and lead to reduced fuel consumption. In practice this means that the ship speed can be adjusted so that the visiting ship does not arrive at the port before a berth or the cargo is available. Sailing slowly is an important aspect in order to keep the fuel consumption down.

Taking energy use in shipping a step closer to fossil independence includes fuel shifts. Electricity use at berth is available in some ports and the first large ships with fully electric powertrains are about to become reality on the ferry line between Helsingborg and Helsingör (HH-ferries, 2016). Following a European Directive many ports shall also provide liquefied natural gas (LNG) as bunker fuel in 2025. The roles of the ports as administrators are pointed out in the Directive (The European Parliament and The Council of the European Union, 2014). Although LNG is not a fossil free fuel alternative, its infrastructure may be used for liquefied biogas in the future.

Sweden has 54 public ports and additionally several industrial and private ports that serve cargo ships. The public ports are loosely defined as ports that are, or have been, of particular importance to public transports and communications. These ports offer berths to all visiting ships. Industrial ports and private ports are most often highly specialized for certain types of cargoes and ships. Many parameters, such as port size, port ownership and type of traffic, influence the potential to facilitate a more energy efficient shipping to and from a port.

Categorising ship traffic can be based on ship types (i.e. what cargo or carrier is transported). Certain improvement measures are tightly coupled to the characteristic design of a ship type or to typical logistic characteristics of the shipping services. One extreme example is bulk ships for liquid or dry bulk. These ships are designed to efficiently fill cargo holds with payload only and generally sail relatively slowly. On the opposite extreme are ships that have requirements on high speeds. These are typically large passenger ships and ships for rolling cargo (RoRo ships). Consequently, the energy efficiency measured as mass of fuel used for transporting a specified amount of cargo or passengers a certain distance (typically represented in units of g/tonnekm or g/passengerkm) differ significantly from one ship type to another.

Another way to distinguish traffic categories is to divide them between liner shipping, i.e. services with fixed sailing schedules that call a small number of specific ports, or services on the spot market. Ships on the spot market have in general short planning horizons and do not call specific ports on a regular basis. The ships are often hired on time basis or for a single voyage, but exceptions with long term contracts between cargo owners and ship operators exist.

2.2 Purpose and scope

The purposes of this study are to calculate the fuel consumption and CO_2 emissions for Swedish shipping and for a selection of national and foreign ports. Potentials for abatement measures in different ports and for different shipping segments have also been considered. Specific focus has been placed on the different options to direct the energy efficiency of calling ships, from a port perspective.

In this study, we have considered all ship traffic to and from Swedish ports as contributing to Swedish shipping. We have chosen to divide all transport distances between port of departure and port of arrival in two and allocate half of the journey and the fuel consumed for this distance to Sweden. This is the definition of Swedish shipping used in this report. In principle, the argument for this is that all ships to and from Sweden are part of our transport system and fulfil our transport needs. This scope does not represent a jurisdictional reach; Swedish regulations cannot be applied to limit the energy use of these transports.

The work includes case studies of three Swedish ports and additionally three foreign ports. Climate gas emissions of ship traffic in the six ports are analyzed with respect to ship types, frequency of calls, and ship operational modes. Since all energy on ships is liquid fossil fuels and almost exclusively consists of oil, the CO_2 emissions are directly proportional to the amount of fuel used. In addition to CO_2, emissions of CH_4 and N_2O are included.

In all our port case studies presented in Chapter 4, ships' fuel consumption and GHG emissions, are presented in relation to how often a ship calls the individual port. Similarly, the national inventory of fuel consumption is done with this as a central parameter for the analysis of results. The motivation is that the success of certain energy efficiency measures is more likely for those that come often. The major part of efforts made by ports to reduce emissions from fuel consumption of visiting ships has also been directed towards the frequent visitors.

3 Analysis of national ship call statistics

3.1 Frequencies of calls

Statistics provided by the Swedish Maritime Administration covering ships in traffic to and from Swedish ports in 2014, has enabled an analysis of shipping with respect to distances travelled, ports visited and ship types.

Sweden received approximately 74 000 ship calls in 2014. This means 74 000 times, ships used the fairway channels to enter and depart from Swedish ports. As illustrated in Figure 1, the absolute majority of all ship calls are made by ships in the category RoRo/Ferry (53 375 calls). The other ship types listed in order of descending number of visits are general cargo ships (9715), tankers (4903), container ships (2504), bulk carriers (1178), vehicle carriers (760), liquefied gas tankers (633), and cruise ships (618). It was not possible to establish the ship type for 151 ships.

Even though the RoRo/Ferry ships are dominating the number of calls, the number of individual ships that call at the ports is not that high. Instead the same ships tend to return often to Swedish ports due to a high share of liner shipping services. We have chosen to present the ship call statistics in 11 categories of number of calls to Swedish ports, and we distinguish between eight ship types. RoRo/Ferry ships most often have more than 100 returns to the same port[1], and RoRo/Ferry ships completely dominate the category with more than 100 visits per year, which is

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[1] The statistics show return to any Swedish port, however, in the case of RoRo/Ferry ships they do not normally change port but make all their calls to the same port.

illustrated in Figure 1. In the categories with fewer calls per year other ship types are more abundant.

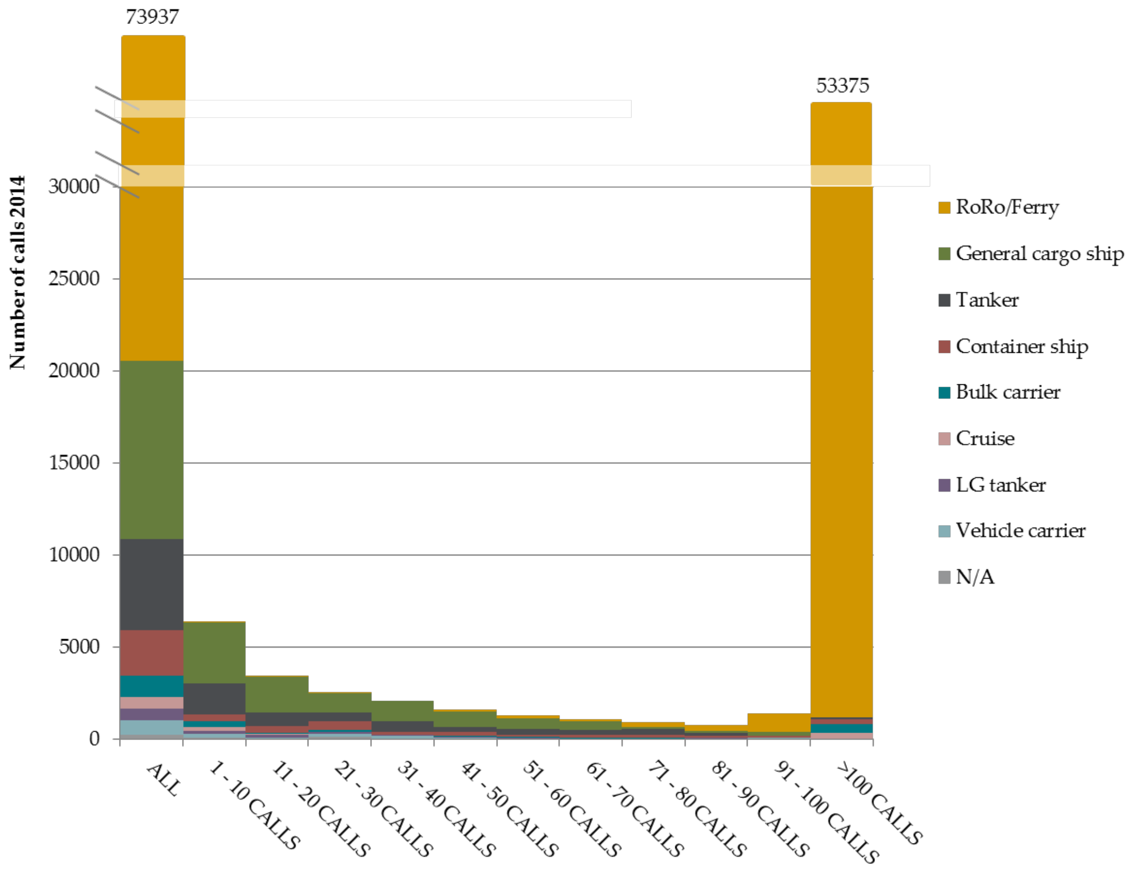

Figure 1. Number of calls of different ship types in traffic to Swedish ports in 2014 (Swedish Maritime Administration, 2015).

Different ship types have different prerequisites for implementing energy efficiency measures due to for examples ship design, regularity, cargo handling facilities and logistics. Typically, certain ship types are also more or less involved in liner shipping or spot market shipping. These different shipping arrangements entail very different planning horizons and thus potential to save fuel. An important aspect of this is the possibility for cooperation in the field of energy efficiency between a port and a ship operator. Charter agreements are used in spot market shipping on time or voyage basis. Within specifically those agreements for chartering a ship for one voyage only, there might be causes for split incentives to save fuel (Styhre, Winnes et al., 2014). For example, if the cargo owner, and not the ship operator, pays for the fuel, there are no incentives for the ship crew to reduce speed and save fuel.

An analysis of how often ships of different types return to Swedish ports is presented in Figure 2. It can be seen in the figure that RoRo/Ferry and Cruise ships tend to frequently visit the same ports. RoRo/Ferry ships are voluminous in design, and especially ships intended to carry passengers in combination with goods have large areas dedicated for leisure activities instead of cargo holds. Pure RoRo ships are more efficiently loaded but still carry a lot of empty volumes, both due to not fully loaded cargo carriers and in limitations of how trailers and cars can be placed and lashed on a cargo deck. This is sometimes referred to as the double load factor problem (Hjelle and Fridell, 2012). These ships are almost exclusively engaged in liner services and have sailing speeds adjusted to time tables, often higher than many other ship types. Cruise ships that return to the same port more than 100 times per year are also in liner services. These include the most modern passenger ships in service between Sweden and Finland. Cruise ships are often equipped with large engines in order to be able to fulfil passengers' requirements of a pleasant retreat.

Bulk carriers also have a large share of high-frequency calls, as shown in Figure 2. This is mainly a result of small bulk ships in traffic around Gotland. They transport cargo a very short distance, often to larger bulk ships located outside the port limit, where the cargo is transferred between the ships. The larger ships cannot enter the ports due to size restrictions.

Apart from these few ships that represent a large share of all calls by bulk ships, most ships have very few calls per year to Sweden. Container ships and vehicle carriers are often employed in liner service. However, due to long trades over oceans these ships often only have few returns to Swedish ports annually. These ship types are similar to RoRo ships designed to transport voluminous goods and cargo carriers, making them less energy efficient per transported tonnes of cargo than ships carrying bulk goods. Because of the high values of the products transported in these ships, they often sail rather fast. Tankers for liquid bulk (categories Tanker and LG tanker in Figure 2) have rather low call frequencies to the same ports. There is however ships in this category that are engaged in long term contracts and that frequently visit the same ports. Ships carrying liquid or dry bulk cargo have potential to efficiently fill cargo carrying spaces on board, resulting in high energy efficiency. They also often have lower design speeds than other ship types. General cargo ships are often small sized vessels carrying different kind of cargo. It is difficult to draw conclusions on this category as these ships are less uniform than ships in the other categories.

The number of returns per year to Swedish ports may be an indicator of whether the ship is liner or spot traffic. Still, there is no limit for how often a ship returns to a Swedish port that indicates if the ship is in liner service or spot market shipping. The analysis and Figure 2 thus only indicate how often ships of different types returned to Swedish ports in 2014, and is vaguely representing typical characters of shipping arrangements of different ship types.

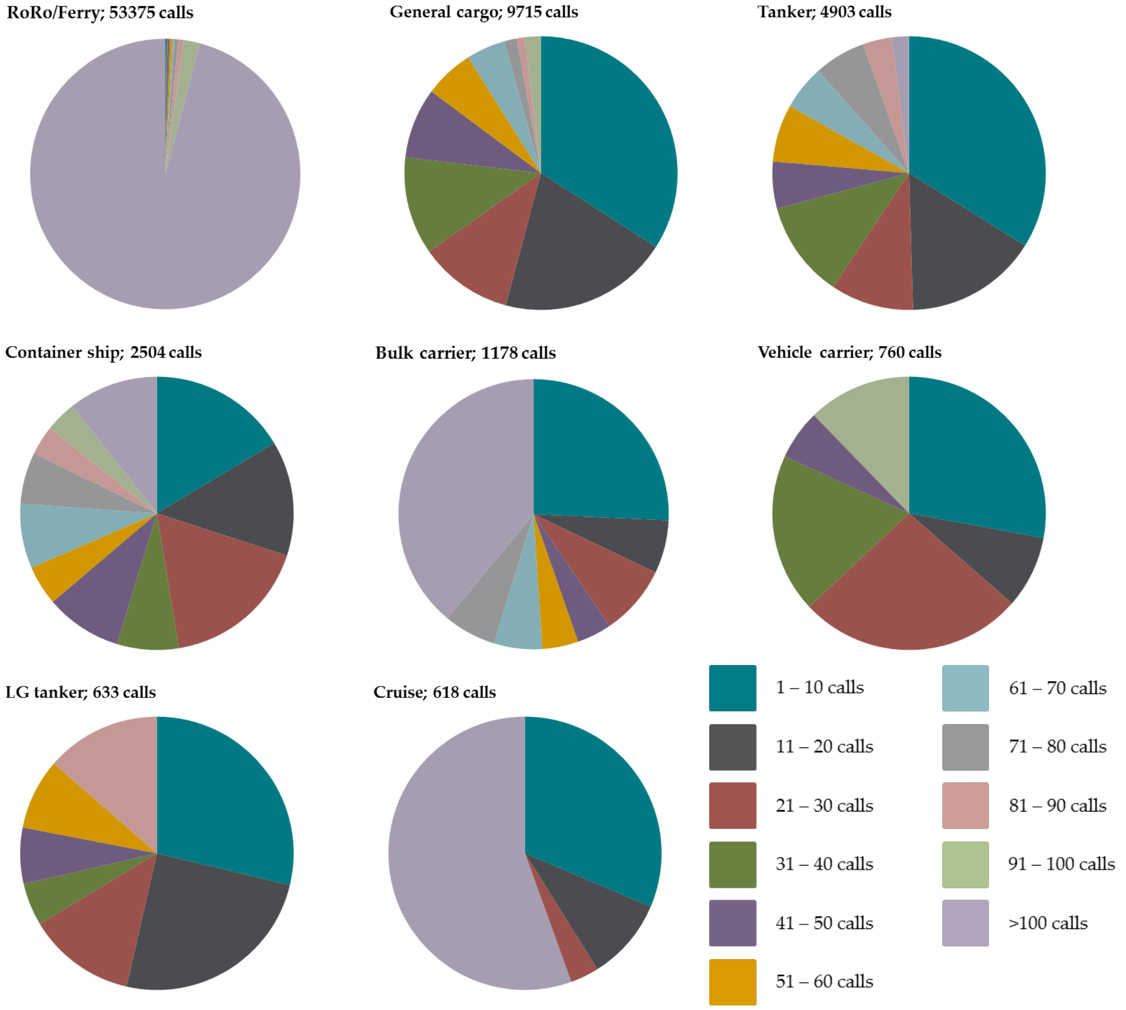

Figure 2. Frequency of visits of different ship types to Swedish ports.

As mentioned before, the potential to achieve more efficient energy use of ships is partly related to how often ships visit the same ports. Measures such as fuel shifts, and converting to on-shore power supply often include high investment costs that are jointly taken by a port and a ship owner. These are therefore not economically viable option for most ship owners with ships in traffic between many and varying ports. Similarly, ports are reluctant to invest if the equipment is not used. If low-frequency shipping services contribute to a relatively large share of fuel consumption in a port it thus decreases the potential of many measures.

3.2 Port calls and sizes of ships and machinery

Another important parameter in order to calculate fuel used by ships is the installed engine power. A combination of the call statistics and data from the Seaweb database on ship specifics (Seaweb, 2015) has been used in order to describe the ship sizes and machinery for the different ship types.

The average main engine power installed in ships of different ship types that call Swedish ports is presented in Table 1. Cruise ships have the highest average values of all ship types followed by RoRo/Ferry, container ships, vehicle carriers, tankers, LG tankers, bulk carriers and general cargo ships, in descending order. Generalisations like average values can however be misleading, and examples of large engines in tankers and bulk carriers exist. The size of the engine can be used as a proxy for ship size, but can also indicate design speed of ships.

Table 1. Average main engine installed power (kW) of ships calling Swedish ports per ship type.

Ship type	Average main engine installed power (kW) of ships calling Swedish ports
RoRo/Ferry	16 000
General cargo	2300
Tanker	4900
Bulk carrier	3100
Container ship	12 000
Vehicle carrier	9300
LG tanker	4300
Cruise	30 000

113 ports received ship calls in Sweden in 2014. Of the total number, 47 had less than one call per week, 38 ports had between one call per day and one call per week, and 28 ports had more than one call per day. The ports with less than one call per week in total received 838 calls in 2014, of which all were made by ships with less than 10 000 kW installed in main engine power, see Figure 3. For these port calls, most of the main engine power is installed on ships with main engines of less than 5000 kW, see Figure 4. Ports with between one and seven calls per week together received 5787 calls in 2014. Also for these ships, a major part of all main engine power is installed in small engines (Figure 5) – mainly in engines of less than 5000 kW, see Figure 6. The category of ports with more than one call per day contains ports in a wide size span; from Jättersön that received 395 calls to Helsingborg that had 25 975 calls. There are industrial ports as well as public ports. Ships that visit these ports are of all sizes and ship types. The variation in traffic with respect to frequency of calls and visiting ship types is presented in Table 2. Many calls are made by ships with main engine power of 5000 –10 000 kW, see Figure 7. However, the ship with the largest engine has over 100 000 kW installed. The distribution of main engine power of ships in traffic to these ports is rather evenly distributed between 5000 and 55 000 kW, Figure 8.

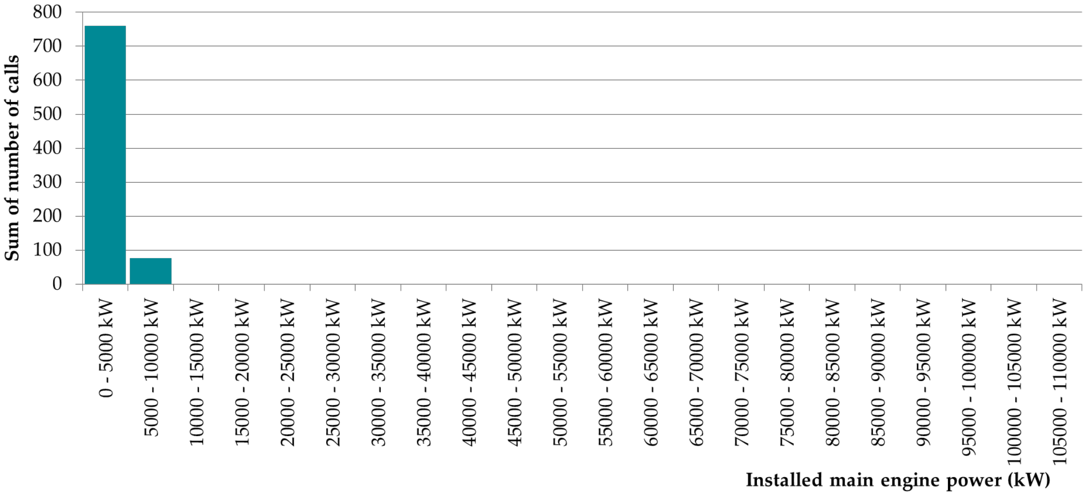

Figure 3. Number of calls made by ships to port receiving less than one call per week.

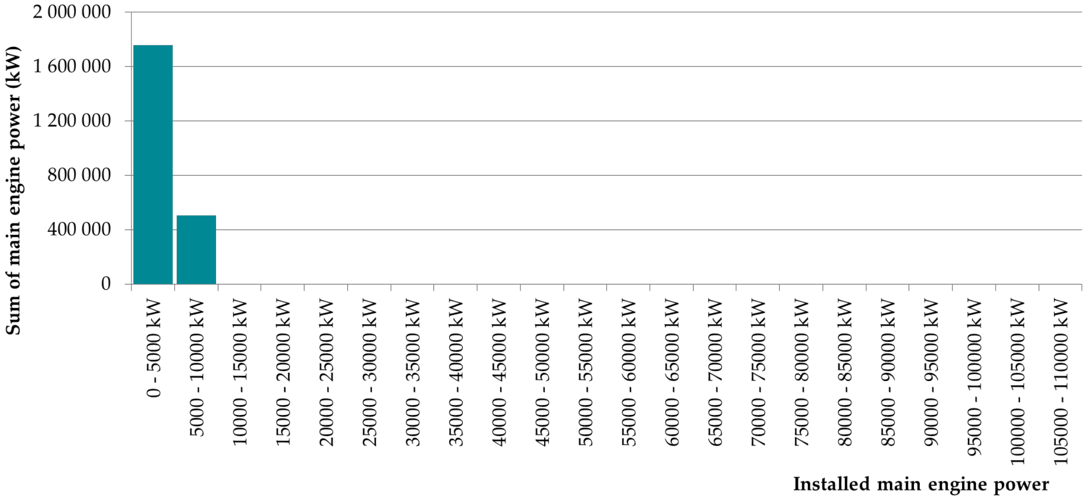

Figure 4. Total installed main engine power in ships in ports receiving less than one call per week.

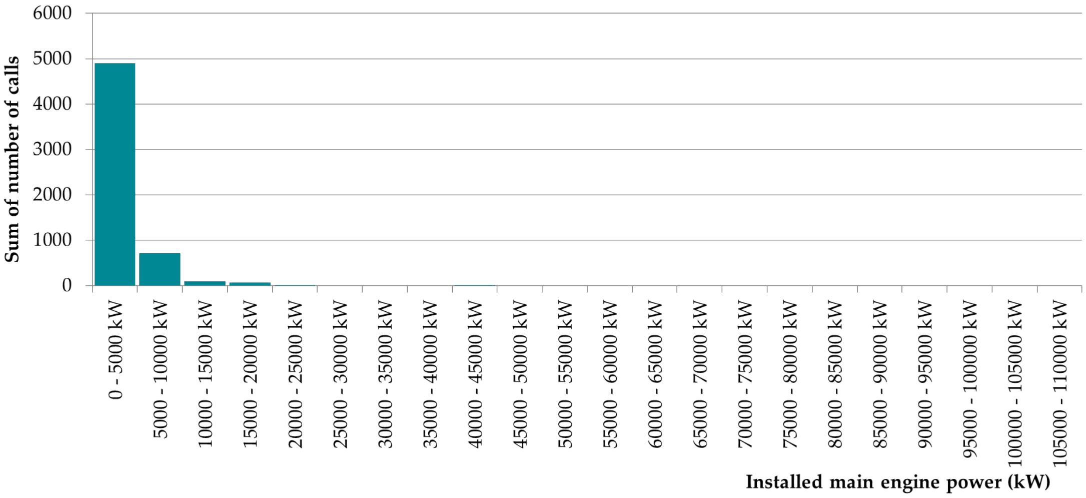

Figure 5. Number of calls made by ships to port receiving more than one call per week but less than one call per day.

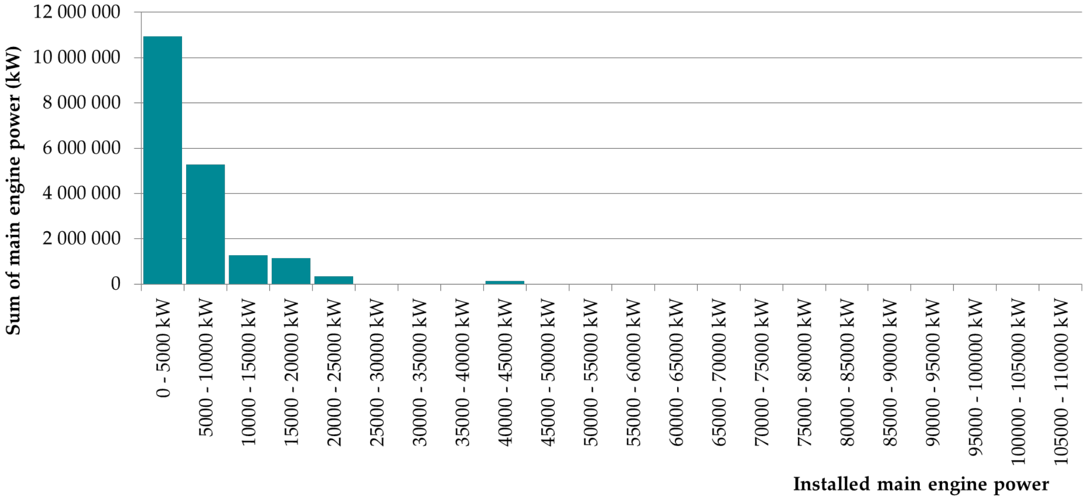

Figure 6. Total installed main engine power in ships in ports receiving more than one call per week but less than one call per day.

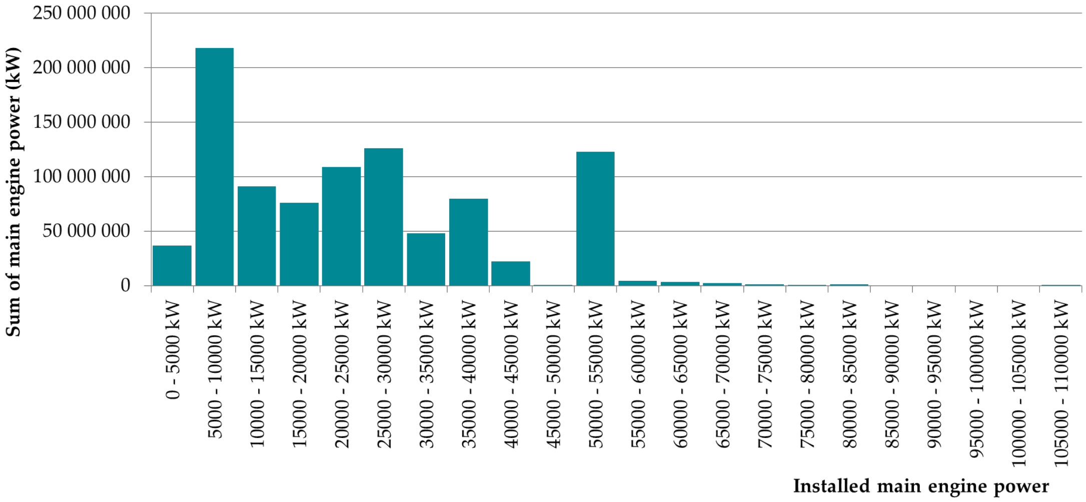

Figure 7. Number of calls made by ships to port receiving more than one call per day.

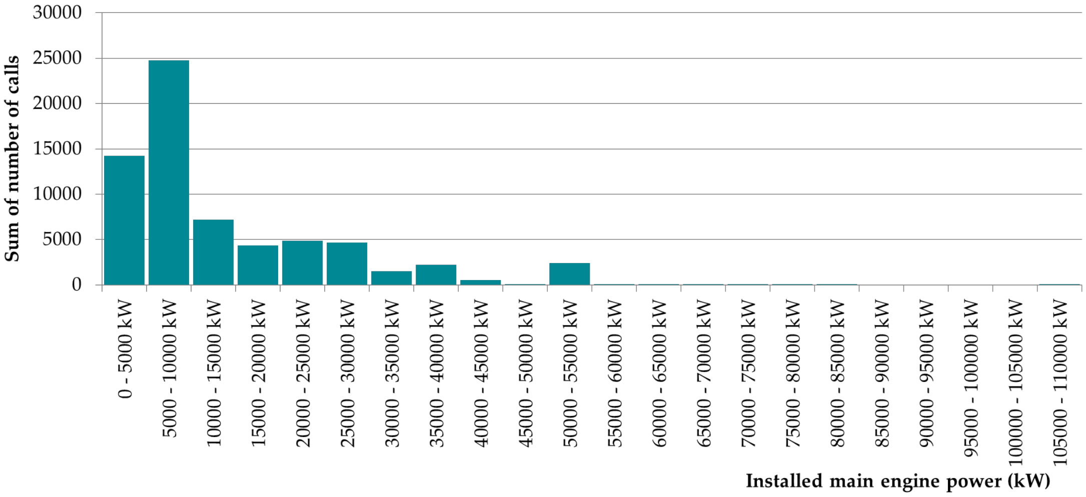

Figure 8. Total installed main engine power in ships in ports receiving less than more than one call per day.

The busiest port in terms of port calls is the Port of Helsingborg serving the frequent ferry traffic over Öresund, see Table 2. The number of passengers is however larger in Ports of Stockholm. The Port of Gothenburg is the largest cargo port in Sweden, and handles bulk cargo as well as unitised cargo and passengers.

Table 2. The busiest Swedish ports with respect to ship calls 2014, incl. number of calls by different ship types.

Port	Number of calls	RoRo/Ferry	General cargo	Tanker	Container ship	Bulk carrier	Vehicle carrier	LG tanker	Cruise
Helsingborg	25975	25055	261	140	496	17			5
Göteborg	6060	3250	93	1623	840	15	124	55	60
Trelleborg	5152	5069	22	23	0				
Stockholm*	4609	3462	38	171	167	224			535
Ystad	3473	3426	47	0	0				
Visby	2934	2906	14	2	0	1			7
Malmö	2853	1916	213	303	53	25	325	16	1
Kapellskärs hamn*	2190	2189	1	0	0				
Strömstad	1757	1757		0	0				
Varberg	1068	553	444	13	51	1			
Karslshamn	1038	368	409	187	31	8		19	
Brofjorden	975			807	0			151	
Grisslehamn	962	962		0	0				
Karslkrona	763	745	4	4	0				0
Nynäshamn*	723	444		250	0			23	6
Norrköping	692		402	116	147	19			
Holmsund	661	489	84	31	48	9			
Gävle	658		284	121	249	4			
Slite	653		258	16	0	377			
Stenungsund	644		102	249	0	6		286	
Husum	567	225	310	25	0				
Halmstad	559		245	58	131	30	95		
Oxelösund	514	45	292	63	55	56			
Södertälje	447	61	192	57	51	1	47	38	
Luleå	445		355	41	0	49			0
Västerås	422		328	57	0	36		1	
Jättersön	395		365	9	0	2			

*The calls to Ports of Stockholm are accounted for separately.

3.3 Total fuel consumption of Swedish shipping

3.3.1 TRACCS methodology

In order to quantify fuel and energy needs for Swedish shipping, two different methods have been used. The first model was developed by IVL Swedish Environmental Research Institute in the EU project TRACCS. The second model is an improvement of this method to calculate fuel consumption more in detail for Swedish shipping.

TRACCS model

The TRACCS study was carried out jointly by Emisia, IVL Swedish Environmental Research Institute and Infras for the European Commission in 2013 and 2014. The purpose was to quantify fuel and energy needs of European transports based mainly on data from Eurostat.

A model for fuel consumption and CO_2 emissions for waterborne transports were developed by IVL. The model divides generic values for nautical distances between countries in half in order to allocate fuel consumption of ships to the country of departure and the country of arrival. Ships are divided into eight different ship types and three ship size classes. For all ship types and size classes, the freight measured as transport work in tonne*km and tonnes are calculated. The CO_2 emissions are then related to the transport work conducted.

For each ship type and each ship size class a generic emission factor in gram CO_2 per tonne-km is calculated. The average size of a ship in each size category is used in formulas corresponding to IMO EEDI calculation (MEPC, 2011) for different ship types resulting in an emission factor in kg CO_2/km. The average dwt is multiplied by an estimated ship type specific cargo carrying capacity, and an estimated average load factor to obtain the freight transported by a ship in tonnes. Load factors from International Maritime Organization (2009) are used and the correlation between payload (in tonnes) and dwt is from clean shipping index (Clean Shipping Index, 2010). Table 3 gives the average load capacity utilisation factors and the resulting ratios for payload for different types of ships.

Table 3. Capacity utilisation factors and payload of different ship types.

Type of ship	Capacity utilisation	payload:dwt ratio
Oil tanker	0.48	0.95
Chemical tanker	0.64	0.95
LG tanker	0.48	0.95
Bulk carrier	0.55	0.9
General cargo	0.6	0.9
Container ship	0.7	0.8
RoRo/Ferry	0.7	0.5
Vehicle carrier	0.7	0.5

The emission factor can then be divided by this average freight to obtain the emission factors in CO_2/tonne-km. The emission factors are then multiplied by transport work (tonne-km) for each respective ship type as reported to Eurostat. Size class and the total mass of emitted CO_2 are then calculated. The fuel consumed is assumed to be exclusively marine fuel oil with a fuel to CO_2 conversion factor of 3.1.

More details on the method developed in TRACCS is presented in the report Papadimitriou et al. (2013) and in the paper by Papadimitriou et al. (2014).

TRACCS model improved

This study is based on the same allocation principle that is used in TRACCS. The estimated fuel consumption of a ship's journey is divided in half between country of departure and country of arrival. Compared to the original TRACCS model, more efforts have been made to estimate the distance travelled by the most frequent shipping lines. All lines with more than one call every other week has been verified and entered as input data to the model.

Generic average values on ship speed of different ship types and ship sizes have been applied to all ship calls. These values are from the Third IMO GHG Study report (International Maritime Organization, 2014).

The calculation of total energy need has been refined from the original version of the model and is calculated by the formula:

$$FC = t \times P_{ME} \times u \times SFOC$$

where *FC* is fuel consumption for each individual ship call; *t* is the time for half the journey between port of departure and port of arrival; *u* is utilised main engine power; and *SFOC* is specific fuel oil consumption of the ship engine.

Time is calculated by dividing the distance between ports with the average speed of the ship type and size of each respective call. Statistics on main engine power is collected from the Seaweb ship database for each individual ship. Utilisation of main engine power is calculated according to the speed law stating that the needed main engine power load can be approximated by the cube of the ratio between actual speed and design speed $(v_{actual}/v_{design})^{\wedge 3}$. Both the values of actual speed (V_{actual}) and design speed (V_{design}) are generic values for ship types and ship size classes from International Maritime Organization (2014). The value on SFOC varies between engine sizes and engine types, engine age and fuels used. It is common that values fall in the range 175 to 225 g/kWh. In these calculations a value of 200 g/kWh is used for all engines.

3.3.2 Total fuel consumption

The total fuel consumption for Swedish shipping was calculated to be approximately 1 500 000 tonnes for 2014. The twelve ports for which the visiting ships caused the most fuel consumption during sea journeys represents two thirds of the total fuel consumption. Gothenburg is in top with 247 000 tonnes fuel for the visiting traffic followed by Stockholm; Malmö, Brofjorden, Helsingborg, Gävle, Visby, Oxelösund, Trelleborg, Norrköping, Karlshamn, and Halland in descending order, see Table 4. Ships that visited Swedish ports more than 100 times in 2014, consumed 19% of all the fuel used. Ships with few calls contributed a much larger share of total fuel consumption; ships with less than 20 calls to Swedish ports per year accounted for half of all fuel consumption, see Figure 9.

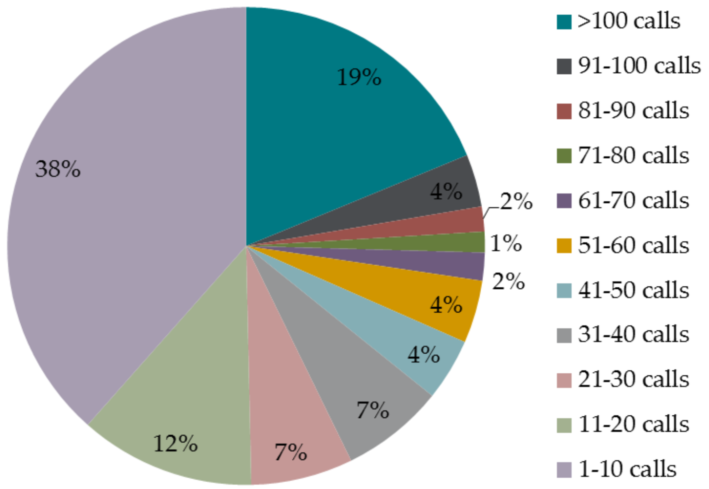

Figure 9. Share of fuel consumption by ships categorised by the number of calls made to Swedish ports.

The emission factor for CO_2 from marine fuel used in TRACCS is 3.1 g/g fuel. Total CO_2 emissions can thus be calculated to be 4 600 000 tonnes year 2014.

Table 4. The twelve Swedish ports for which visiting ships caused the most fuel consumption during sea journeys

Row Labels	Fuel consumption on ships in traffic to and from the port (ktonne)
Gothenburg	247
Stockholm	197
Malmö	87
Brofjorden	87
Helsingborg	48
Gävle	47
Visby	43
Oxelösund	40
Trelleborg	38
Norrköping	37
Karlshamn	36
Halland (Varberg and Halmstad)	36

No analysis of energy requirements and CO_2 emissions in port areas are included in the TRACCS method. We have therefore used the results from the case studies of three Swedish ports to analyse the ratio between fuel used during journeys and fuel used in ports. The analysis is presented in Chapter 4.2.2.

The cargo carrying capacity estimates and the estimated average load factors (Table 3) are multiplied with the deadweight of ships in Swedish shipping to have approximations of the amount of cargo loaded on different ship types. Knowing the distances travelled, a ratio is then calculated for the fuel consumption and the transport work for different ship types. This ratio is often expressed in the unit g/tonnekm and describes how much fuel that is used to transport one tonne of cargo one km. It can serve as a useful energy efficiency measure and is often used to compare environmental performance of different transport modes. For ship types in Swedish shipping 2014, these values spanned from 4 g/tonnekm for container ships and general cargo ships, to 20 g/tonnekm for RoRo/Ferry ships, see Table 5. These values are based on generic figures and include a lot of uncertainties.

Table 5. Average fuel consumption per transport work for cargo carrying ship types in Swedish shipping.

Ship type	Average fuel consumption (g/tonnekm)
RoRo/Ferry	20
Vehicle carrier	10
Tanker	5
LG tanker	8
Container ship	4
General cargo	4
Bulk carrier	5

4 Ships’ fuel consumption and GHG emissions in port areas

4.1 Methodology

4.1.1 Case studies

Case studies of six ports have been carried out in collaboration with the port authorities. Three Swedish ports and three international ports have been included. Case study methodology was selected due to the broad and comprehensive approach taken in this work. Data on a large number of variables for ports of various sizes and conditions and in different geographical areas were gathered. This allowed for an assessment of transcontinental similarities and disparities, which gave the work an increased international relevance.

The case studies are based on both quantitative and qualitative data, including ship call statistics for the ports, interviews and literature studies (scientific papers, published company information, reports, etc.). Based on a literature review and pre-understanding from previous work, a guide for semi-structured interviews were composed. The interview guide consists of three sections including “Energy / CO_2 emission reduction measures”, “Market Aspects”, and “Port operation”. Interviews were carried out with the sustainability manager and the harbour master in the Port of Gothenburg, with the director of port and traffic development in Ports of Stockholm and with the sustainability manager in Port of Halland. A pilot that works in Gothenburg was also interviewed. In Sydney Ports we had meetings with the sustainability manager, the environment operations manage and the commercial and technical officer. No formal interviews were held in the Port of Osaka and the Port of Long Beach.

The Port of Gothenburg receives 6 000 to 7 000 calls per year including between 1 000 and 2 000 ships passing the port. It 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 Authority owns the land and the infrastructure, and international port operators handle the cargo in all terminals except the port’s energy terminal. 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. Ships can bunker LNG in the port since 2015, and an LNG terminal is planned for 2017.

Port of Halland is located on the west coast of Sweden and was founded in January 2013 as a result of the merger into a single company of the two port companies in Halmstad and Varberg. The port is owned jointly by the municipality of Halmstad (50%) and the municipality of Varberg (50%). It is a full service port in the areas of container shipping, RoRo, bulk, liquid bulk, biomass, cars, project cargoes, recycling and forestry products. Every year the ports handle about 4.4 million tonnes. Traditionally, the ports have long been amongst the leaders in forestry products, especially timber, in Sweden. There are no environmental incentive programs for shipping companies.

The Port of Long Beach (POLB) is a gateway for international trade between the United States and the Pacific Rim trading economies, ranking as the 21st busiest port globally and as the 2nd in the USA. With 22 shipping terminals, the port’s terminals accommodate bulk, break bulk, liquid bulk and containers for a combined annual tonnage of exceeding 82 million tonnes of cargo. In 2015 POLB handled approximately 7.2 MTEU. POLB has 21 container shipping routes calling at the port. Overall, the port serves more than 140 shipping lines with trading connections to 217 ports worldwide. POLB has a long history of working with sustainable port operations. Running programmes include the Green Flag Program encouraging vessel operators to slowing speeds within 40 miles of the harbour, and the Green Ship Program incentivising vessels with Tier II or Tier III main engines, with low NO_X emissions, calling at the port. Further the port has a vast programme to supply ships with on shore power following regulations from the Californian Air Resource Board.

The Port of Osaka, is one of the designated Strategic International Container Ports in Japan, receives both international and coastal vessels and handled 86 million tonnes of total freights in 2014. The international container trade has been steadily increasing to 2.2 million TEU. The City of Osaka as the port authority has encouraged “modal shift” – a change in use of transport modes from trucks to rail or ships - to reduce the GHG emissions over the city and to boost the maritime transport to and from the Osaka Port. There are several subsidies primarily for shippers to encourage this modal shift, whereas on-shore power supply or environmental incentive programs for shipping operators are not found.

Ports of Stockholm consists of the ports in Stockholm, Kapellskär (90 km north of Stockholm) and Nynäshamn (60 km south of Stockholm). Each year more than 11 million passengers and 8 million tonnes of goods pass though the ports. Ports of Stockholm has the following business units: RoRo/ferry traffic, containers, bulk, international cruises, archipelago traffic and properties. The port offers shipping companies services to encourage them to implement measures to reduce the environmental impact of vessels. These includes environmentally differentiated port fees for vessels that run on LNG, vessels that reduce their nitrous oxide emissions, and cruise ships that offload sorted waste. The port also has on-shore power supply at several quays, where vessels that are retrofit to enable shore-provided electricity connection can receive a grant of SEK 1 million. The port also hosts a supplier of LNG bunker to ships.

Sydney Ports are located on the east coast of Australia and consist of two parts. Port Botany, a deep-water port located in Botany Bay dominated by trade in containerised manufactured products and bulk liquid imports including petroleum and natural gas. The annual total container trade is approximately 1.7 million TEU, and non-containerised imports are about 2.4 million mass tonnes. The port is administered by New South Wales (NSW) Ports that entered into a 99-year lease agreement with the NSW Government in 2013. Port Jackson is the natural harbour of Sydney and extends 19 km westward from the single entrance at Sydney heads. The port is an important destination for cruise shipping. The port handles also a wide range of cargo including dry and liquid bulk, and general cargo through berths at Glebe Island and White Bay. Additional private facilities are located at Gore Cove. There are no on-shore power supply or environmental incentives programs for visiting ships.

4.1.2 How to calculate energy and GHG emissions from ships in port

This study includes an inventory of the GHG emissions from the ships in the six case ports for one year (Gothenburg, Long Beach, Halland for year 2015; Stockholm, Osaka for 2014 and Sydney for 2013). Port call statistics including IMO number, ship name, berth number and time spent at berth for each ship call were received from the participating ports. 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 installed main engine power, size (length, dwt, GT) and type of the vessel, and vessel age.

All data were analysed with a model developed by IVL Swedish Environmental Research Institute for the purpose of quantifying fuel consumption and GHG emissions (as CO_2-equivalent) from ships in the port area. The model was used for the calculation of GHG emissions from different ship types in the six ports. Emissions from up to 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".

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 CO_2, CH_4 and N_2O are included in the calculations and calculated as CO_2 equivalents (CO_2-e). CO_2 is, in general, the dominating GHG from marine engines: CH_4 and N_2O represent only around 1 – 2% of CO_2-e emissions. The used values for CO_2-eqv are 34 for CH_4 and 298 for N_2O (Myhre et al., 2013). Emission factors for CO_2, CH_4 and N_2O for main engines and auxiliary engines are from Cooper and Gustavsson (2004). Variations of emission factors for CH_4 and N_2O during different operational loads reported in Cooper and Gustavsson (2004) are included in the calculations. At low engine loads the specific fuel consumption increases;

in a comparison between the preferable load of the engine (often around 80% of maximum continuous rating) and low loads, the engine needs more fuel to produce the same amount of work (measured as e.g. kWh) at periods with low loads. The adjustment factors differ somewhat between 4-stroke engines (~ medium- and high-speed engines) and 2-stroke engines (~ slow speed engines). These adjustment factors are used in the calculations of CO_2 from main engines. CO_2 emissions are practically directly proportional to the amount of fuel combusted. In the close to port areas the ships seldom use the full power of the main engines. In Table 6 the factors used are presented; the values should be considered approximations (Faber et al., 2010). Emission factors for boilers are from USEPA (1999).

Table 6. Adjustment factors for specific fuel consumption (SFOC) at different engine loads.

	ENGINE SFOC	
Engine load range	4-stroke	2-stroke
>50% MCR*	nominal	nominal
25-50% MCR*	1.15*nominal	1.1 times nominal
<25% MCR*	1.7*nominal	1.7*nominal

* maximum continuous rating

The utilised engine power and the time are the other two factors used in the emission calculations. The data from the six ports are similar, but small differences have necessitated the use of slightly different approaches to the emission calculations for each port. An overview of these approaches is given in the following paragraphs and in Table 7.

Information on the power installed in main engines of ships is from the Seaweb database. Knowledge of auxiliary engine power is however seldom reported and more generic values are therefore used for emissions from these engines. For the ships visiting Port of Long Beach, values from IMO (2014) are used. These data originate to a large extent from studies on ships in the Port of Long Beach and are likely representative for those ships. For the other ports, installed auxiliary engine power is based on ship types and size categories from relationships established and reported in Sjöbris et al. (2005).

The main engine loads (in % of total installed main engine power) during passages in the fairway channel, in the port area, and during manoeuvring, have been set from the approximate relationship of ships actual speed and the maximum speed:

$$\text{Engine load} = (v_{actual}/v_{maximum})^3$$

Ships' speeds are either estimated speed of ships from generic values from IMO (2014) specified for ship types and size categories, or based on actual time statistics, see Table 7.

Engine loads for auxiliary engines are derived from Entec (2002) with the exception of some frequent callers in Gothenburg for which the actual power has been used.

There are distinctive differences between the ports in the detail level at which the time in the port area and in the fairway channel has been determined. Consequently, calculations for the Port of Long Beach do not include any time in the fairway channel and only contain generic values on time to and from different berths in the port area. Similarly, calculations for the Port of Osaka do not include any times at anchor and generic values for time in the port area received by the port authorities. For the Port of Gothenburg, calculations are based on distances and generic values on ships' actual speeds for different ship types and size categories from IMO (2014). Times at berth are precisely given for all ports. Manoeuvring emissions from Ports of Stockholm and Port of Halland, have been included in the emission category “in port basin”. For Ports of Stockholm, slow speed is used for a relatively long distance. The distinction between port basin and fairway channel was not relevant to make, thus the emissions presented for “In port basin” contains areas outside the actual basin.

Table 7. Overview of data sources and approaches for calculating times and power needs at different operational modes, for the six ports.

	IN FAIRWAY CHANNEL	AT ANCHOR	IN PORT BASIN	MANOEUV-RING	AT BERTH	AE power	ME power
GOTHENBURG	Distance at sea calculated as 8.7 NM. If berth is outside speed limit zone, the distance between berth and speed limit zone is subtracted. Speed assumed from MEPC - "actual speed"	Time at anchor from statistics. Anchoring outside the traffic area not included	Time in port calculated from “actual speed” of ships according to MEPC. Distance for each separate berth.	Estimated 20 minutes for each call (in and out). If more than one berth per call, then an additional 20 minutes is counted etc.	From statistics	Based on ship sizes, Sjöbris et al. (2005), Engine load: “In fairway ch.”: 30% “At anchor”: 40% “In port”: 40% “Man.”: 50% “At berth”: 40%	“In fairway channel” power and “In port” power calculated as (v_{actual}/v_{design})^3. “Manoeuvring” power 10% Specific power is known for certain ships.
HALLAND	Distance in fairway channel measured on map; Varberg 2 NM and Halmstad 4.4 NM Speed assumed from MEPC - "actual speed	No time at anchor in port statistics	Time in port calculated from “actual speed” of ships according to MEPC. Distance in Varberg 1.4 km, in Halmstad 0.5 km.	Manoeuvring time assumed to be included in time estimate for “In port basin”	From statistics	Based on ship sizes, Sjöbris et al. (2005), Engine load: “In fairway ch.”: 30% “In port”: 40% “At berth”: 40%	“In fairway channel” power and “In port” power calculated as (v_{actual}/v_{design})^3
LONG BEACH	No distance for at sea operations are included	Anchorage points both inside and outside breakwater included	Time in port stated to be between 1 and 2 hours; assumption that “inner” ports requires 2 hours and “outer” ports require 1 hour transport time, manoeuvring time (20 min) subtracted. Movements between anchorages and berths included.	20 minutes total per movement.	From statistics	From generic values for ship types and size classes from MEPC - those data originates to a large extent from VBP POLB. Values are representing different operational modes	“In port” power calculated as (v_{actual}/v_{design})^3. “Manoeuvring” power same as In port.
OSAKA	15 minutes. No distance estimated. Speed assumed from MEPC - "actual speed"	No anchorage included	30 min to and from berth, 10 minutes subtracted for manoeuvring each way. In total 40 minutes. No distances estimated, speed assumed same as at sea.	Estimated10 minutes each way	From statistics	Based on ship sizes, Sjöbris et al. (2005) Engine load: “In fairway ch.”: 30% “At anchor”: 40% “In port”: 40% “Man.”: 50% “At berth”: 40%	“In fairway channel” power calculated as (v_{actual}/v_{design})^3. “In port” power and “Manoeuvring” power = 10%.
STOCKHOLM	Fairway channel emissions are not separated from “in port basin” emissions. These emissions represent specific distances to all berths.	No anchorage included	Distances and speeds from personal communication with port representatives. In port basin represent transit distances between 0.1 and 5.6 km.	Manoeuvring time assumed to be included in time estimate for “In port basin”	From statistics	Based on ship sizes, Sjöbris et al. (2005) Engine load: “In port basin”50% (Cruise 41%) “At berth”: 40% (Liquid bulk 60%, Cruise 29%)	“In port basin” 20%, Cruise 30%
SYDNEY	4 NM at sea, time in fairway channel from port statistics, speed calculated as distance/time at sea	Five anchorage points included	Distance to port, and time in port are from port statistics, speed is calculated as distance/time in port (manoeuvring time subtracted)	Estimated 10-30 min.	From statistics	Based on ship sizes, Sjöbris et al. (2005), Engine load: “In fairway ch.”: 30% “At anchor”: 40% “In port”: 40% “Man.”: 50% “At berth”: 40%	“In fairway channel” power and “In port” power calculated as (v_{actual}/v_{design})^3. “Manoeuvring” power same as In port.

GHG emission reduction measures already in use in the ports are accounted for in the calculations. This includes the use of on-shore power supply (OPS) in the Port of Gothenburg, Ports of Stockholm and in the Port of Long Beach. The extent of OPS use in Port of Long Beach has been estimated based on regulatory actions for reducing emissions from container ships, passenger ships, and ships for refrigerated cargo, at berth. The regulations aim for that 70% of all calls by the mentioned ship types connect to on-shore power sources at berth by 2017, increasing from 50% in 2014. Since statistics on actual use were not available, 50% of the calculated emissions at berth from the relevant ship types are subtracted from the total emissions. The scope is loosely confirmed by detailed information in the port's yearly air emission inventory for emissions 2014, when 26% of total calls used the OPS (Starcrest, 2015).

The study comprises only merchant ships, which are divided into the following six categories: ferry/RoRo, general cargo ship, cruise ship, container ship, liquid bulk and dry bulk. Excluded ships in the analysis are other vessels such as bunker vessels, local ferries for commuting, charter boats, patrol vessels, service provider ships, fishing boats, tugs, dredgers and military ships.

4.2 Results from the six port cases

The case studies include three ports from Sweden: Port of Gothenburg, Port of Halland, and Ports of Stockholm, and three ports abroad; Port of Long Beach, Port of Osaka, and Ports of Sydney. The analysis of the cases is similar although the input data may vary and cause different degrees of uncertainty of results. The analysis of Swedish ports is extended to include a comparison with fuel consumption of ships in traffic to and from the respective ports.

4.2.1 Background and port characteristics

The six ports have different characteristics that affect the energy use and emissions. The Port of Gothenburg, Ports of Stockholm and the Port of Osaka have very large shares of emissions from RoRo vessels and ferries, whilst these ships scarcely exist on the East coast of Australia (except for vehicle carriers that call at neighboring ports). Furthermore, both in Japan and Scandinavia, short sea shipping with smaller vessels calling at the ports is a common feature, and there is a large network of container feeders connecting Gothenburg to other parts of Northern Europe. Due to the geographic location and conditions of Australia and the USA, the ships are in general larger and ocean going. The number of very small ships (e.g. between 100 and 500 GT) is much higher for Japan than for the other regions. The number of ship calls per ship type is presented in Table 8 for the six ports.

Table 8. Number of ship calls of different ship types in the six case ports.

Ports	Year	Container	Dry bulk	Liquid bulk	General cargo	Ferry/RoRo	Cruise	TOTAL (no.)
Gothenburg	2015	785	77	1 386	653	3 048	50	**5999**
Halland	2015	206	74	175	626	646	1	**1728**
Long Beach	2015	1116	299	903	40	189	259	**2806**
Osaka	2014	3812	1001	844*	3581	3148	13	**12399**
Stockholm	2014	129	153	214	100	7520	265	**8381**
Sydney	2013	813	71	391	23	2	70	**1370**

** Bunker ships were not possible to separate from other liquid tankers in Port of Osaka, and are consequently included in the liquid bulk category. For the other ports, these vessels are subtracted.*

4.2.2 Fuel consumption and CO_2 emissions

Fuel consumption and CO_2 emissions from the marine engines are tightly linked since the carbon in the fuel forms CO_2 to such a large extent that it can be approximated that there is a linear relation between the two and that all carbon forms CO_2. In our calculation model for the ports we have used an emission factor of 3.179 g CO_2 per g fuel combusted. In some parts in this study we focus on fuel consumption and in others on CO_2 emissions. Since the aim of this study is foremost to investigate potentials for energy savings from shipping in order to reduce climate impact, we have chosen to use CO_2-equivalent emissions and fuel consumption arbitrarily. To calculate GHG emissions, it was relevant to include the greenhouse gases methane (CH_4) and nitrous oxide (N_2O). The CO_2 emissions contribute 98 – 99% of CO_2 equivalent emissions from ship engines. The 1 – 2% that is left can be attributed to emissions of CH_4 and N_2O. For the purpose of energy efficiency discussions, it might be more relevant to include fuel use data.

In Table 9 the ports are presented together with the total amount of fuel used in ports, and the emissions of CO_2 equivalents. For the Swedish ports the total fuel consumption of the journeys to and from the ports made by the visiting ships is also presented. In the final column the ratio between emissions in port areas and the emissions from visiting ships' journeys are presented. For Gothenburg, Halland and Stockholm the ratios are 1:5, 1:11, and 1:7 respectively. These figures indicate that as expected the emissions in ports are less than emissions during journeys. There might be overlaps between the two posts for fuel calculations, and the resulting ratio is an approximation. Further, for the calculations it has been assumed that there have been no significant differences in ship traffic to the ports between adjacent years.

Table 9. Calculated fuel use and CO_2-e from ships in the six case ports.

Ports	Fuel used in port (ktonne)	Emissions of CO_2 equivalent (ktonne)	Fuel consumption of ships in traffic to and from Swedish ports (TRACCS method), (ktonne)	Ratio between emissions in port area and emissions from main engine during journeys to and from ports
Gothenburg	46	150	247	1:5
Halland	3.4	11	36	1:11
Long Beach	74	240	n.a.	n.a.
Osaka	30	97	n.a.	n.a.
Stockholm	30	97	197	1:7
Sydney	29	95	n.a.	n.a.

4.2.3 GHG emissions

GHG emissions for the individual ports were also calculated. Table 10 shows calculated amounts of GHG emissions from ships calling at the six ports. These calculations were carried out on a 'per call' basis by the emissions calculation model developed by IVL Swedish Environmental Research Institute (see Chapter 4.1.2). The GHG emissions from ships in the Port of Gothenburg are 150 000 tonnes CO_2-e, compared with 240 000 tonnes in the Port of Long Beach, 97 000 tonnes CO_2-e in the Port of Osaka, and 95 000 tonnes CO_2-e in the Sydney Ports. In Port of Halland the GHG emissions was 11 000 and in Port of Stockholm 97 000 tonnes.

Comparisons between the ports can be made only in a context of ship traffic characteristics, such as type of shipping, ship types and ship sizes, to give three examples. Further, the geographical boundaries of the emission inventory affect the result. For example, the fairway channels in the Port of Gothenburg, the Ports of Stockholm and the Port of Sydney are longer than for the other ports. The two major sources of GHG emissions are the liquid bulk tankers and ferry/RoRo vessels for the Port of Gothenburg, liquid bulk tankers and container ships for Long Beach, container ships and ferry/RoRo for the Port of Osaka, container ships and liquid bulk tankers for Sydney Ports, ferry/RoRo and cruise for Stockholm, and general cargo and container in Halland.

Table 10. Calculated tonnes CO_2-e from ships in the six case ports.

Ports	Container	Dry bulk	Liquid bulk	General cargo	Ferry/RoRo	Cruise	TOTAL (tonnes CO_2-e)
Gothenburg	26 000	140	44 000	1 500	71 000	2 500	**150 000**
Halland	2 100	1 300	1 600	3 400	2 100	500	**11 000**
Long Beach	83 000	11 000	121 000	980	5 500	17 000	**240 000**
Osaka	32 000	7 400	3 200	14 000	38 000	1 700	**97 000**
Stockholm	1 600	660	3 200	380	73 000	18 000	**97 000**
Sydney	62 000	1 500	28 000	550	130	3 700	**95 000**

** Bunker ships were not possible to separate from other liquid tankers in Port of Osaka, and are consequently included in the liquid bulk category.*

The average CO_2-e emission per port call reveals great differences between the ports; 25, 6, 69, 8, 12, and 70 tonnes per call for the Port of Gothenburg, the Port of Halland, the Port of Long Beach, the Port of Osaka, the Ports of Stockholm and the Ports of Sydney, respectively. The Port of Long Beach and The Port of Sydney have a high ratio of large ships, which partly explain the high average CO_2-e emissions per port call. Large ships imply larger installed main engines and auxiliary engines, as well as a longer time at berth for the loading and unloading of cargo. The CO_2-e emission per port call in Osaka and Halland are less than for the other ports, partly due to short times at berth and mainly due to small engines. A more relevant ratio to compare might be the average CO_2-e emissions for different ship types and sizes (measured as dead weight tonnes or gross tonnage) in the same categories. Which port performing better than the others - based on this comparison - is not consistent for the different ship types, see Table 11.

Table 11. Average CO2-e emissions from ships at berth in the case study ports for different ship types expressed as kg/DWT or kg/GT. The values are excluded if there was two or fewer calls for a specific ship type.

Ship type	Size measure	GOTHENBURG	HALLAND	LONG BEACH	OSAKA	STOCKHOLM	SYDNEY
Tanker	DWT	1.6	1.3	1.2	1.6	1.4	1.4
LG tanker	DWT	4.0	6.6	n.a.	n.a.	n.a.	2.9
General cargo	DWT	0.7	1.4	1.3	1.3	0.6	1.0
RoRo/Ferry	GT	0.8	0.1	n.a.	1.1	0.3	n.a.
Bulk carrier	DWT	0.9	1.3	0.7	0.6	0.6	0.7
Container ship	DWT	1.3	0.8	1.0	0.5	0.9	1.6
Cruise	GT	0.7	n.a.	0.9	2.0	1.1	0.6
Reefer	DWT	n.a.	n.a.	1.6	3.6	n.a.	n.a.
Vehicle carrier	GT	1.0	0.8	0.5	0.5	n.a.	n.a.

Port of Sydney and Port of Long Beach have published emission inventories for ships, for years adjacent to the year of this emission inventory. The total emissions in the Sydney Ports (Port Botany and Port Jackson) were reported to be approximately 123 000 tonnes in 2013 in a study by DNV GL for the NSW Environmental Protection Authority (DNV GL, 2015). The higher figure in the study by DNV GL is mainly due to a much larger area for the inventory. Further differences include that the DNV GL study relies on input from AIS signals, which could be expected to give different results than the port statistics used in this study. Emissions of GHG emissions in the Port of Long Beach are reported yearly in the annual Port of Long Beach Air Emission Inventory report. In 2014, ocean going vessels in the port were reported to cause a total of approximately 290 000 tonnes of CO_2-e emissions (Starcrest, 2015). Emissions from time in fairway channels is included in the study and contributed approximately 80 000 tonnes to total emissions. The emissions from the other operational modes are comparable in size between the Port of Long Beach Air Emission Inventory 2014, and the inventory presented here. Further differences are expected to be mainly related to differences in ship traffic between the years, a more detailed knowledge of the use of OPS in the Port of Long Beach Air Emission Inventory 2014, and minor methodological differences.

Call frequency

The call frequency of individual ships is of high relevance to the potential implementation of different emission reduction measures. The Port of Gothenburg, Port of Stockholm, Port of Halland, and the Port of Osaka, that all have extensive short sea shipping networks, have a large share of vessels that calls at the port regularly. Ships that visit the port more than 10 times per year contributed to 79% of all emissions of CO_2-e in Stockholm, 61% in Gothenburg, 45% in the Port of Halland, and 66% in the Port of Osaka, which can be compared with 8% in the Sydney Ports, and 18% in the Port of Long Beach. In Figure 9, the contribution of CO_2-e from different ship types are split into categories based on frequency of calls. The number of calls in the different categories is indicated.

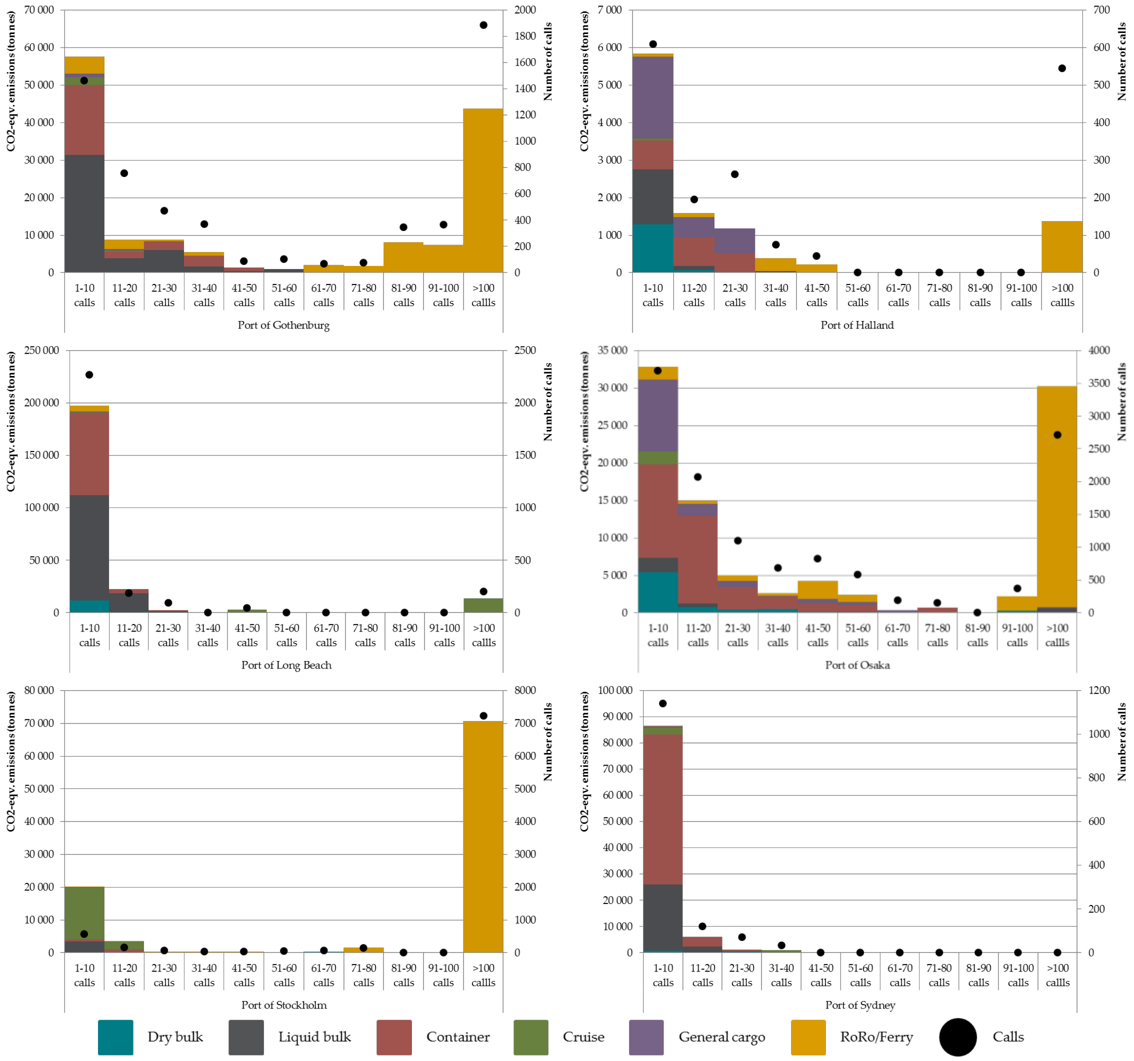

Figure 10. CO_2-e emissions in categories based on frequencies of calls in Port of Gothenburg, Port of Halland, Port of Long Beach. Port of Osaka, Ports of Stockholm and Sydney Ports.

Operational modes

Another important aspect is where emissions occur in the port, since emissions from different operational modes (i.e. “in fairway channel”; “at anchor”; “in port basin”; “manoeuvring”; or “at berth”) are targeted by different measures. The division of emissions from the five operational modes is shown in Figure 10. Over half of the emissions originate from the “at berth” mode for all the ports. The GHG emissions in “the fairway channel”, expressed as a percentage, are higher for

Gothenburg (25%), Osaka (16%), and Halland (13%) than for Sydney (4.5%). There are no data to compare Long Beach and Stockholm because fairway emissions are excluded from the inventory in these studies. The difference between the ports is partly due to length of the fairway channels. Other ship types than liquid bulk tankers seldom need to anchor in the studied ports. There was no information on time in anchorage in Osaka, Halland or Stockholm.

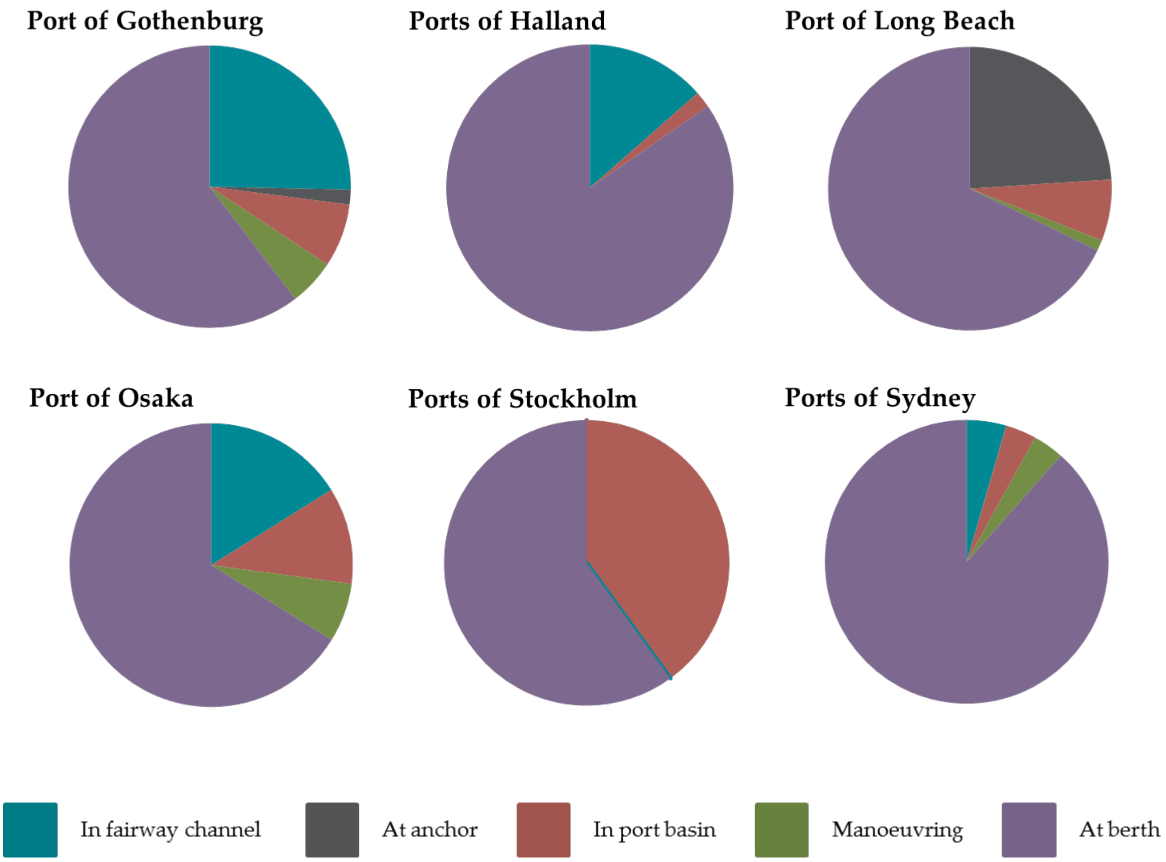

Figure 11. Emissions from ships for different operational modes in the port area for Port of Gothenburg, Port of Halland, Port of Long Beach. Port of Osaka, Ports of Stockholm and Sydney Ports

For ships in the category ”>100 calls” a larger share of emissions are attributable to other modes than at berth for most ports. The share of CO_2-e emissions from different operational modes are shown in Figure 11.

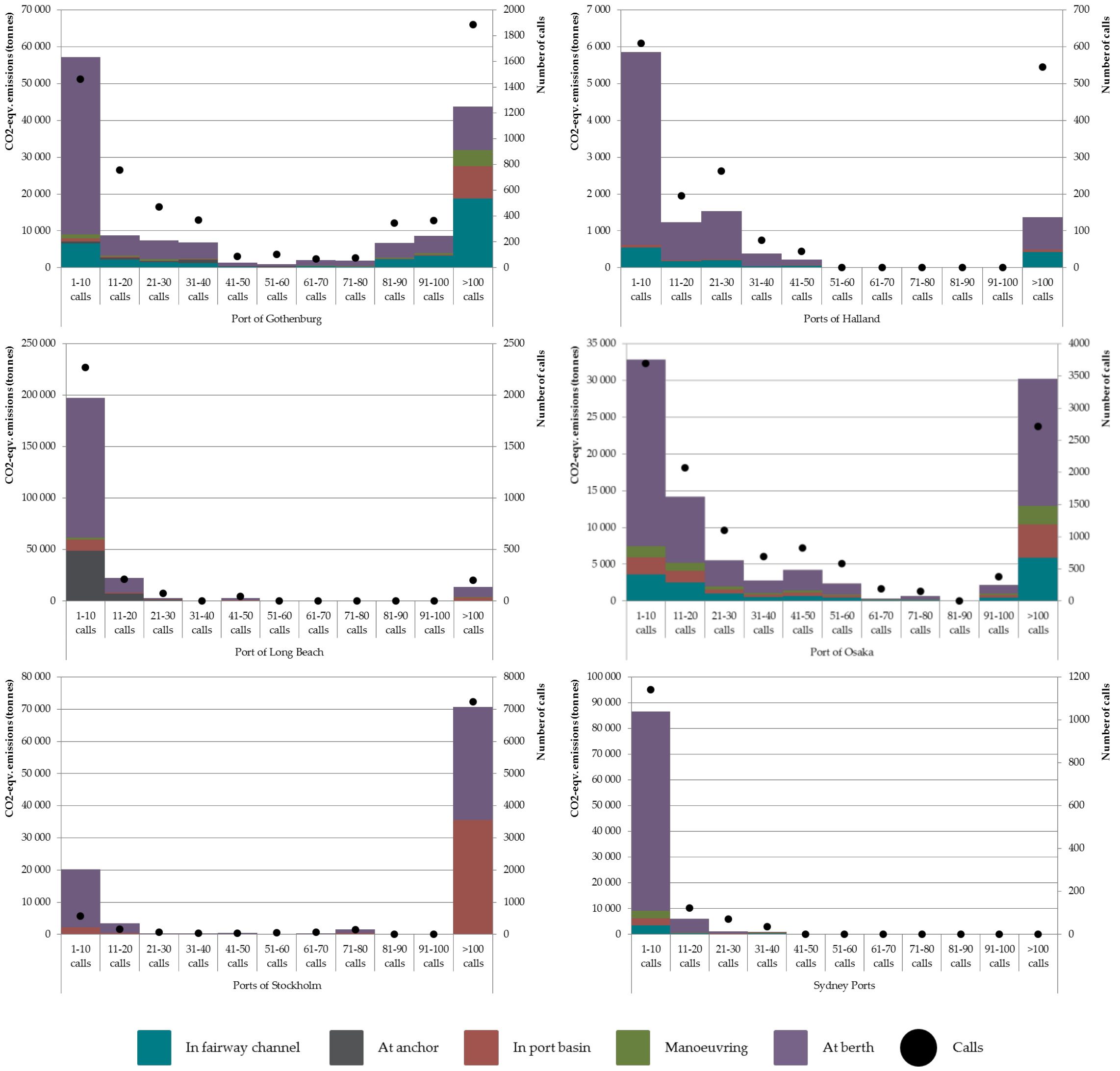

Figure 12. Shares of CO2-e emissions from different operational modes in Port of Gothenburg, Port of Halland, Port of Long Beach. Port of Osaka, Ports of Stockholm and Sydney Ports.

4.2.4 Interview findings

The quantitative analysis was combined with interviews with in total seven port representatives from four of the six ports; Gothenburg, Halland; Stockholm and Sydney. Also a pilot at the Swedish Maritime Administration was interviewed.

Some important findings from the interviews are that the ports have different approaches to improve energy efficiency of the visiting ships. They find the task challenging, often because they have limited possibilities to influence ship owners' decisions. A few comments and conclusions that exemplify the differences between the ports are presented below.

In the Port of Gothenburg, the issue of energy efficient ship transport has been addressed for many years. More recently, the port experience explicit demands from their owner to coordinate efforts to reduce CO_2 emissions from ships by 20% from 2010 levels by 2030. The port control, the traffic information of the maritime administration and the pilot planners, who are all important actors for efficient port calls, are located in the same office. This facilitates that information is made available to the ship masters faster than usual, and ship speeds can be adjusted according to information on the current traffic situation in the port. The Port of Gothenburg offers discount to the port fee according to an index system that considers amongst other aspects CO_2 emissions from ships.

Gothenburg is a large port by Scandinavian measures serving a large variety of ship types and ship sizes. The port representatives mentioned difficulties in making parts of the tanker segment joining efforts to improve energy efficiency. As an example, they highlighted the difficulties in reducing the anchorage time for the liquid bulk segment. The waiting time is often due to speculation and waiting for the market price to change, rather than waiting for available berth or cargo in port.

Speed restrictions were not discussed as a potential energy efficiency measure for ships by the port at the time of the interview. However, in an interview with a pilot in Gothenburg he suggested a reduction of the speed down to 12 knots for Port of Gothenburg. The pilot stated that this would increase the time in the fairway with only 8 minutes for the ships that today go by 15 knots, but would result in an important reduction of both local pollutants as well as GHG emissions.

The potential to influence the energy efficiency by a strong differentiation of the port dues was questioned by one of the port respondents that were interviewed. He stated that the incentive could not be made high enough only based on port fee differentiation.

The representative for the Port of Halland, which is the smallest of the case study ports, states that only little effort can be put into this kind of work in a small organisation. He stressed the fact that a minor and streamlined organisation has limited possibilities to set aside time for acquisition of knowledge and to identify possible environmental measures in its own operations.

The Port of Stockholm, with a high share of high frequent visitors, has since long offered on-shore electricity to ferries and have a subsidy in place for ship owners who want to convert their ships. The interest among ship owners is however low.

The representative also discussed that ships in liner services have a limited potential to reduce speeds due to the fixed time tables. The port representative points out that even if they would enforce speed limits in the fairway channel it might not lead to overall reductions in fuel consumption. Since the ship sailing schedule may be tight, and speed might need to be increased at sea in order to compensate for time loss.

It was clear from the interview with Sydney Ports that environmental improvement of the shipping industry has not yet been a prioritised issue in Australia. However, the cruise ships were pointed out as an emerging issue, mainly due to their emissions to air and noise disturbing Sydney residents. The interviews with port representatives revealed that as the cruise ships servicing Sydney are not, in general, new ships but are cascaded down when they are superseded in other overseas cruise markets, it is unlikely that cruise vessels visiting Sydney will have the provision to accept shore power in the short or medium term.

Three of the port representatives also mentioned that a major reason for working on environmental improvements in port often is to have a good relationship with the citizens living close to the port area.

5 Improvement potential

5.1 Potential fuel reduction for Swedish shipping

An estimate of the relative potential for uptake of energy efficiency measures by different ships and shipping types can either be made very general or very site specific, for example a very in depth analysis of a specific port or shipping line. For the purpose of this study, the general approach was chosen in combination with detailed analyses of ship traffic and fuel consumption for Swedish shipping and for six case study ports. In the second GHG study by the IMO (International Maritime Organization, 2009) a maximum reduction potential of CO_2 emissions from shipping of 75 % is outlined. No other study has taken an overall approach to the issue to the same extent, comprising both design related and operational abatement measures. In our study this potential is used to represent maximum potential fuel consumption reduction. In order to fulfil this potential a combination of several measures are needed. Reduced speed of all ships is an absolute necessity. In addition, powerful regulatory measures and incentive structures are needed as well as cooperative efforts of many different actors. This can also be expected to take several decades, in the IMO report, the time horizon is 2050.

Of the approximately 1 500 000 tonne fuel used, a maximum of around 1100 000 tonnes of fuel could be avoided through a combination of different measures using the argumentation above. This absolute figure is of limited relevance since the amount of fuel used in Swedish shipping will change over time.

5.2 Barriers to energy efficiency

Maritime transport is, in many aspects, an energy efficient mode of transport. Incentives for further improvements are constantly adopted by the industry, even though there are cost-efficient measures available that are not always implemented due to existence of barriers to energy efficiency (e.g. Johnson et al., 2014; Rehmatulla and Smith, 2015). These barriers are mechanisms that prevent investment in technologies that are both energy efficient and economically efficient (Sorrel et al., 2004). Examples of barriers are related to the types of charter contracts that hinder an implementation, lack of reliable information on costs and savings, and lack of direct control over operations (Rehmatulla and 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 and Winnes, 2013).

Measures for reduced ship emissions can be applied to the entire ship service life cycle and on different organisational levels. However, some measures, especially technical measures and the ones related to alternative fuels and/or power sources, are, in practice, more or less limited to new ships (Eide et al., 2011), because retrofit can be a very costly procedure. Considering the long life of a vessel - often around 35 years - new technologies are slowly being implemented in the world’s fleet.

5.3 Improvement measures

In previously research carried out by IVL Swedish Environmental Research Institute, a model was developed to calculate GHG emission reduction from ships in port for various scenarios (Winnes et al., 2015). Different kinds of measures for emission reductions were investigated for diverse types of vessels and parts of the port area. After the model was developed, it was used to calculate GHG emission reduction potential for different scenarios for Port of Gothenburg. The result was compared with a business as usual (BAU) scenario.

This model includes 12 improvement measures divided in three areas:

1. **Alternative to conventional marine fuels for propulsion and on board electricity**
    - Conventional fuel to LNG (Liquefied Natural Gas)
    - Conventional fuel to LBG (Liquefied Bio Gas)
    - Conventional fuel to methanol (MeOH) from fossil sources
    - Conventional fuel to methanol (MeOH) from renewable sources
    - Connection to on-shore power supply
2. **Ship design**
    - Increased share of modern ships
    - Ship design improvements above EEDI 3 levels
3. **Ship and port operation**
    - Reduced speed in fairway channel
    - Reduced turnaround time at berth
    - Reduced lay time at anchor
    - Eco-driving during manoeuvring
    - Faster connection to on-shore power supply

Three scenarios were studied in detail for Port of Gothenburg in the previously conducted study. 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. A detailed description of the methodology is given in Winnes et al., 2015.

The operational measures that contribute most to the emission reductions in the 'Operation' scenario are reduced speed and reduced turnaround time (lay time) at berth. Measures targeting operation result in relatively large reductions, in total 10% compared to the business as usual (BAU) scenario. 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. A 3% reduction in CO_2-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 CO_2-e emissions instead increase by 3%. This is due to the different expected lifetimes of the greenhouse gases in the atmosphere. Methane emissions from the LNG driven ships in the "Fuel" scenario have a stronger relative importance from a 20 year perspective than from a 100 year perspective. Design efforts accomplish 1% reduction in total CO_2-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. An overview of these results is presented in Figure 13.

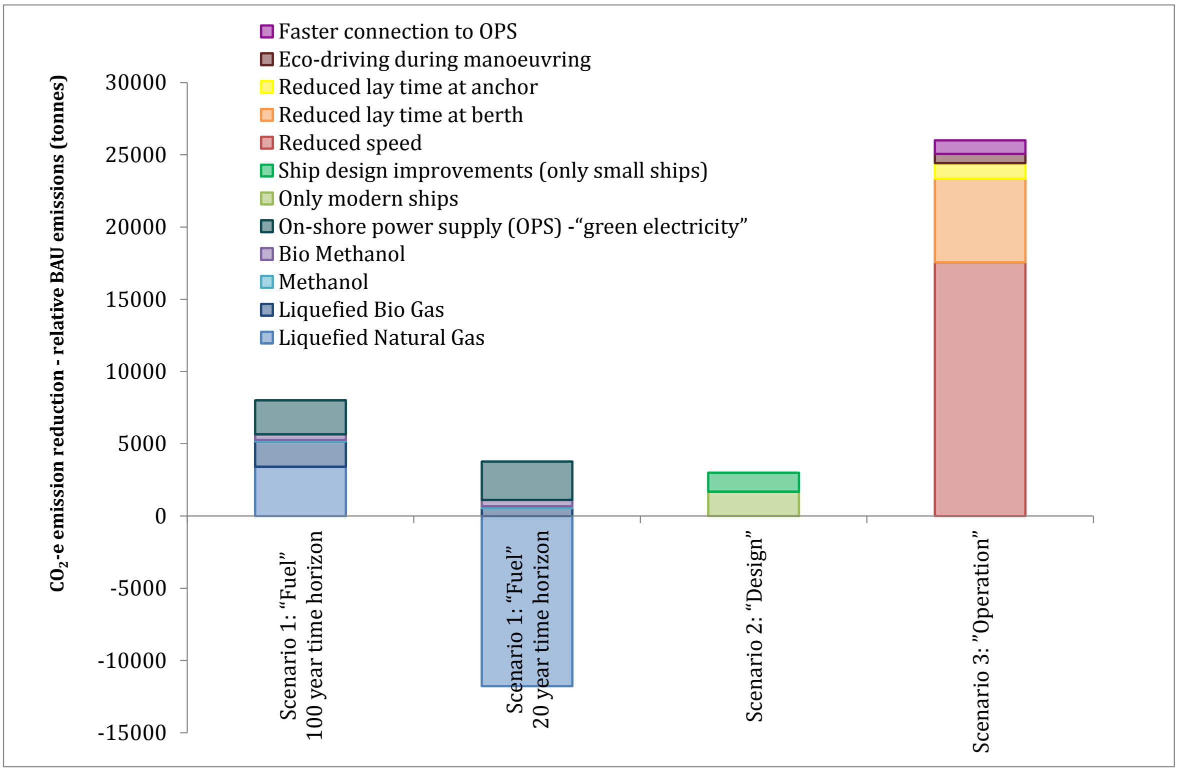

Figure 13. CO2-e emission reductions in the different scenarios and the respective reduction contributions of different measures - Port of Gothenburg 2030 (Winnes et al., 2015).

In this report, the four most important measures identified in that study was selected for further investigation: reduced speed in fairway channels; reduced turnaround time at berth; connection to on-shore power supply: and alternative fuels (LNG, LBG and MeOH).

5.3.1 Reduced speed in fairway channels

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 et al., 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 reduced speed, i.e. slow steaming.

The diminishing demand for transport in the autumn of 2008, due to the financial crisis and the economic downturn, in combination with the arrival of many new-built vessels from the shipyards, resulted in a great level of excess capacity in the world fleet (UNCTAD, 2011). As a consequence, the shipping companies also decreased speed to reduce the excess capacity by tying up existing capacity and to save costs related to bunker fuel (Styhre, 2010). Slow steaming was also widely used in the 1970s during and after the oil crisis (Ronen, 1982).

There has been a significant reduction in CO_2 emissions per unit of 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 et al., 2012; Smith, 2012), and the slow steaming option might not always be a preferable strategy for fleet utilisation. Thus, there is a risk that profit maximisation in shipping can result in higher speed and, consequently, increased emissions in a strong economy (Lindstad et al., 2011). Suggestions to maintain slow speed operations in the international fleet in order to reduce CO_2 emissions from ships include fuel taxes (Cariou, 2011; Corbett et al., 2009) and regulated speed restrictions for ships (Faber et al., 2012; Lindstad et al., 2011).

As the relationship between ship speed and fuel consumption per unit time is approximately cubically increasing, a minor speed reduction can have a great influence on fuel consumption. In general, slow steaming is the GHG reduction measure that is expected to have the highest savings potential (e.g., International Maritime Organization, 2009). However, this potential can be expected to vary significantly between different shipping sectors and operating speeds. In a study within the EU, up to a 30% reduction of the energy need is often realistic at constant transport work for single ships (European Commission, 2012). At constant transport work, reduced speed can be achieved by an increased number of ships in the fleet or by reduced turnaround time in port.

However, there are technical limitations: ships are built to operate effectively at the design speed. Much lower speeds can result in higher levels of pollutants in the exhaust gases and increased maintenance costs. Furthermore, a reduced speed only reduces bunker consumption down to a certain point, which can be called the most energy efficient speed. Below this speed, the fuel consumption increases per transported unit (Cariou, 2011). Technical problems that arise when operating vessels at lower speeds than the design speed can be overcome with adjustments to existing engines (Faber et al., 2012).

Most ports include a fairway channel. Reduced speed in fairway channels can be a large contributing operational measure to CO_2-e emission reductions in ports. The size of the traffic area around a port will determine the potential for this measure. For ports with a limited traffic area, only smaller fractions of total emissions in the port area are likely to be attributed to this mode. However, the potential can be expected to vary significantly between different shipping sectors and operating speeds. Ships with significant power installed in their main engines will contribute more to emission reductions than ships with smaller engines, which in general also have lower design speed. Reduced speed in the fairway is a measure that can be applied on a port level, without interfering with international regulations.

5.3.2 Reduced turnaround time at berth

Reduced turnaround time for a ship at berth allows the vessel to reduce speed at sea and still carry out the same amount of transport work on an annual basis. Faber et al. (2009) have estimated that up to a 10% improvement is possible, and Bazari and Longva (2011) have shown that approximately 10-20% can be achieved depending on ship type and size. Eide et al. (2011) conclude that increased port efficiency is among the measures that have the greatest potential to reduce GHG emissions, and is also one of the least costly. Kontovas and Psaraftis (2011) investigated the effects of different berthing policies on speed reduction. The result shows that a change from a first-come-first-serve policy to a system with pre-booked specific time slots in ports would reduce waiting time for the vessels.

Johnson and Styhre (2015) combined quantitative operational data from Voyage Reports and Statement of Facts with interviews. They concluded that merely by reducing unproductive waiting times, on average, between one and four hours of the time in port could be reduced for a bulk shipping company. For the two ships included in the study, this would correspond to potential fuel consumption reductions from 2 to 8%. In addition to shorter waiting times, the times for the vessel in port can be reduced through more efficient loading and unloading activities, i.e. productivity improvements. Reduced turnaround time for ships also gives the port a benefit of increased berth throughput.

The calculation of improvement potential for Port of Gothenburg in previous research (see further Winnes et al., 2015) showed that the measure with the highest potential was the reduced speed followed by the reduced time at berth. The GHG emissions from ships at berth contribute to between 60 and 88% of the total emissions in the six case ports. Thus, reduced turnaround time for the ships at berth would have a direct effect on this amount of emissions. Reduced turnaround time has many advantages: it reduces the emissions from the auxiliary engines in port. It also allows the shipping company to increase transport work, or reduce speed at sea, and it increases the berth capacity for the port. The turnaround time can be enhanced, for example, by increased productivity, reduced waiting time for stevedores to start loading/unloading and for pilot, reduced congestions, and more efficient clearance procedures (Johnson and Styhre, 2015). The emission reduction potential due to a shorter time at berth is much greater for bigger ships that spend many hours at berth, which often is the case for the liquid bulk ships. In Sydney, for example, the oil tankers, chemical tankers and LG tankers that stay at berth for in average of between 32 and 52 hours. Container shipping is another segment that would indeed benefit from reduced time at berth. The container ships contribute to a large extent to the total GHG emissions in Port of Gothenburg, Port of Halland, Port of Long Beach, Port of Osaka and Sydney Ports.

5.3.3 On-shore power supply (OPS)

Shore-side electricity technology, also known as on-shore power supply (OPS), or "Cold Ironing", replace the on-board generated power from diesel auxiliary engines with electricity supplied from shore. Connecting to on-shore power supply for ships at berth is a measure that can improve air quality in port cities, reduce emissions of air pollutants and reduce noise. Even if OPS is an option that can give significant reductions of local air pollutants from ship auxiliary engines, the emissions issue is being transferred to the point of electricity generation. The potential to also reduce emissions of GHGs is high but that depends on the source of electricity. The use of, for example, wind or hydro generated electricity will give large reductions in the GHG emissions, whilst the use of coal power may give even higher emissions than electricity generated on board the ship. However, it is safe to assume that population exposure to pollutants in the vicinity of the port can be significantly reduced with OPS.

Ship on-board installations for shore-side electricity do normally not impose any major technical implications for new-buildings nor for retrofit on existing ships. However, a mismatch in connection standards and different AC frequency, 50 or 60 Hz, may add to the connection system complexity. The technology includes significant installation costs for both ship and port operators. The use of OPS is therefore most often a result of cooperation efforts between ports and ship operators that frequently visit the same berth. For ships with a limited turnaround time in a port, shore-connection can be impracticable. The on-shore supply capacity varies from port to port and may in some cases be insufficient when the power demand is high, e.g. for large passenger ships but also for tanker ships when cargo pumps are in operation.

The Port of Gothenburg offers connections to the on-shore power (OPS) grid at six RoRo. In the Port of Long Beach, the Shore Power Regulation implies that shipping companies must shut down their auxiliary engines and plug into the electrical grid while at berth. The port will also outfit all of its container terminals with on-shore power in preparation for state regulation requirements. In Ports of Stockholm, OPS is used by a number of the ferries. The port is however ready to install more if ship owners are interested in converting their ships. There are no on-shore power supply in the Port of Halland, Sydney Ports and the Port of Osaka. A recent inquiry by the Government of New South Wales has recommended that on-shore power should be installed at the White Bay Cruise Terminal in Port Jackson after local residents' complaints about air and noise pollution from berthed cruise ships.

Connecting ships at berth to on-shore power is an option that can give significant reductions in the emissions of local air pollutants from auxiliary engines in port, while climate gas reductions depend on the source of electric energy. Ports and ship owner/operators normally take joint investment decisions in OPS solutions. This is mainly due to high capital costs for both sides. Ship owners with ships in liner service might however experience return on investments depending on electricity versus fuel prices and on potential negotiated port due rebates.

For cruise ships there is increased pressure from authorities, customers and community around the world to reduce noise and pollution. Due to the high electricity demands of these ships, the use of OPS on cruise ships has a potential to accomplish large reductions of air pollutants. The total amount of CO_2-e emissions from cruise ships is low for Gothenburg and Osaka, approximately 1000 tonnes CO_2-e, due to few port calls. Sydney, on the other hand, is a major destination for cruise ships around the Pacific Ocean and the number of calls is steadily increasing and in Stockholm the cruise ships contribute with 17% of all emissions. The potential of reductions from OPS installations for cruise ships thus is higher in Stockholm and in Sydney, but implementation faces other difficulties. The relatively short duration stay of the 'domestic' cruise vessels at berth in White Bay (less than 24 hours), and the large costs involved in providing shore power to vessels, together with the required retrofit at a significant cost, caused the use of on-shore power to be considered unreasonable or unfeasible by the New South Wales Government (Black and Styhre, 2015).

5.3.4 Alternative fuels

Fuel shifts from fossil to bio fuels are far from being realised in the transport sector. Major reductions of emissions of GHGs from marine engines can be achieved by replacing fossil fuels with renewable ones. In shipping, an increased use of liquefied natural gas (LNG) and methanol provides potential bridges in order to achieve low-carbon ship transport (Bengtsson et al., 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, SO_2 and particulate matter. The CO_2 emissions are about 25% lower compared with fuel oils but the total emissions of CO_2-equivalents are not necessarily in favour of LNG as a marine fuel since a few per cent of the fuel methane slip through the combustion process unburnt (Bengtsson et al., 2011). Methane is a potent GHG: 86 times more powerful than CO_2 in a 20-year perspective and 34 times as powerful from a 100-year perspective (Myhre et al., 2013). The differences for the two time horizons are due to differences in residence times and reactivity of CH_4 and CO_2 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 causes lower emissions of CO_2-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 (Brynolf et al., 2014).

An introduction of alternative fuels places high demands on the supply infrastructure. Ships that visit several different ports during a year need to be guaranteed that there is a reliable fuel supply for normal operations. Ports can administer the supply of fuels and can further incentivise ships that use cleaner fuels. However, in areas with few supply points, only ships in frequent traffic to these are potential to shift fuel.

Ports of Stockholm is one of the first ports in the world to offer a bunkering infrastructure solution for the provision of LNG to a large passenger ferry. For this reason, logistics and safety procedures have been developed in close collaboration between AGA, the supplier of the gas, Viking Line, who invested in the new vessel, Ports of Stockholm and the relevant authorities. The Port of Gothenburg accommodates an LNG-bunkering facility since 2015, mainly supplying small tanker vessels. The use of LNG and methanol does not necessarily improve the emissions of CO_2-e. However, an introduction of these fuels could be motivated by lower emission levels of local air pollutants and the potential to gradually replace the fossil fuels with fuels with renewable origin.

5.4 Improvement potentials by different ship types

The total calculated amount of fuel used in Swedish shipping, i.e. approximately 1 500 000 tonnes, can be distributed between the ship types, see Table 12. Liquid bulk ships (Tankers) consume more fuel than any other ship type on their journeys to and from Swedish ports. RoRo/Ferry ships are the second largest contributor to fuel consumption in Swedish shipping followed by general cargo ships, container ships, cruise ships, vehicle carriers, bulk carriers and LG tankers, in that order.

Table 12. Fuel consumption of different ship types in Swedish shipping, according to the improved TRACCS model.

Ship type	Fuel consumed (ktonnes)	Fuel/ transport work Swedish shipping (g/tonnekm)
Liquid bulk	360	5
RoRo/Ferry	330	20
General cargo	320	4
Container ship	170	4
Cruise	120	n.a.
Vehicle carrier	68	10
Bulk carrier	57	5
LG tanker	38	8

The data on fuel consumption of different ship types should be considered together with data on expected capacity utilisation of ships. While the liquid bulk needs approximately 5 g of fuel to transport one tonne one km, the RoRo/Ferry ships consumes approximately 20 g for the same amount of transport work, as indicated in Table 12. In order to properly address energy efficiency measures for different ships types both fuel consumption and fuel consumption per transport work are important input. By increasing the capacity utilisation of ships of all types the transport work factor can be improved. Highest potential most likely lies in the RoRo/Ferry category with high fuel consumption per transport work and with a high absolute amount of fuel combusted.

5.5 Improvement potentials in ports

It is argued that the ports can create incentives for shipping companies to reduce their fuel consumption in the port area. For example, some ports are using environmental differentiated port dues, are offering alternative fuel supply and are providing on-shore power supply to visiting ships. The “at berth” mode contributes to more than half of the ship emissions for the ports. Measures that specifically target emissions from at berth mode (e.g. on-shore power supply and reduced time at berth) are similarly effective, especially for terminals with many ships in liner service and high call frequency. Targeting the fuel consumption of the low frequent visitors in the liquid bulk and general cargo categories are difficult. It seems from a port perspective that a focus on incentivising operational methods such as slow speed that do not involve installation costs should hold the most potential for these categories. Vessel speed reductions to and from the port, such as the vessel speed reduction program of the Port of Long Beach, can prove highly efficient for overall CO_2 reductions. However, there are also measures that are more difficult for the ports to have an influence upon. Ship owners, ship operators or cargo owners have more influence over these issues, such as measures related to ship design.

The possibility to influence the shipping companies depends on the port’s position and size. In Sweden, most ports are owned by the local authority. The ports generally form an integral part of the local authority and are treated the same way as any other service. Many ports are small or even very small. This implies that the individual port may not have a strong negotiation power or the assets to invest in expensive equipment, such as on-shore power supply. Especially considering that the utilisation of equipment and facilities in Swedish ports are low due to the large number of ports and rather low cargo volumes.

6 Concluding remarks

Greenhouse gas emissions from shipping are expected to increase in the future (International Maritime Organization, 2014). This stands in contrast to ambitions to reduce the use of fossil fuels. For example, the European Commission has set a goal to reduce emissions from European shipping by at least 40% by 2050. The goal to keep the increase in global mean temperature well below 2°C, as settled in the Paris agreement, is difficult to reach since global action has been slow and all greenhouse gas emitting sectors must now decarbonise rapidly within a few decades. Energy efficiency measures are vital to implement in order to decrease fuel use, although significant reduction in CO_2- emissions can be achieved only by the replacement of fossil fuels with renewable fuels.

In order to reach sustainability objectives for the shipping sector and to decrease the GHG emissions significantly, international steps towards more strict policies and regulations related to alternative fuels and ship operations are central. National efforts are in many ways limited to voluntary incentive schemes, and local port initiatives cannot significantly influence overall energy needs and emission levels. Individual ports can still facilitate a transfer to more energy efficient shipping and a reduction of emissions from ships in the port areas. For example, environmentally differentiated port dues are sometimes used by ports to give rebates to ship owners that perform well. However, it should be noted that there are no evidences that the environmentally differentiated port dues in Sweden are sharp enough to really make a difference. Also coordinating bunkering facilities for alternative fuels to visiting ships is an effort where port engagement is fundamental.

The diverse conditions the ports experience suggest that emission reduction measures need to be customer-tailored for specific ports. Low-frequency shipping services contribute to a relatively large share of GHG emissions in the studied ports. In all ports with the exception of Ports of Stockholm the ships returning between one and ten times to the port cause more emissions than any other frequency category (Figure 9). In Sydney, Long Beach and Halland emissions from this category are completely dominating, while for Gothenburg and Osaka there are also significant emissions from ships in the category of more than 100 calls per year. A high share of emissions from low frequent visitors decreases the ports' potentials to offer significant incentives for fuel shifts, on-shore power supply and design improvements, since these measures often involve high investment costs. For those ports, measures directing ship operations and reducing turnaround time at berth are of more importance. Stockholm is different compared with the other ports, with most emissions from ships in the category more than 100 calls per year.

The ports in the case studies have had different approaches to these issues. From a Swedish perspective the Port of Halland, which is considerably smaller than the Port of Gothenburg and the Ports of Stockholm, does not have the same conditions for proactively addressing environment improvements. The potential reduction is also, naturally, less for small ports than for larger ones with more calls and larger ships. For the Port of Halland the relative importance of fuel consumption in port compared to fuel consumption of ship journeys is less than for the more busy ports. If this is related to the size of visiting ships and a greater share of shorter distances at sea remain to be confirmed with more studies.

The total fuel consumption of Swedish shipping, excluding fuel consumption in port areas has been calculated to approximately 1 500 000 tonnes. If it were possible to decrease this amount of fuel by voluntary incentive systems for speed reductions, more reductions could be accomplished than by single actions in individual ports. This is emphasised by the finding that a substantial share of fuel is used by ships that visit Sweden with low frequencies, emphasising a need for measures relating to ship operations such as speed reductions, to give one example. Significantly more fuel is used during ship journeys than time spent in port areas. Subsequently, there is a higher absolute fuel reduction potential during ships' journeys than in port areas. Actions in ports can however be highly valuable from a port city perspective and contribute to reduced levels of air pollutants in the port city environment.

A lot of work remains in order to have a reliable value of fuel use per unit of transport work. Relating fuel consumption to the service it provides is a part of the concept of energy efficiency in transport. Generic values for capacity utilisation and transport work of Swedish shipping have been calculated in this study, but are not robust enough to support very specific or in-depth analyses. The existence of large differences in energy efficiency between ship types is however clear.

Four different energy efficiency measures have been studied in detail; alternative fuels, reduced turnaround time at berth; on shore power supply; and reduced speed in fairway channels. From a port perspective they could all be of interest. It has been concluded that in all studied ports a majority of emissions come from the "At berth" mode. Measures that specifically target emissions from at berth mode are therefore effective, and the on-shore power supply has already proven successful to reduce fuel consumption and CO_2 emissions for ships in liner services. Alternative fuels are supplied by actors in the port area. In order to use alternative fuels exclusively, a ship will need to visit ports that supply this fuel on a regular basis. Technical solutions that support the use of two different fuels in the same engine exist and make it possible also for ships with less frequent traffic to a bunkering port to use alternative fuels. Still, there are cost issues not considered in this study that of course is of importance for both ship operators and ports before decisions. The operational aspects of reduced time in port and reduced speed in fairway channels can have significant impact, especially the latter, depending on the channel length.

In order to increase the knowledge of ships' emissions and fuel consumption, further steps need to be taken. It is suggested that further research is directed toward better understanding and quantification of the potential for speed reduction, both at sea and in the fairway channels. Lower speed in the fairway channel means lower levels of local pollutants as well as GHG emissions, but it also contributes to less coastal erosion and smaller waves from ships. Further, development of suitable instruments for improvements in different shipping types and segments need to be higher on the research agenda. Further research is suggested to investigate the necessary level of differentiated port dues and decision making processes in shipping companies. Such knowledge could bring new perspectives for practitioners, academia and policy-makers.

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IVL Swedish Environmental Research Institute Ltd.
P.O. Box 210 60 // S-100 31 Stockholm // Sweden
Phone +46-(0)10-7886500 // Fax +46-(0)10-7886590 // www.ivl.se