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Based on AIS data for 2015

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Foreword

Shipping is a major source of emissions of harmful air pollutants and greenhouse gas emissions. The purpose of the "Carrots and sticks" project was to identify the policy instruments and measures that can reduce air emissions from shipping and contribute to the fulfilment of the Swedish environmental quality objectives *Reduced climate impact*, *Clean Air*, *Natural acidification only* and *Zero eutrophication* in a cost-effective way. The project has been carried out by a research team from the Swedish National Road and Transport Research Institute (VTI) and the University of Gothenburg (GU) between the end of 2017 and the beginning of 2020.

During that period several things happened that had a significant impact on the project:

(1) The Swedish environmental quality objectives were revised and comprise, except for the climate goal, no longer quantitative targets. The International Maritime Organization (IMO) agreed on a goal to reduce the greenhouse gas emissions from international shipping by at least 50 percent by 2050, as compared to the 2008 level.

(2) Sweden's official statistics on air emissions from shipping were improved using data from the Automatic information system (AIS). The "Carrots and sticks" applied a similar AIS-based approach to calculate the emissions and compared the outcome, as far as possible, to the official statistics that were published in the end of 2019. See Trosvik et al. (2020).

(3) The Swedish Transport Administration commissioned a study on emission factors for sea transports that are supposed to be used in the Swedish CBA guidelines. This study (Carlsson et al, 2019) was published in august 2019. The "Carrots and sticks" project used emission factors from the literature and compared them to the emission factors in Carlsson et al. (2019). See data set A and B in Holmgren (2020).

(4) The Swedish Maritime Administration appointed VTI to evaluate the impacts of the in 2018 revised fairway dues, see Johansson et al. (2020). The "Carrots and sticks" project used the results regarding port calls and environmental discounts derived in this study. See Vierth (2020).

A summary of Trosvik et al. (2020), Holmgren (2020) and Vierth (2020) is available in Vierth et al. (2020), which includes results and recommendations from the three reports.

The authors would like to thank the participants of the reference group, Sofi Holmin-Fridell (Swedish Maritime Administration), Leif Holmberg and Per Andersson (Swedish Environmental Protection Agency), Katarina Wigler (Swedish Transport Agency), Björn Garberg (Swedish Transport Administration), Helena Leander and Katarina Händel (Swedish Energy Agency), Christine Hanefalk (Ports of Sweden), Åsa Burman (Lighthouse), Fredrik Larsson (Swedish Shipowners´ Association), Christer Ågren (Air Pollution and Climate Secretariat) and Siri Strandenes (Norwegian School of Economics NHH) for their contributions. We especially thank Siri and Christer for valuable comments on earlier versions of our reports.

Furthermore, we thank the Swedish Transport Administration and Sweden's Innovation Agency (Vinnova) for funding the project.

Stockholm, March 2020

Inge Vierth
Projektledare

Quality review

Internal peer review was performed on 13 mars 2020 by Jan-Erik Swärdh. The head of research Mattias Haraldsson examined and approved the report for publication on 19 March 2020. Lina Trosvik, Inge Vierth and Yvonne Andersson-Sköld have made alterations to the final manuscript of the report. The conclusions and recommendations expressed are the authors' and do not necessarily reflect VTI's opinion as an authority. Prof. Kevin Cullinane, University of Gothenburg has reviewed the script.

Kvalitetsgranskning

Intern peer review har genomförts 13 mars 2020 av Jan-Erik Swärdh. Forskningschef Mattias Haraldsson har därefter granskat och godkänt publikationen för publicering 19 mars 2020. Lina Trosvik, Inge Vierth och Yvonne Andersson-Sköld har genomfört justeringar av slutligt rapportmanus. De slutsatser och rekommendationer som uttrycks är författarnas egna och speglar inte nödvändigtvis myndigheten VTI:s uppfattning. Prof. Kevin Cullinane, Göteborgs universitet har språkgranskat manuset.

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Summary

Maritime transport and air emissions in Sweden and business-as-usual scenarios for 2030 and 2045. Based on AIS data for 2015

by Lina Trosvik (VTI), Inge Vierth (VTI) and Yvonne Andersson-Sköld (VTI)

This report is part of the Carrots & Sticks project, which has the main purpose of analysing policy instruments and measures that most cost-effectively can reduce emissions from maritime transport in Sweden. The purpose of this report is to provide an overview of the current situation of maritime transport in Sweden and to provide business-as-usual (BAU) scenarios for the future development of air emissions. By using AIS data (Automatic Identification System) for 2015, this report uses a bottom-up method to estimate air emissions from maritime transport. The report also examines how the estimated emissions contribute to the achievement of Swedish environmental quality objectives.

The environmental quality objectives of relevance when examining emissions to air from maritime transport, and which are of relevance within the Carrots & Sticks project, are *Reduced climate impact, Clean air, Natural acidification only* and *Zero eutrophication.* This report therefore focuses on the development of emissions to air related to these four objectives, which include emissions of carbon dioxide (CO_2), sulphur dioxide (SO_2), particulate matter (PM) and nitrogen oxide (NO_X).

The method used in the official statistics for estimating air emissions from maritime transport has recently (December 2019) been substantially modified. The previous estimation method had ambiguities related to the data collection process, which was the main reason for the modification of the method. Due to these uncertainties, this report develops an alternative method for estimation of emissions. The main advantages of the estimation method used in this report compared to the method used in the official statistics are that it allows a classification of the traffic types domestic, international and transit and that it covers a specific geographical area surrounding Sweden, which provides more information about where the emissions are emitted. Furthermore, recently developed emission factors are applied, which take current and decided policy instruments into account. The dataset also allows for the possibility of separating emissions emitted at sea and at berth, which can facilitate the analysis of the potential that policy instruments can have on emissions reduction.

For the estimation of emissions in 2015, this report finds that emissions of CO_2, SO_2, PM_{10} and NO_X from domestic maritime transport are at least twice as high as the emissions in official statistics based on the previous estimation method. Compared with the emissions estimated by the new official method, the estimated emissions in this report are about the same for SO_2 and PM_{10}, but slightly lower for CO_2 and slightly higher for NO_X. The estimated emissions from transit and international maritime transport are substantially higher than the emissions from domestic maritime transport, both according to the official statistics and the estimation method used in this report.

This report estimates four BAU scenarios of emissions until 2030 and 2045, using 2015 as the base year, in which different assumptions are made regarding future transport demand, energy efficiency improvements and fuel switches. For domestic traffic, the highest scenario indicates increased emissions of CO_2, SO_2, and PM_{10} by about 28% over the period 2015–2045. NO_X emissions are instead indicated to decrease by about 55% over the time period. In the lowest scenario, which includes a fuel switch towards a higher share of carbon-neutral fuels, all emissions are indicated to decrease over the period 2015–2045. For international traffic, the highest scenario indicates increased emissions of CO_2, SO_2, and PM_{10} by about 37% and NO_X emissions are instead indicated to decrease by about 51% over the period 2015–2045. In the lowest scenario, which includes a fuel switch towards a higher share of carbon-neutral fuels, all emissions are indicated to decrease over the period 2015–2045. Hence, since all scenarios indicate decreasing emissions of NO_X, the development over time is

different from the trends of the other emissions. The different trend for NO_X emissions can be explained by assumptions made regarding the introduction of the NO_X Emission Control Area (NECA).

Based on the estimated BAU scenarios until 2045, the targets related to the Swedish environmental quality objective of *Reduced climate impact* are indicated to not be achieved. In the lowest scenario, emissions of CO_2 from domestic maritime transport are expected to decrease by 19% by 2030 and by 45% by 2045. When including the additional methane emissions associated with the use of LNG, the total greenhouse gas (GHG) emissions are instead found to decrease by 15% by 2030 and by 39% by 2045. Hence, comparing these estimated reductions to the Swedish GHG targets of reducing emissions by 70% by 2030 (compared to 2010 emission levels) and achieving zero net GHG emissions by 2045, it is clear these targets will be far from being reached by continuing with business as usual.

Regarding the Swedish environmental quality objectives of *Clean air, Natural acidification only* and *Zero eutrophication*, the estimated emissions of SO_2, PM_{10} and NO_X are found to be at least twice as high as previous estimations in official statistics. Hence, achieving these objectives can be expected to be even further away. Moreover, the findings in this report suggest that international and transit traffic contribute to considerably higher levels of emissions than domestic traffic and that the share from international maritime transport has been increasing over time. Even though emissions from international and transit traffic are mainly emitted outside of Sweden, air pollutants can be transported by winds and also affect the Swedish environment. Hence, this demonstrates that it is important to consider emissions from international maritime transport when examining Swedish environmental objectives.

Sammanfattning

Sjöfart och utsläpp till luft i Sverige och ”business-as-usual” scenarier till 2030 och 2045. Baserat på AIS-data från 2015

av Lina Trosvik (VTI), Inge Vierth (VTI) och Yvonne Andersson-Sköld (VTI)

Denna rapport är en del i projektet Morötter och Piskor, vilket har som huvudsakliga syfte att analysera vilka styrmedel och åtgärder som mest kostnadseffektivt kan bidra till att minska utsläpp till luft från sjöfarten i Sverige. Denna rapport syftar till att ge en översikt av nuläget inom sjöfarten i Sverige samt att estimera ”business-as-usual” (BAU)-scenarier för den framtida utvecklingen av utsläpp till luft. Baserat på AIS (Automatic Identification System)-data från 2015 estimerar denna rapport, med hjälp av en ”botten-upp”-metod, utsläpp till luft från sjöfarten. Vidare undersöker rapporten hur de estimerade utsläppen bidrar till uppfyllandet av svenska miljökvalitetsmål.

De miljökvalitetsmål som är relevanta vid analyser av utsläpp från sjöfart inom detta projekt är *Begränsad klimatpåverkan*, *Frisk luft*, *Bara naturlig försurning* och *Ingen övergödning*. Denna rapport fokuserar därför på utvecklingen av utsläpp till luft relaterat till dessa fyra mål, vilka inkluderar utsläpp av koldioxid (CO_2), svaveldioxid (SO_2), luftburna partiklar (PM) och kväveoxider (NO_X).

Metoden som används i den officiella statistiken för att estimera utsläpp till luft från sjöfarten har nyligen (december 2019) modifierats avsevärt. Den tidigare officiella estimeringsmetoden innebar osäkerheter relaterade till datainsamlingen, vilket är den främsta anledningen till att metoden modifierades. På grund av dessa osäkerheter använder denna rapport en alternativ metod för att estimera utsläpp. De främsta fördelarna med metoden som används i denna rapport jämfört med den officiella metoden är att den ger möjlighet att klassificera utsläppen på trafiktyperna inrikes, utrikes och transit, samt att den omfattar utsläpp från ett specifikt geografiskt område kring Sverige, vilket ger mer information om var utsläppen har gjorts. Vidare används nyligen publicerade emissionsfaktorer som tar hänsyn till existerande och beslutade styrmedel. Datasetet ger även möjlighet att separera vilka utsläpp som har gjorts i hamn och till havs, vilket kan underlätta analysen av vilken effekt potentiella styrmedel kan förväntas ha på utsläppsminskningar.

Estimeringsresultaten för år 2015 indikerar att utsläppen av CO_2, SO_2, PM_{10} och NO_X från inrikes sjöfart är minst dubbelt så höga jämfört med den officiella statistiken som baseras på den äldre officiella metoden. Jämfört med statistiken som baseras på den uppdaterade officiella metoden är estimeringsresultaten av SO_2 och PM_{10} är ungefär lika stora, medan CO_2 är något lägre och NO_X är något högre. Utsläpp till luft från utrikes och transit sjöfart är betydligt högre än utsläppen från inrikes sjöfart, både baserat på resultaten i denna rapport och enligt den officiella statistiken.

Med år 2015 som basår estimerar denna rapport fyra BAU-scenarier för utsläpp till 2030 och 2045 i vilka olika antaganden har gjorts om framtida transportefterfrågan, energieffektiviseringar och bränslebyten. För inrikes sjöfart indikerar det högsta scenariot ökade utsläpp av CO_2, SO_2 och PM_{10} med omkring 28 % mellan 2015–2045. Utsläpp av NO_X är istället indikerade att minska med omkring 55 % över tidsperioden. Det lägsta scenariot, vilket bland annat inkluderar ett bränslebyte mot en högre andel koldioxidneutrala bränslen, indikerar en minskning av alla utsläpp mellan 2015–2045. För utrikes sjöfart indikerar det högsta scenariot ökade utsläpp av CO_2, SO_2 och PM_{10} med omkring 37 % mellan 2015–2045. Utsläpp av NO_X är istället indikerade att minska med omkring 51 % över tidsperioden. Det lägsta scenariot, vilket bland annat inkluderar ett bränslebyte mot en högre andel koldioxidneutrala bränslen, indikerar en minskning av alla utsläpp mellan 2015–2045. Då alla scenarier indikerar minskande utsläpp av NO_X är den estimerade utvecklingen över tid annorlunda från utvecklingen av de övriga utsläppen. Den annorlunda trenden av NO_X-utsläpp kan förklaras av

antaganden som gjorts angående introduktionen av den så kallade ”NO_X Emission Control Area” (NECA).

Baserat på de estimerade BAU-scenarierna till 2045 är målen som är relaterade till miljökvalitetsmålet *Begränsad klimatpåverkan* indikerade att inte nås. I det lägsta scenariot förväntas CO_2-utsläppen från inrikes sjöfart att minska med omkring 19 % till 2030 och med 45 % till 2045. När metanutsläpp relaterade till användningen av LNG inkluderas i estimeringen är de totala växthusgasutsläppen istället indikerade att minska med omkring 15 % till 2030 och med 39 % till 2045. I en jämförelse mellan de estimerade utsläppsminskningarna och de svenska klimatmålen om att minska växthusgasutsläpp från inrikes transporter (exklusive flyg) med 70 % till 2030 (jämfört med 2010 års nivåer) och att nå nettonollutsläpp till 2045 är det tydligt att dessa mål är långt ifrån att uppnås genom att fortsätta med ”business-as-usual”.

Angående miljökvalitetsmålen *Frisk luft*, *Bara naturlig försurning* och *Ingen övergödning* indikerar estimeringsresultaten dubbelt så höga utsläpp av SO_2, PM_{10} och NO_X jämfört med statistik baserat på den äldre estimeringsmetoden. Att nå dessa mål kan alltså förväntas vara längre bort än tidigare. Vidare indikerar resultaten i denna rapport att utrikes och transit sjöfart bidrar med betydligt högre utsläpp än inrikes sjöfart samt att andelen utsläpp från utrikes sjöfart har ökat över tid. Även om utsläppen från utrikes och transit sjöfart huvudsakligen görs utanför Sverige kan luftföroreningar transporteras med vindar och således påverka Sveriges miljö. Detta påvisar att det är viktigt att ta hänsyn till utsläpp från utrikes sjöfart när svenska miljökvalitetsmål analyseras.

List of acronyms

AE	Auxiliary engine
AIS	Automatic Identification System
BAU	Business-as-usual
CO_2	Carbon dioxide
EEA	European Environment Agency
EEDI	Energy Efficiency Design Index
EMEP	European Monitoring and Evaluation Programme
GHG	Greenhouse gas
GT	Gross Tonnage
GWP	Global Warming Potential
HFO	Heavy Fuel Oil
HSFO	High Sulphur Fuel Oil
IMO	International Maritime Organisation
LNG	Liquefied Natural Gas
ME	Main engine
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
NECA	Nitrogen oxide Emission Control Area
NO_X	Nitrogen oxide
OPS	On-shore Power Supply
PM	Particulate matter
SECA	Sulphur Emission Control Area
SEEMP	Ship Energy Efficiency Management Plan
SO_2	Sulphur dioxide
TTP	Tank-to-propeller
ULSFO	Ultra-Low Sulphur Heavy Fuel Oil
WTP	Well-to-propeller
WTT	Well-to-tank

1. Introduction

This report is part of the Carrots & Sticks project, which has the main purpose of analysing policy instruments and measures that most cost-effectively can reduce emissions from maritime transport in Sweden. The main purpose of this report is to provide an overview of the current situation of maritime transport in Sweden and to provide business-as-usual (BAU) scenarios for the future development of air emissions from maritime transport. The report also aims to examine how the emissions from maritime transport contribute to the achievement of the Swedish environmental quality objectives.

Sweden has 16 environmental quality objectives describing the quality of the environment that Sweden aims to achieve (Swedish EPA, 2019a). The environmental quality objectives of relevance when examining emissions to air from maritime transport, and which are of relevance within the Carrots & Sticks project, are *Reduced climate impact, Clean air, Natural acidification only* and *Zero eutrophication.* This report therefore focuses on the development of emissions to air from maritime transport related to these four environmental quality objectives. More specifically, the report focuses on emissions of carbon dioxide (CO_2), sulphur dioxide (SO_2), particulate matter (PM) and nitrogen oxide (NO_X).

The method used in the official statistics for estimating emissions from maritime transport has recently (December 2019) been substantially modified. The main reason for developing a new estimation method was that the previous method had uncertainties related to the data collection process. For example, in 2019, the previous estimation method was highlighted in the media for producing results which were inconsistent with new estimations conducted by the Swedish Meteorological and Hydrological Institute (SMHI). The new estimations of domestic marine fuel consumption, which are based on AIS data (Automatic Identification System, a global system that identifies vessels and their movements), were found to be almost twice as high as in the official statistics (Windmark et al., 2017). There were also fluctuations in the official statistics for which the Swedish EPA (2019a) could not find explanations and the distribution of fuel consumption between domestic and international maritime transport were said to be afflicted with measurement errors. The main difference between the new and the previous official estimation method is that the new method is partly based on AIS data.

Due to these ambiguities related to the official statistics, it is relevant to use an alternative method to estimate emissions from maritime transport and to compare them with the official statistics. This report therefore uses a bottom-up approach, which is based completely on AIS data. The data, developed by Windmark (2019), is based on the so-called Shipair model and includes information about the number of ships, the characteristics of the ships and the fuel consumption at sea and at berth of ships in the model area (covering the Baltic Sea, Skagerrak and Kattegat). The data are divided into 11 ship types and into three categories of traffic: domestic, international, and transit traffic. To be able to compare results between the estimation methods, this report focuses on eight commercial ship types that the official statistics are also based upon.

Compared to the previous and new estimation methods used in official statistics, the estimation method used in this report has several advantages. First, the estimation of the fuel consumption is based on a reliable method where ship movements are considered and it also allows a clear classification of domestic, international and transit traffic. More specifically, the newly updated official statistics only estimate emissions from international ship journeys departing from Sweden, whereas the AIS data used in this report include journeys both departing from and arriving in Sweden. Second, the official statistics include international journeys to all non-Swedish destinations, whereas the data used in this report cover a specific geographical area surrounding Sweden, which hence provides more information about where the emissions are emitted. This facilitates the analysis of the effects from the emissions on the Swedish environmental quality objectives. Third, another advantage of using AIS data, which is different from the new official publication of statistics, is that the emissions from vessels at sea and at berth can be separated. This information can be useful, for example, when analysing effects from the emissions on people's health or the environment, since emissions at berth are often closer to where people live compared to emissions at sea.

The estimated emissions in this report are compared to the official statistics and are also used as the base in the estimation of BAU scenarios of future emissions from maritime transport. The BAU scenarios are estimated until 2030 and 2045, using the year of 2015 as a base. The choice of years is based on the Swedish climate targets, which is to achieve zero net greenhouse gas (GHG) emissions by 2045 and thereafter achieve negative emissions. There is also an interim target relevant for maritime transport, which is to reduce GHG emissions from domestic transport (excluding aviation) by at least 70% by 2030, compared to 2010 emission levels (SOU 2016:47). In addition, the BAU scenarios take some decided and/or implemented policy instruments into account. For example, the Sulphur Emission Control Area (SECA), the NO_X Emission Control Area (NECA), the Energy Efficiency Design Index (EEDI), and the Ship Energy Efficiency Management Plan (SEEMP) are included in the estimations by using updated emission factors and estimates of future energy efficiency improvements.[1]

The results of this report will be further used within the Carrots & Sticks project. For example, the identification of average vessel types is used in Holmgren (2020), in which the vessel types and their fuel consumption are used to calculate the potential emission reductions from various policy instruments and measures. The estimated emissions in the BAU scenarios from this report are used in Vierth (2020) in a cost-benefit analysis of different policy instruments and combinations of policy instruments.

This report is structured as follows. Section 2 presents the environmental quality objectives of relevance for this report, along with an overview of international objectives and how these are related to maritime transport. Section 3 describes the data and the alternative method for estimation of emissions used in this report. Section 4 is based on official statistics and presents the historic development of emissions from maritime transport. The section also shows the development of tonne- and passenger-kilometres and presents an overview of the Swedish vessel fleet. Section 5 is based on AIS data and presents an overview of maritime transport in 2015. The section identifies average vessel types and estimates fuel consumption in total and at berth. The estimated fuel consumption is then used as a base for the estimation of emissions from maritime transport, which is presented at the end of the section. Section 6 presents forecasts of factors that may affect the future development of maritime transport. Section 7 presents the estimated BAU scenarios until 2030 and 2045. Section 8 provides a discussion and section 9 concludes.

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[1] The SECA covers the Baltic Sea, the North Sea, and the English Channel and mandates the use of fuel with no more than 0.1% sulphur content or the use of scrubbers to achieve the equivalent, as from 1 January 2015. NECA will cover the Baltic Sea, the North Sea, and the English Channel and will require all new vessels built after 1 January 2021 to apply certain emission standards for nitrogen oxides. EEDI and SEEMP are measures aimed at promoting the use of more energy efficient equipment and engines and requires all ship owners to manage ship and fleet efficiency performance over time.

2. Environmental objectives

This section presents the environmental objectives of relevance for this report and describes how they are related to maritime transport. Swedish objectives are presented in section 2.1 and international objectives are presented in section 2.2.

2.1. Swedish objectives

Sweden has 16 environmental quality objectives that describe the quality of the environment that Sweden aims to achieve by 2020. The objectives cover different areas and include specifications of the state of the environment to be attained (Swedish EPA, 2019a). The environmental quality objectives of relevance when examining emissions to air from maritime transport are *Reduced climate impact, Clean air, Natural acidification only* and *Zero eutrophication.* This section presents these objectives and describes how maritime transport affects them (see Table 1 for a summary).

The objective *Reduced climate impact* specifies that Sweden will work internationally to ensure that efforts are directed towards achieving the goal of limiting the global average temperature increase to well below 2 degrees Celsius above pre-industrial levels, and that efforts are made to keep the increase below 1.5 degrees Celsius above pre-industrial levels (Swedish EPA, 2019a). More specifically, Sweden's domestic overarching climate target is to achieve zero net GHG emissions by 2045 and, thereafter, to achieve negative emissions. There is also an interim target relevant for maritime transport, which is to reduce GHG emissions from domestic transport (excluding aviation) by at least 70% by 2030, compared to 2010 emission levels (SOU 2016:47). The 2030-target covers emissions at the tank-to-propeller (TTP) perspective, whereas the 2045-target covers emissions at the well-to-propeller (WTP) perspective.[2]

The objective *Clean air* has the aim of ensuring that the air is clean enough not to represent a risk to human health or to animals, plants or cultural assets. For this purpose, ten target values of concentrations of air pollutants have been set. The target values specify the maximum concentration (micrograms per cubic metre) of ten different air pollutants (Swedish EPA, 2019a). There are target values for selected volatile hydrocarbons, particulate matter ($PM_{2.5}$ and PM_{10}), NO_X and surface ozone. As the ozone concentration depends on the NO_X concentrations (as well in as other pollutants, radiation and additional interacting factors in a non-linear way), the emissions of particulate matter from maritime transport is related to the emissions of SO_2 and ammonia, and the formation of secondary organic particles depend on NO_X. According to the Swedish EPA (2019a), it will not be possible to achieve the objective by 2020 based on already decided or planned policy instruments. The main positive developments towards achieving the target are increasingly efficient engines and less environmentally damaging fuels which, however, are partly offset by traffic growth. Moreover, several of the pollutants included in the objective can be transported long distances across national borders, hence making international cooperation important to reduce the emissions (Swedish EPA, 2019a).

The objective *Natural acidification only* has the aim of ensuring that the acidifying effects of deposition and land use do not exceed the limits that can be tolerated by soil and water. There are four specifications in the objective, one of which is relevant for emissions related to maritime transport: the deposition of airborne sulphur and nitrogen compounds from Swedish and international sources shall not contribute to exceeding the critical load for soil and water acidification. The relevant acidifying air pollutants related to emissions from maritime transport are sulphur and nitrogen compounds. International shipping is one of the main sources of acidifying pollutants in Sweden, due to the emissions of NO_X (Swedish EPA, 2019a). According to the Swedish EPA (2019a), it will not be

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[2] The TTP perspective includes the emissions from the combustion of the fuel. The WTP perspective includes the emissions from the production to the combustion of the fuel.

possible to achieve the objective by 2020 based on already decided or planned policy instruments. Many acidifying pollutants are transported by winds from other countries or from international shipping, hence making international cooperation important to reduce emissions.

The objective *Zero eutrophication* has the aim of ensuring that nutrient levels in soil and water do not negatively affect human health, biological diversity or the possibility of varied use of land and water (Swedish EPA, 2019a). There are four specifications in the objective, two of which are relevant for emissions related to maritime transport: 1) atmospheric deposition should not result in ecosystems showing any significant long-term adverse effects of eutrophicating substances in Sweden, and 2) the seas have, at least, good environmental status with respect to eutrophication under the marine Environment Regulation (Swedish EPA, 2019a). Eutrophication is caused by excessive levels of nitrogen and phosphorus and is currently a significant threat to the marine environment, especially in the Baltic Sea, but also in lakes, rivers and soils. In Sweden, NO_X emissions from maritime transport are a major contributor to eutrophication. According to the Swedish EPA (2019a), it will not be possible to achieve the objective by 2020 based on already decided or planned policy instruments. Most atmospheric deposition of eutrophying pollutants are transported by winds from other countries or from international shipping, hence making international cooperation important to reduce emissions.

Table 1. Description of the Swedish environmental quality objectives related to maritime transporation and the effects of the emissions of different pollutants.

	Reduced climate impact	**Clean air**	**Natural acidification only**	**Zero eutrophication**
Objective	To ensure that efforts are directed towards achieving the goal of limiting the global average temperature increase to well below 2 degrees Celsius above pre-industrial levels, and efforts are made to keep the increase below 1.5 degrees Celsius above pre-industrial levels.	To ensure that the air is clean enough not to represent a risk to human health or to animals, plants or cultural assets.	To ensure that the acidifying effects of deposition and land use do not exceed the limits that can be tolerated by soil and water.	To ensure that nutrient levels in soil and water do not negatively affect human health, biological diversity or the possibility of varied use of land and water.
Interim targets relevant for maritime transport	1) Achieve -70% GHG emissions from domestic transport (excluding aviation) by 2030, compared to levels in 2010. 2) Achieve zero net GHG emissions by 2045.	Achieve ten target values of concentrations of air pollutants by 2020. Air pollutants related to maritime transport include SO_2, NO_X and PM emissions from sea transport in the Baltic Sea and the North Sea.	One (out of four) specification relevant for maritime transport: The deposition of airborne sulphur and nitrogen compounds from Swedish and international sources shall not contribute to exceeding the critical load for soil and water acidification in any part of Sweden.	Two (out of four) specifications relevant for maritime transport: 1) Atmospheric deposition does not result in ecosystems showing any significant long-term adverse effects of eutrophicating substances. 2) The seas have, at least, good environmental status with respect to eutrophication under the marine Environment Regulation.
Indicators relevant for maritime transport	GHG emissions, energy/fuel consumption and fuel types.	Emissions of NO_X, SO_2, $PM_{2.5.}$ NO_X contributes to ozone and NO_X and SO_2 to secondary $PM_{2.5}$	Emissions of acidifying substances by maritime transport (SO_2 and NO_X)	Nitrogen and phosphorus deposition to terrestrial and freshwater ecosystems and to the sea (mainly from land sources, but also deposition of airborne NO_X).
Effects from GHG emissions at sea	**Direct effect** All ships using oil, LNG or LBG contribute to GHG emissions, both at sea and at berth. To what extent electrified ships contribute depends on how the electricity is produced.	**No impact**	**Indirect effect** Not included in the objective, but CO_2 has an acidifying effect in seas.	**No impact**

	Reduced climate impact	Clean air	Natural acidification only	Zero eutrophication
Effects from SO_2 emissions at sea	**No impact**	**Indirect effect** Maritime transport contributes to SO_2 which contributes to formation of secondary $PM_{2.5}$.	**Direct effect** Maritime transport contributes to SO_2 emissions.	**No impact**.
Effects from PM emissions at sea	**Direct and indirect effect** Maritime transport contributes to PM containing black carbon altering the radiation especially deposited in the arctic region.	**Direct effect** Maritime transport contributes to PM emissions. $PM_{2.5}$ from NO_X and SO_2 emissions.	**Direct effect** Maritime transport contributes to PM emissions. PM emissions correlate to SO_2 emissions.	**No impact**
Effects from NO_X emissions at sea	**No impact**	**Direct effect** Maritime transport contributes to background levels. NO_X contributes to ozone and $PM_{2.5}$.	**Direct effect** Maritime transport contributes to NO_X emissions.	**Direct effect** Maritime transport contributes to NO_X emissions.
Effects from local emissions in Swedish ports	**Direct effect** All ships using oil, LNG and LBG at berth contribute to GHG emissions. To what extent electrified ships contribute depends on how the electricity is produced.	**Direct effect** Emissions of NO_X in ports contributes to increased local concentrations of SO_2, NO_2 and $PM_{2.5}$. In addition, the emissions contribute to increased concentrations of secondary $PM_{2.5}$ and long-distance transportation.	**Direct effect** Emissions of NO_X and SO_2 in ports contributes to its long-distance transport to all recipients.	**Direct effect** Emissions of NO_X in ports contributes to its long-distance transport to all recipients.

Sources: Swedish EPA (2019a; 2019i).

2.2. International objectives

There are also international environmental targets and objectives that are relevant when examining emissions from maritime transport. However, since the main purpose of this study is to follow up on Swedish environmental objectives, the international environmental objectives will mainly be included for comparison reasons and for following up on emissions from international traffic.

The EU National Emission Ceilings (NEC) Directive, which entered into force in 2016, sets emission reduction commitments until 2020 and 2030 for member states and the EU for the five air pollutants NO_X, non-methane volatile organic compounds (NMVOCs), SO_2, ammonia (NH_3) and fine particulate matter ($PM_{2.5}$) (Directive (EU) 2016/2284). According to the Swedish EPA (2019b), Sweden has achieved the emissions reduction commitments for 2020 in the NEC Directive for SO_2, NO_X and $PM_{2.5}$. The EU NEC Directive also specifies that all EU member countries develop and implement national air pollution control programs that describe how they will reduce emissions in order to achieve the emission reduction commitments. Sweden has implemented such a program, in which it is described that, in order to achieve the commitments until 2030, measures mainly will have to be taken to reduce emissions of NH_3 and NO_X, while the emission reduction commitments for SO_2 and $PM_{2.5}$ are expected to be achieved. More specifically, to reduce emissions of NO_X, the Swedish EPA (2019c) emphasises measures to reduce emissions from domestic transport and the industry sector.

Another international target is the International Maritime Organisation's (IMO) reduction target for GHG emissions from ships. The target specifies a reduction of GHG emissions from international maritime transport of at least 50% by 2050, compared to the levels in 2008 (IMO, 2018). Furthermore, in a white paper about the future European transport area, the European Commission (2011) provides a target of reducing CO_2 emissions from maritime bunker fuels by 40% (or by 50% if feasible) by 2050, compared to 2005 levels.

3. Methods and data description

To examine how maritime transport contributes to the achievement of the environmental quality objectives, this report studies the development of emissions from maritime transport. However, there are ambiguities related to the Swedish official statistics for maritime transport, which is why this report also uses an alternative method for the estimation of emissions. Section 3.1 provides a data description of the official statistics and of the AIS data, upon which the alternative estimation method is based. Section 3.2 presents the alternative method used in this report for the estimation of emissions.

3.1. Data overview

Emissions to air from maritime transport are estimated based on fuel consumption. When examining whether the environmental quality objectives can be achieved, it is therefore important to have an accurate estimation of the total fuel consumption. Section 3.1.1 presents the old and new method used in official statistics for the estimation of fuel consumption from maritime transport and section 3.1.2 presents the alternative fuel estimation method based on AIS-data.

3.1.1. Official statistics

Previous official estimation method

In the official statistics estimated by the previous estimation method, the fuel consumption both for domestic and international maritime transport was based on the amount of fuels that are purchased and consumed according to a monthly survey on the supply and delivery of petroleum products, conducted by Statistics Sweden (Swedish EPA, 2019d). The data are collected from oil companies and other oil suppliers that keep stocks of petroleum products and coal in Sweden. The fuels used for maritime transport were separated by the survey respondents into domestic and international fuel consumption.

The fuel consumption from domestic transport is defined as fuels bought in Sweden that are used for journeys that both depart and arrive in Sweden. Fuel consumption by international transport, referred to as ‘international bunkers’, is defined as fuels bought in Sweden by Swedish or foreign-registered ships that are used for transport from Sweden to non-Swedish destinations (Swedish EPA, 2019d). Commercial ships and leisure boats are included in the statistics but are reported separately.[3] The petroleum products for maritime transport in Sweden (excluding petroleum products used for inland waterway transport) are divided into three types: diesel, eo1 and eo2-6.[4] To estimate emissions from maritime transport, the sold volumes of these three fuel types are multiplied by emission factors for each fuel type and for different pollutants.

According to the Swedish EPA (2018a), the estimations based on the monthly survey are considered to be of high quality. However, the statistics show fluctuations to which the Swedish EPA (2018a) has not been able to find explanations for. Furthermore, there are indications that the distribution of fuel consumption between domestic and international maritime transport may be afflicted with measurement errors (Swedish EPA, 2018b). Due to these uncertainties, the official statistics for fuel consumption from maritime transport (both domestic and international) are now, as of December 2019, estimated by using new estimation methods.

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[3] Emissions from military ships are reported separately and fishing vessels are reported under the category “off-road vehicles and other machinery” in Statistics Sweden (2019a).

[4] The fuel type eo1 (eldingsolja 1) includes marine distillates similar to diesel oil. The fuel type eo2–6 (eldingsolja 2–6) includes heavy fuel oils.

Current official estimation method

The new, currently used, method for estimating fuel consumption from maritime transport is partly based on a revised survey of the supply and delivery of petroleum products and partly on AIS data from a collaboration with the Swedish Energy Agency and SMHI. The main changes that were made to the revised monthly survey of the amount of fuels that are purchased and consumed are: 1) The fuel consumption is not separated between domestic and international maritime transport. It is instead only the total fuel consumption from all maritime transport that is reported. The reason for this is that the previous method for separating the fuel consumption between domestic and international maritime transport was not considered to be reliable. 2) The new survey reports the fuel types diesel and eo1 together, and not separately as they were in the previous survey (Eklund et al., 2019). However, after 2021, the plan is to again report the fuels separately. In the data publication in December 2019, the separation between diesel and eo1 had to be estimated (Eklund et al., 2019).

To estimate the domestic fuel consumption from maritime transport (excluding leisure boats), the official statistics in the modified method are also partly based on AIS data developed by SMHI based on the Shipair model, and partly on information from vessel databases. Fuel consumption from international maritime transport is calculated as the difference between the total delivered petroleum according to the survey minus the estimated fuel consumption for domestic transport based on AIS data. There are two main problems with this method: 1) AIS data are only available since 2013 and, therefore, the fuel consumption for years before 2013 has to be estimated in another way. 2) The Shipair model does not give any information about the fuel types used (Eklund et al., 2019).

Because the new method for estimating fuel consumption from domestic maritime transport only gives information since 2013 and contains no information about the fuel types used, data on the fuel consumption of the largest actors within maritime transport has been collected and analysed. To estimate the fuel consumption for the years previous to 2013, fuel consumption data from large actors within maritime transport were used. For years where such data were not available, different types of interpolation between years and moving averages were used to fill in the data gaps (Eklund et al., 2019). As the fuel consumption for domestic maritime transport is low in comparison with international maritime transport, the differences in the data of international fuel consumption is small between the updated data and the previous data.

In both methods, emission factors are used to estimate the emissions from maritime transport. As from 2016, it is the Swedish Transport Agency that provides emission factors (Swedish EPA, 2019d). Furthermore, default emission factors from the EMEP/EEA 2016 Guidebook are used to complement the national estimates (Swedish EPA, 2019d). More information about emissions factors used in the official estimation method are provided in the appendix.

3.1.2. AIS data

In collaboration with the Swedish Maritime Administration, SMHI has developed the so-called Shipair shipping model to improve statistics on domestic fuel usage and emissions from maritime transport (Windmark et al., 2017). In this report, data from the Shipair model in 2015 are used to describe the current situation of maritime transport in Sweden and to identify average vessel types.[5] The data are also used to estimate fuel consumption, which is used as the base for estimating emissions to air and the BAU scenarios.

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[5] The Carrots & Sticks project chose to requisition data for 2015 for two reasons. First, the data for 2015 were already developed in the Shipair model, which reduced the delivery time of the dataset. Second, by choosing 2015, the estimated fuel consumption from the Shipair model can be combined with the estimated shares of different fuel types used in 2015 from SSPA (2018).

The Shipair model is based on AIS data, which is a global system that identifies vessels and their movements. Since December 2004, it is mandatory to be fitted with an AIS transceiver for vessels of 300 Gross Tonnage (GT) and upwards engaged in international voyages, cargo ships of 500 GT and upwards not engaged on international voyages and all passenger vessels (IMO, 2019). However, AIS transceivers are also used on most commercial ships and on an increasing number of recreational vessels (Windmark, 2019).

There are 11 ship types included in the dataset from Windmark (2019), which are presented in Table 2. The abbreviations of the ship types will be used in the figures throughout this report. The descriptions of the ship types are based on the StatCode5 classification, which is the industry-standard shiptype coding system (IHS Markit, 2019).[6] Private recreational vessels are not included in the data. Although included in the table, fishing vessels, service ships and other ships will not be included in the data analysis in this report, since these are not commercial vessels.[7]

Table 2. Description of ship types.

Ship type	**Abbreviation**	**Description (according to Statcode5)**
Tanker ship	TA	A1 - Including vessels carrying liquefied gas, chemicals, oil and other liquids
Bulk Carrier	BU	A2 – Including vessels carrying bulk dry, bulk dry/oil, self-discharging bulk dry, and other bulk dry
Cargo Ship	CA	A31, A32, A34, A38 – Including vessels carrying general cargo, passenger/general cargo, refrigerated cargo, and other dry cargo
Container Ship	CO	A33 – Including vessels carrying containers
RoPax	RP	A36 – Including vessels carrying passenger/Ro-Ro cargo
Passenger Cruise	PC	A37A – Including passenger cruise ships
Passenger Ferry	PF	A37B – Including passenger ships
Fishing Vessel	FI	B1 – Including vessels for catching fish and other fishing
Service Ship	SS	B2, B3 – Including vessels for offshore supply (e.g. platform supply ships and pipe burying vessels) and miscellaneous (e.g. research vessels, towing/pushing vessels, icebreakers, and dredging vessels)
Vehicle Carrier	VE	A35 – Including vessels carrying Ro-Ro cargo
Other Ships	OT	W, X, Y, Z – Including all other ships (W = Inland waterways, X = Non-merchant ships, Y = Non-propelled ships and Z = Non-ship structures)

Source: Windmark (2019) and IHS Markit (2019).

The AIS data consist of both dynamic data, such as position, speed, and operating mode, and static statistical parameters, such as vessel identity, size, and year of vessel construction. The statistical parameters are, however, entered into the system manually by the ship operator and, hence, are not quality validated. Therefore, the Shipair model uses the ship identity number to find the ship properties from external databases (Windmark, 2019). Table 3 presents the variables included in the dataset and describes their unit of measurement, along with a description of whether the data were estimated within the Shipair model or extracted from Shipair’s ship database.

In Windmark (2019), the data are also sorted into three traffic types: domestic, all Sweden, and transit. From these traffic types, a fourth traffic type, called international traffic, was generated in this study by taking all Sweden minus domestic (see Table 4 for a description of the four traffic types). Domestic traffic is a subset of the traffic in all Sweden. International traffic includes all international journeys

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[6] For some ship types, there can be ambiguities regarding which StatCode5 classification they belong to. For example, the vehicle ferries owned by the Swedish Transport Administration are sometimes classified under Other ships and sometimes under RoPax (Windmark, 2019).

[7] Commercial ship types include ships that transport cargo or carries passengers for hire.

departing from or arriving in Sweden (that is, all Sweden traffic minus domestic traffic). All traffic in the whole model area is the sum of transit and all Sweden.

The Shipair model area consists of three sea basins: North (Baltic Sea, north of Åland), South (Baltic Sea, south of Åland), and West (Skagerrak/Kattegat), which are illustrated in Figure 1. The whole model area is within the SECA, which is an emission control area that comprises the Baltic Sea, the North Sea and the English Channel and which requires fuel with no more than 0.1 percent sulphur content or filtering technology to achieve the equivalent. The model area will also be within the NECA, which will cover the Baltic Sea, the North Sea and the English Channel and will require all new vessels built after 1 January 2021 to apply certain emission standards for NO_X.

Table 3. Description of variables from the Shipair model.

Variable	Unit	Description
Engine Capacity	kW	Extracted from Shipair's ship database. The variable is sorted into eight intervals of engine capacity
Number of ships		Estimated within the Shipair model
Gross Tonnage		Extracted from Shipair's ship database
Deadweight Tonnage	long ton	Extracted from Shipair's ship database
Age	years	Extracted from Shipair's ship database
Main engine	kW	Extracted from Shipair's ship database
Auxiliary engine	kW	Extracted from Shipair's ship database
Design speed	knots	Extracted from Shipair's ship database
Average speed	knots	Estimated within the Shipair model
Distance	km	Estimated within the Shipair model
Fuel consumption, total*	tonnes	Estimated within the Shipair model
Fuel consumption at berth	tonnes	Estimated within the Shipair model
Time at berth	hours	Estimated within the Shipair model

Source: Windmark (2019). * Total fuel consumption also includes the fuel consumption at berth.

Table 4. Description of traffic types.

Traffic type	Description
Domestic	All ship journeys that both departed and arrived in Sweden
All Sweden	All ship journeys that departed and/or arrived in Sweden
International	All ship journeys that departed or arrived in Sweden (all Sweden – domestic)
Transit	All ship journeys that neither departed nor arrived in Sweden

Source: Windmark (2019).

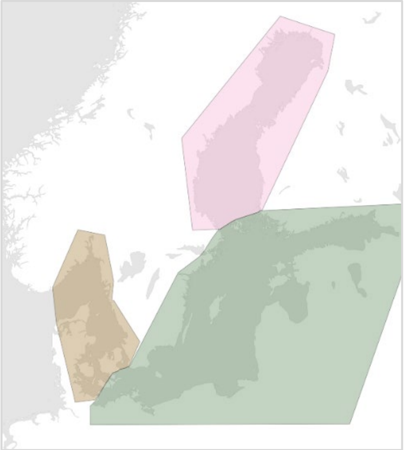

Figure 1. The Shipair model area. Source: Windmark (2019).

3.2. Method for estimation of emissions based on AIS data

This section presents the alternative method used in this report to estimate emissions based on AIS data. Section 3.2.1 first presents the literature and studies that have been used as input to the estimation. Section 3.2.2 presents the estimation method.

3.2.1. Literature used for the estimation of emissions

When estimating the emissions from maritime transport in this report, a number of assumptions have to be made regarding fuel types and emission factors. The AIS data include estimates of the total fuel consumption by maritime transport, but do not include information about different fuel types. Since different fuel types have different emissions profiles, an assumption about the fuel mix has to be made. This report uses an interview study by SSPA (2018) for this purpose, described below. Emissions from different fuel types, represented by emission factors, differ between studies since these can change over time depending on fuel content, engine types and ship types. In this report, a recently published study by Carlsson et al. (2019), on behalf on the Swedish Transport Administration, is used as the main source for emission factors, described below. For the sensitivity analysis, this report has also used alternative sources for the emission factors, which are described in the appendix.

Fuel types

The study by SSPA (2018) quantifies fuel consumption in 2015 for different ship types and traffic types and estimates the usage of different fuel types. SSPA (2018) analysed AIS data to quantify fuel consumption and they conducted interviews with fuel suppliers and shipowners to estimate the usage of different fuel types. The fuel types which were identified as being used in 2015 in Swedish waters are the following:

- **Marine Gas Oil (MGO)**
- **Heavy Fuel Oil (HFO)** – Two types with different sulphur content are used:
    - **Ultra-Low Sulphur Heavy Fuel Oil (ULSFO)** – maximum 0.1% sulphur content
    - **High Sulphur Fuel Oil (HSFO) -** maximum 3.5% sulphur content
- **Marine Diesel Oil (MDO)** – a mix between MGO and HFO
- **Liquified Natural Gas (LNG)**

Based on the interviews, it was found that the most common fuel types in 2015 were MGO and ULSFO (see Table 5). The use of HSFO is more common for traffic in Swedish waters/economic zone than for domestic traffic.[8] The relatively large amount of HSFO sold, despite its high sulphur content, can be explained by sales to ships operating outside of the SECA and by the fact that some ships use scrubbers to be able to use such fuel within the SECA (SSPA, 2018). LNG is only used for international transport in Swedish waters and economic zone, but not for domestic traffic.

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[8] Swedish waters cover 12 nautical miles from the baseline. The Swedish economic zone follows a central line that has been agreed upon among adjacent states.

Table 5. Share of fuel types used for domestic transport and for international transport in Swedish waters and in the Swedish economic zone (excluding fuel types used for inland waterway transport).

Fuel type	Domestic transport	Swedish waters	Economic zone
HSFO (HFO)	1%	8%	9%
ULSFO (HFO)	37%	40%	41%
MGO	42%	42%	42%
MDO	19%	7%	5%
LNG	0%	3%	2%
Total	**100%**	**100%**	**100%**

Source: SSPA (2018).

The fuel mix used is different between ship types (see Figure 2 and Figure 3). In domestic traffic, MGO and ULSFO are the most common fuel types for most of the ship types, although the share of them is different between ship types. For passenger ships and other ships, the most common fuel type is instead MDO. LNG was not used by any ship types in domestic traffic in 2015. The distribution of fuel types in international traffic (in the Swedish economic zone) is relatively similar to that in domestic traffic. The most notable difference is that the usage of HSFO is more common, at least for the ship types of cruise ships and Ro-Ro ships. Another difference is that LNG is used by RoPax ships.

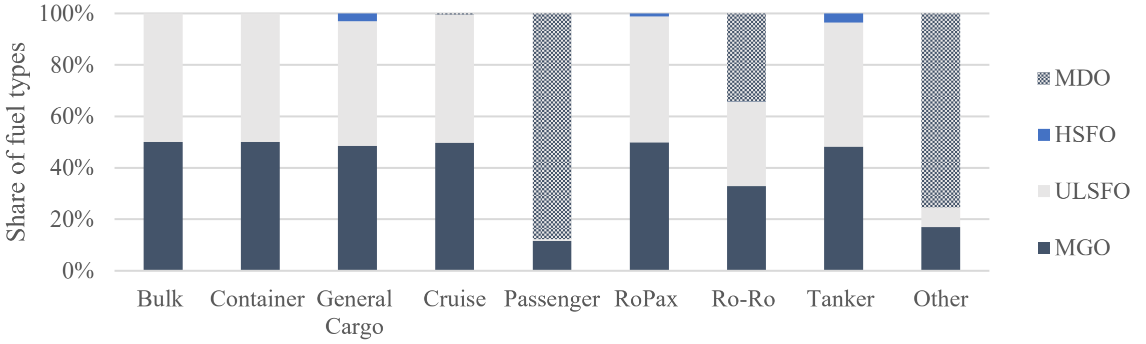

Figure 2. Share of fuel types used by different ship types in domestic traffic in 2015. Source: SSPA (2018).

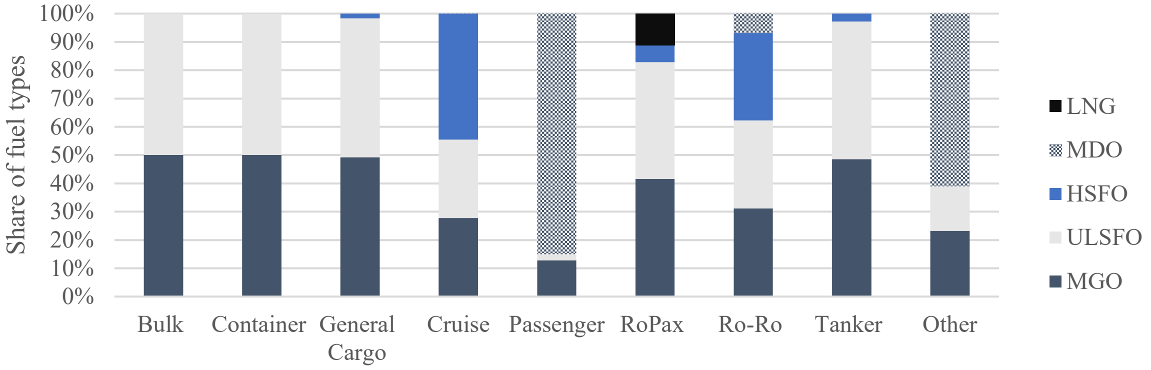

Figure 3. Share of fuel types used by different ship types in international traffic in the Swedish economic zone in 2015. Source: SSPA (2018).

The model area is different between this report and the SSPA (2018) study. In this report, the model area is based on the sea basins used in Windmark (2019), as described in section 3.1.2, whereas in the SSPA (2018) study, the traffic is divided into domestic traffic and international traffic in Swedish waters or in the Swedish economic zone. However, since this study uses other estimations of fuel consumption (see section 3.1.2), only the share of the usage of different fuel types are included from the SSPA (2018) study. Therefore, it is assumed in this study that the share of the consumption of different fuel types is the same, irrespective of how far outside of Swedish waters/economic zone international traffic are sailing. More specifically, it is assumed that the same distribution of fuel types is used in international and transit traffic as within the Swedish waters/economic zone.

Another difference between the SSPA (2018) study and this report is that some of the ship type names are different. See Figure 2 and Figure 3 for the ship type names used in SSPA (2018) and Table 2 for the ship type names used in this report. It is assumed in this study that the ship type of *general cargo* is comparable with *cargo ships* and that the ship type of *Ro-Ro* is comparable with *vehicle carriers*.

Koucky and Partners (2016) is another study that has estimated fuel usage from maritime transport. The study uses interviews of actors delivering fuel for maritime transport in the Swedish market in 2015-2016 and divides delivered fuel into three categories: HFO (or other heavy oils), MGO (or other gas oils), and ULSFO (or other low sulphur fuels). It is estimated that the fuels have the following shares of the market: 20%, 50%, and 30% for HFO, MGO and ULSFO, respectively.

For the purposes of this report, the estimated fuel mix from SSPA (2018) is more suitable than the estimated fuel mix from Koucky and Partners (2016). The SSPA (2018) estimation includes more fuel types, which makes it possible to use specific emission factors for each fuel type, rather than using average emission factors for fuel categories containing several fuel types. Furthermore, the SSPA (2018) study separates the fuel mix used for different ship types into domestic traffic and international traffic, whereas Koucky and Partners (2016) only presents the total estimated fuel mix for the whole ship fleet. Since this report uses data on the fuel consumption for different ship types, it is useful to have an estimation of the fuel mix for each ship type.

Regarding assumptions about fuel types used at berth, the majority of all north-Atlantic ships use MGO/MDO as fuel for auxiliary engines (AEs) according to Carlsson et al. (2019). In this report, it is assumed, therefore, that the fuel type used for AEs is MGO/MDO.

Emission factors

Emission factors can be used to estimate the emissions to air from different sources, such as maritime transport. The size of emission factors depends on fuel type, engine type and ship size, the different activities ships operate in and the usage degree of auxiliary engines. ASEK 6.1, a report by the Swedish Transport Administration (2018b), provides recommendations about values to use in economic estimations for the transport sector, and it also includes emission factors for maritime transport. However, the current emission factors in ASEK 6.1 have some limitations. First, it only includes average emission factors and does not separate different ship types or engine sizes. Second, it does not separate emission factors between different fuel types; it only includes an average for MGO/MDO. Third, the method for how these values are developed is not presented in ASEK 6.1 but, according to a study by Carlsson et al. (2019), they are based on previous studies which use information from the IMO, IVL and Traffic Analysis. Finally, there is currently no available emission factor for PM emissions. Due to these limitations, this study uses emission factors from Carlsson et al. (2019) to estimate emissions. For sensitivity analyses, emission factors from other sources are also used, which are described in the appendix.

On behalf on the Swedish Transport Administration, Carlsson et al. (2019) has developed emission factors for maritime transport by compiling and comparing emission factors from several previous studies. These emission factors are aimed to be included in a future ASEK report. The emission factors include the TTP-perspective, which include emissions from the fuel combustion for ship propulsion. For CO_2, SO_2 and PM_{10}, the emission factors are presented as aggregated values for each fuel type, whereas the emission factors for NO_X are presented as disaggregated values, since they vary with ship size. The fuels HFO/IFO and MGO/MDO also differ depending on the engine type, where smaller ships have lower emission factors, whereas larger ships have higher emission factors (see Table 6 and

Table 7 for all emission factors used in this report). Emission factors for NO_X will further be reduced over time due to the decided implementation of NECA in 2021 (a reduction of 5.3% per year for HFO/IFO and of 5.4% per year for MGO/MDO if the reduction would be linear). The reductions are estimated to continue until 2046, when all ships are expected to fulfil the strictest, currently known, requirements.

Emission factors for PM_{10} depends on the fuel type, the sulphur content of the fuel, the combustion of the fuel, the engine size and the engine efficiency. This implies that the PM_{10} emissions vary with ship size and ship types. Therefore, Carlsson et al. (2019) provides both aggregated and disaggregated emission factors for PM. Emission factors are only presented for PM_{10}, since $PM_{2.5}$ constitutes a subset of PM_{10} emissions.

Private recreational vessels, service ships, military ships and other ships are excluded from the report. For the emission factors of fuel used in auxiliary engines (AEs) at berth, the literature is more limited and the values are hence more uncertain. Therefore, this report uses the main engine (ME) emission factors for the estimation of emissions at berth as well.

Table 6. Emission factors for CO_2, SO_2 and PM_{10} (g/kg fuel in ME) used in this report.

	Fuel type	CO_2	SO_2	PM_{10}
2017	HFO/IFO	3 114	2	4
	MDO/MGO	3 206	2	1
	LNG	2 750	0	0.18
2025	HFO/IFO	3 114	2	4
	MDO/MGO	3 206	2	1
	LNG	2 750	0	0.18
2040	HFO/IFO	3 114	2	4
	MDO/MGO	3 206	2	1
	LNG	2 750	0	0.18

Source: Carlsson et al. (2019).

Table 7. Emission factors for NO_X (g/kg fuel in ME) used in this report.

	Ship size	HFO/IFO	MGO/MDO	LNG
2017	0–10 000	61.7	71.7	7.8
	10 000–25 000	73.3	79.2	7.8
	25 000–50 000	83.7	86	7.8
	50 000–100 000	85	87.7	7.8
	>100 000	84.9	88	7.8
2025	0–10 000	48.2	54.8	7.8
	10 000–25 000	58	60.8	7.8
	25 000–50 000	66.8	66.3	7.8
	50 000-10 0000	67.8	67.7	7.8
	>10 0000	67.8	67.9	7.8
2040	0–10 000	21.9	24.9	7.8
	10 000–25 000	26.4	27.7	7.8
	25 000–50 000	30.4	30.3	7.8
	50 000–100 000	30.9	30.9	7.8
	>100 000	30.9	31	7.8

Source: Carlsson et al. (2019).

3.2.2. Estimation method

To estimate the emissions from domestic and international maritime transport, the following method has been used in this report:

The estimated fuel consumption for 2015, based on AIS data from Windmark (2019) (see section 3.1.2 for a data description), was divided into different fuel types based on a study by SSPA (2018) in which the distribution of fuel types is estimated (see section 3.2.1 for a description of the study). This was made by multiplying the fuel consumption per ship type with the estimated shares of different fuel types. The following assumptions and steps were made: 1) The fuel consumption from all commercial ship types was included for the purpose of being able to compare the new estimated emissions with the emissions from official statistics. Hence, the ship types of fishing vessels, service ships and other ships were excluded. 2) As described in section 3.2.1, the model area in SSPA (2018) is different from the model area in Windmark (2019). However, this report assumes that the same distribution of fuel types was used in the international traffic type as within the Swedish economic zone.

To estimate emissions from maritime transport, this report uses the same method as in the national emission inventories by the European Monitoring and Evaluation Programme (EMEP) and the European Environment Agency (EEA) (EEA, 2019). The emissions factors in Carlsson et al. (2019), on behalf of the Swedish Transport Administration, are used in this study (see section 3.2.1 for a more detailed description).

To estimate the emissions of CO_2, SO_2 or PM_{10}, the "Tier 1 default approach" was chosen due to data availability[9], and the method can be explained by equation 1.

$$E_p = \sum_m (F_m \times EF_{p,m}) \qquad (1)$$

Where E_p is the emission p (CO_2, SO_2 or PM_{10}), F_m is the mass of fuel type m, $EF_{p,m}$ is the emission factor of emission p for fuel type m. The product $F_m \times EF_{p,m}$ is summed over five types of fuel (described in section 3.2.1) to estimate the total emissions from domestic, international and transit maritime transport, respectively.

The same approach was used to estimate the emissions of NO_X, but since emission factors differ with ship size, the method is slightly different and can be explained by equation 2.

$$E_{NOx} = \sum_{m,s} (F_{m,s} \times EF_{NOx,m,s}) \qquad (2)$$

Where E_{NOx} is the emissions of NO_X, $F_{m,s}$ is the mass of fuel type m for vessels with size s (in deadweight tonnage (DWT)), $EF_{NOx,m,s}$ is the emission factor for NO_X and fuel type m for vessels with size s. The product $F_{m,s} \times EF_{NOx,m,s}$ is summed over five types of fuel (described in section 3.2.1) and over five categories of DWT to estimate the total emissions from domestic, international and transit maritime transport, respectively.

The method used for the estimation of BAU scenarios is explained by equation 3 and 4.

$$F_{m,t,i} = F_{m,t-1,i} \times TD_i \times EEI_i \qquad (3)$$

Where $F_{m,t,i}$ is the mass of fuel type m at year t for transport type i (passenger transport or freight transport). TD is the forecasted transport demand in percent for transport type i, and EEI is the energy efficiency improvement in percent for transport type i. In other words, to estimate the fuel

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[9] Statistics Sweden/Swedish EPA uses the Tier 2 approach. This is not possible in this report since data about vessels' operational modes and engine types is not available in Windmark (2019).

consumption in a certain year, the fuel consumption from the previous year for different transport types and fuel types is multiplied with the forecasted transport demand and the forecasted energy efficiency improvement. The estimated fuel consumption is based on data from Windmark (2019), which was divided into different fuel types based on SSPA (2018). The forecasted fuel mix by DNV GL (2018) is used in one of the scenarios. The forecasted freight transport demand is based on the Swedish Transport Administration (2018a) and the passenger transport demand is based on the historical trend of passenger kilometres and number of passengers, see section 6.1 for more details. The energy efficiency improvement is based on DNV GL (2018) and IMO (2015), see section 6.2 for more details. All assumptions are summarised in section 7.

The estimated fuel consumption is then used as a base for the estimation of emissions, which can be explained by equation 4.

$$E_{p,t} = \sum_{m} (F_{m,t} \times EF_{p,m,t}) \tag{4}$$

Where $E_{p,t}$ is the emission of pollutant p at year t, $F_{m,t}$ is the mass of fuel type m at year t, $EF_{p,m,t}$ is the emission factor of emission p for fuel type m at year t. The product $F_m \times EF_{p,m}$ is summed over five types of fuel (described in section 3.2.1) to estimate the total emissions from domestic and international maritime transport, respectively. The forecasted emission factors in Carlsson et al. (2019) are used. For the estimation of NO_X emissions in the BAU scenarios, equation 2 is used for each year.

4. Historical development of maritime transport and emissions

This section presents the historical development of emissions from domestic and international maritime transport, the development of tonne-and passenger-kilometres and a snapshot of the Swedish flag shipping fleet. All data in this section are based on Sweden's official statistics, which themselves are based on the previously and currently used estimation methods (described in section 3.1.1). Section 4.1 presents the development of emissions from maritime transport related to the environmental quality objectives. Section 4.2 presents the development of tonne- and passenger-kilometres for maritime transport. Section 4.3 presents an overview of the Swedish flag shipping fleet.

4.1. Historical emissions according to official statistics

4.1.1. Greenhouse gas emissions

This section examines the development of domestic and international GHG emissions from maritime transport and compares them to the domestic target for 2030. All figures show emissions from commercial vessels (private recreational vessels, fishing vessels and service ships are excluded).

Figure 4 presents the GHG emissions in Sweden, sorted by sector, between 2010 and 2018 (based on the modified currently used official method). In total, the GHG emissions have decreased by about 20% (excluding international transport by air and sea) between 2010 and 2018, and all domestic sectors have reduced their emissions. Domestic transport accounts for about one-third (32% in 2018) of the total GHG emissions.[10] The GHG emissions from international transport decreased between 2010 and 2013, but increased again between 2013 and 2018.[11] In total, the GHG emissions from international transport increased by 24% between 2010 and 2018. In 2018, domestic maritime transport (excluding private recreational vessels) accounted for about 1% of the total domestic emissions and international maritime transport accounted for about 10% of the total emissions (including international transport in the total emissions). GHG emissions from maritime transport is also partly included in the sector of off-road vehicles and other machinery, in which emissions from fishing vessels are included.

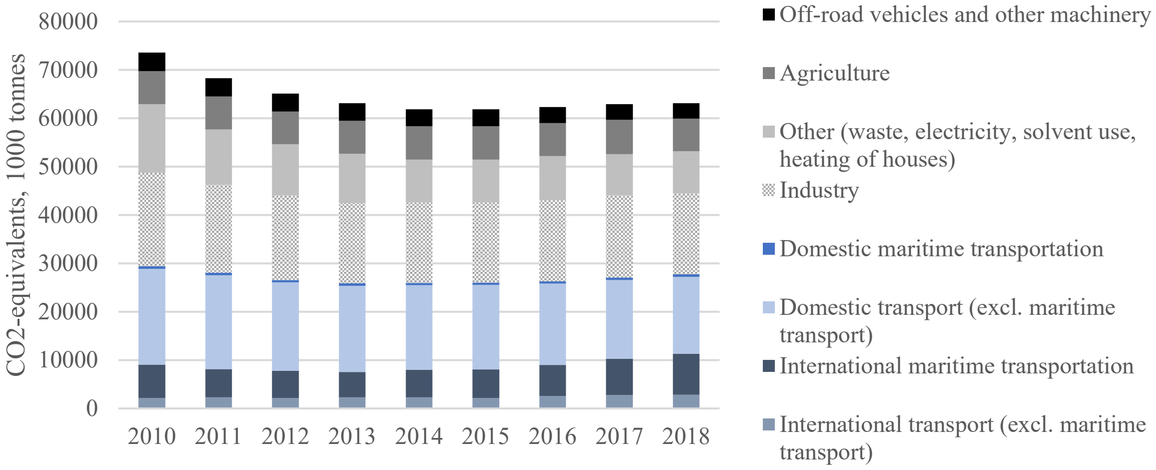

Figure 4. Greenhouse gas emissions (in CO_2-equivalents) in Sweden according to the new method. Source: Statistics Sweden (2020b).

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[10] Domestic transportation refers to road transportation, domestic aviation, domestic maritime transportation, railways and military transport.

[11] International transportation refers to 'international bunkers', i.e. refuelling in Sweden by international maritime transportation and aviation.

Domestic maritime transport only accounts for a small share of the total GHG emissions from domestic transport, although the share has increased between 2017 (using the previous official method) and 2018 (using the new official method). In 2017, based on the previous method, commercial vessels accounted for 0.8%, which can be compared to 3.4% in 2018 based on the new method (see Figure 5). Private recreational vessels accounted for 1.1% both in 2017 and 2018. Military transport also accounts for part of the domestic maritime transport: in total, it accounted for 1.1% in 2017 and 1.0% in 2018 of the total GHG emissions, out of which military ships account for about 18%. As previously mentioned, only commercial vessels are included in the scope of this report, and emissions from military ships and private recreational vessels are therefore excluded in the following figures.

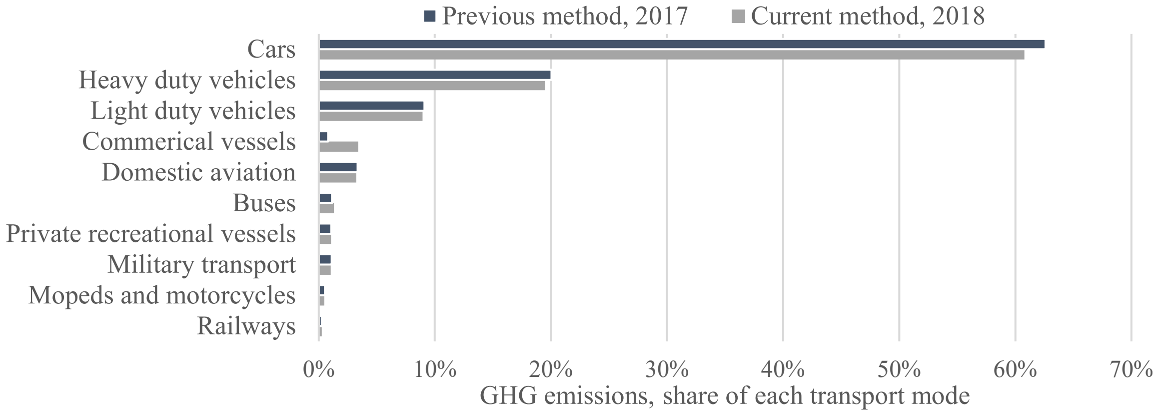

Figure 5. Share of total greenhouse gas emissions from domestic transport for each transport mode in 2017 (previous method) and 2018 (new method). Source: Statistics Sweden (2019a; 2020b).

The development of GHG emissions from domestic maritime transport based on the previous and new method is different over the period 1990-2018. Based on the previous method, the emissions have varied substantially over time, with the highest level in 2003 and the lowest in 2017 (see Figure 6). Based on the new method, the emissions have instead been increasing steadily over time. In total, the GHG emissions from domestic maritime transport have decreased by about 72% over the period 1990-2017 based on the previous method and increased about 65% over the period 1990-2018 based on the new method.

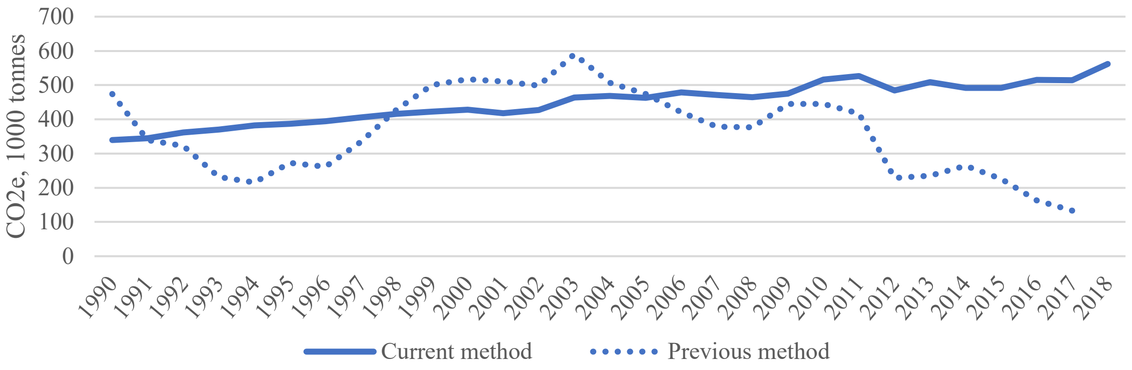

Figure 6. Greenhouse gas emissions from domestic maritime transport (commercial vessels) based on the previous and new method. Source: Statistics Sweden (2019a; 2020b).

GHG emissions from domestic maritime transport are considerably lower compared to the emissions from international maritime transport. Furthermore, emissions from international transport have increased over the time period, both according to the previous and new method (see Figure 7).

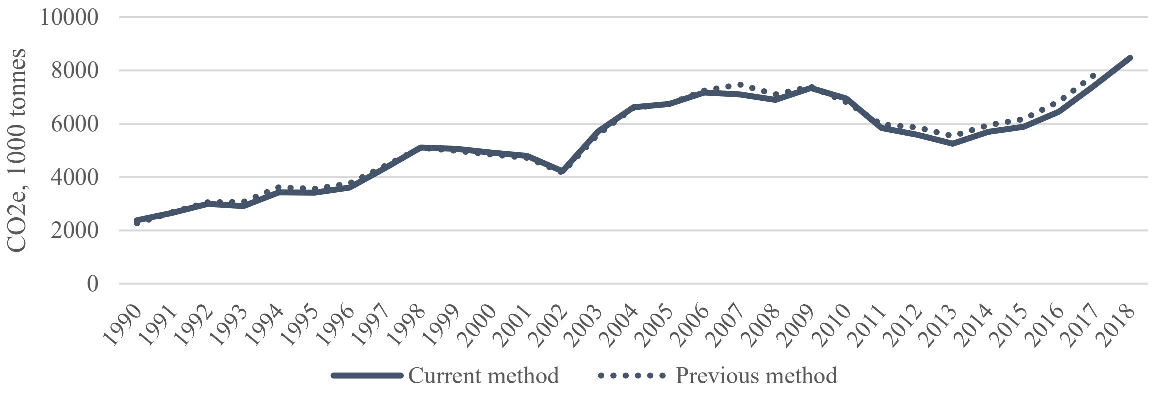

Figure 7. Greenhouse gas emissions (CO_2-equivalents) from international maritime transport based on the previous and new method. Source: Statistics Sweden (2019a; 2020b).

To follow up on how domestic maritime transport contributes to the target for 2030, Figure 8 shows the change in percent of GHG emissions from domestic commercial vessels between 2010 and 2018. The reduction needed to reach the 2030 target (a reduction of GHG emissions by 70% by 2030 compared to 2010) at a linear rate of progress is illustrated by the dashed and dotted lines; the dashed blue line represents the reduction needed from the level of 2018 and the dotted grey line represents the reduction that was needed from the level of 2010. As illustrated in the figure, the GHG emissions from domestic maritime transport have increased between 2010 and 2018 and the reduction needed (in percentage terms) per year to reach the target is now higher than what it was in 2010.

Based on the previous method, GHG emissions have already, in 2018, decreased to the extent needed to reach the 2030 target (a reduction of 70% between 2010-2017), see Figure 6 for the development of emissions. However, due to the uncertainties regarding the previous official method (described in section 3.1.1), the updated new method is probably more reliable.

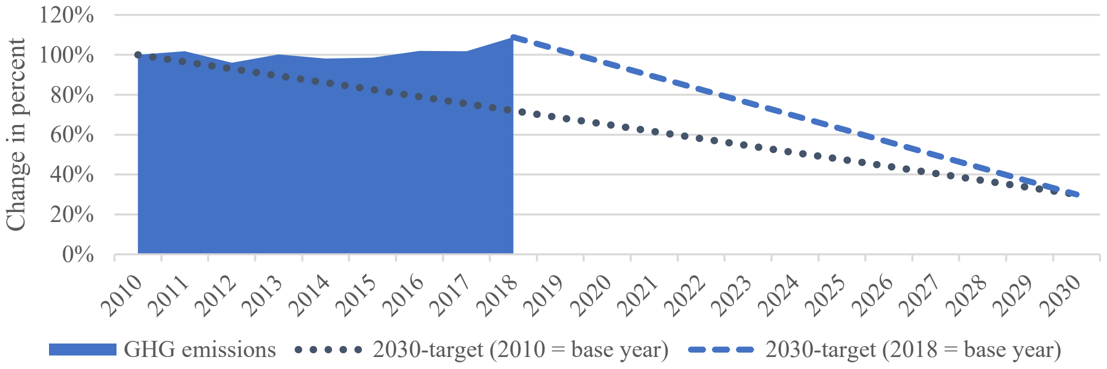

Figure 8. Greenhouse gas emissions from domestic maritime transport according to the new method and the 2030-target. Source: Statistics Sweden (2020b).

4.1.2. Sulphur dioxide emissions

The domestic emissions of SO_2 (excluding international transport) have decreased by about 40% over the period 2010-2018 and the main explanation is the transition towards fuels with low sulphur content (Swedish EPA, 2019e). The industry sector is the main domestic emitter of SO_2 emissions, which accounted for 76% of the total domestic emissions in 2018. When including the SO_2 emissions from international transport, the total emissions have instead increased over the period 2010-2018 (see Figure 9). Over this time period, the SO_2 emissions from domestic transport have decreased by 78%, while the SO_2 emissions from international transport have increased by 108%. In 2018, international maritime transport accounted for 81% of the total SO_2 emissions (including international transport), while domestic maritime transport only accounted for 0.02% of the total SO_2 emissions (excluding international transport). Of the emissions from international transport, maritime transport accounts for 98 percent of the emissions and aviation accounts for the other 2 percent. Hence, the main contributor of SO_2 emissions in Sweden is international maritime transport.

As illustrated in Figure 9, the SO_2 emissions from international maritime transport fluctuate from year to year. The main explanation is that in some years vessels bunker more fuels in Sweden and in other years bunker more fuels outside of Sweden. The choice of where to bunker is mainly affected by the price of fuels in Sweden relative to the price at the vessels' next destination (Swedish EPA, 2019f). The emissions can hence fluctuate, even if the number of vessels and the travelled distances are about the same over time (Swedish EPA, 2019f). Another explanation for the fluctuations in SO_2 emissions from international transport is that the bunkered fuel types with different sulphur content may vary from year to year. Even after SECA entered into force in 2015, vessels may bunker fuels with high sulphur content if they travel to destinations outside of the SECA and switch fuel when crossing the SECA border (Swedish EPA, 2019f) or have scrubbers installed.

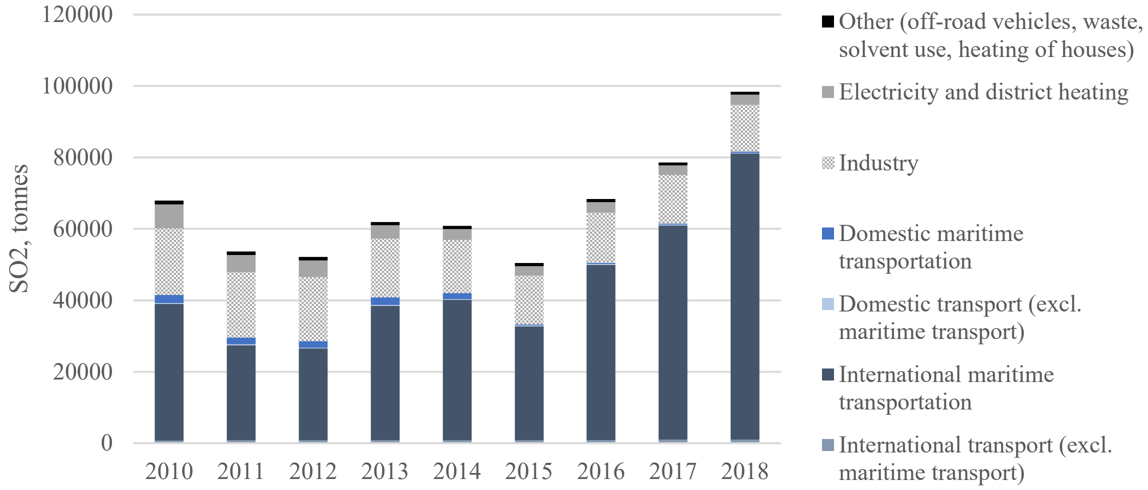

Figure 9. SO_2 emissions in Sweden (including international transport) according to the new method. Source: Statistics Sweden (2020a).

Over a longer time period, 1990-2018, the emissions of SO_2 from domestic maritime transport have been decreasing, both according to the previous and new method (see Figure 10). However, during the most recent years, 2015-2018, the figure shows a drastic reduction in emissions, which can be mainly explained by the SECA entering into force on January 1st, 2015.

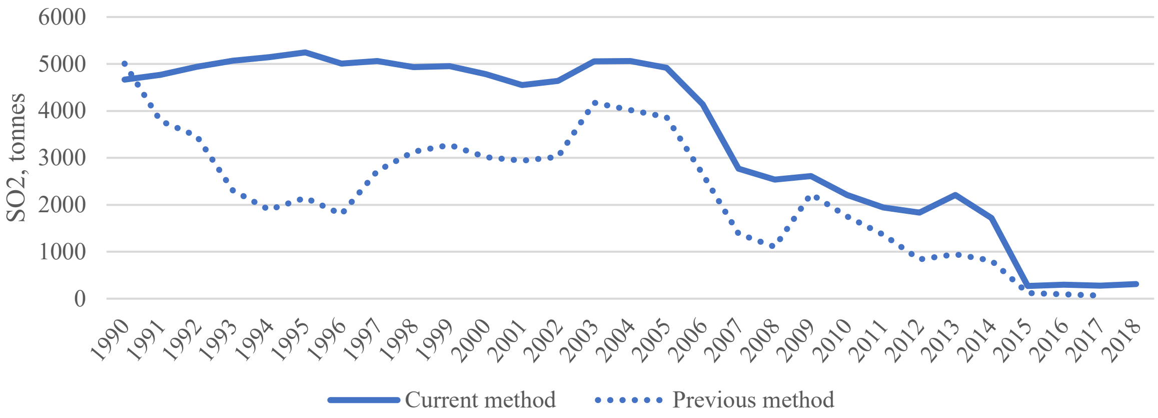

Figure 10. SO_2 emissions from domestic maritime transport (commercial vessels) based on the previous and new method. Source: Statistics Sweden (2019b; 2020a).

4.1.3. Particulate matter

Particulate matter (PM) is commonly divided into $PM_{2.5}$ and PM_{10}, which refer to the particles in air that are smaller than 2.5 and 10 micrometres (µm), respectively. The larger particles, PM_{10}, are mainly emitted through the wear of tyres and roads, whereas the smaller particles, $PM_{2.5}$, are mainly emitted through different combustion and industry processes (Swedish EPA, 2019h). This report focuses on emissions of PM_{10} to be able to compare emissions from official statistics with emissions estimated in this report (only PM_{10} emissions are estimated due to the availability of emission factors).

The total domestic emissions of PM_{10} (excluding international transport) have decreased by 14% over the period 2010-2018 (see Figure 11). Domestic transport, excluding domestic maritime transport, is the largest contributor of domestic emissions (46%), followed by the industry sector (17%). Domestic maritime transport accounts for 1% of the total emissions (excluding international transport) and international maritime transport accounts for 22% of the total emissions (including international transport).

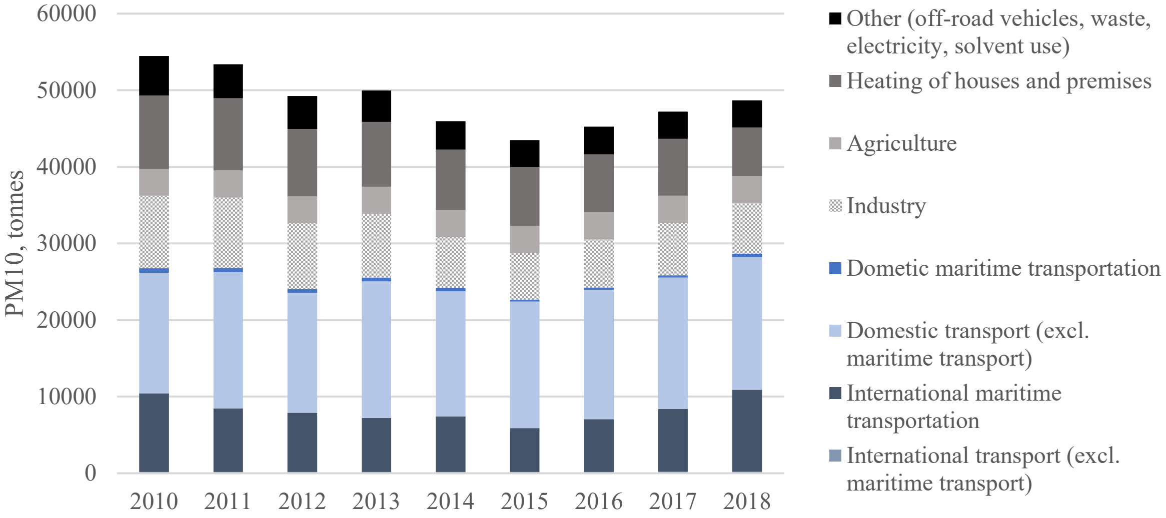

Figure 11. PM_{10} emissions in Sweden (including international transport) according to the new method. Source: Statistics Sweden (2020a).

The development of PM_{10} emissions from domestic maritime transport over a longer time period, 1990-2018, show decreasing emissions, both according to the previous and new method (see Figure 12). The previous method indicates more fluctuating emissions, while the new method indicates more consistently decreasing emissions, except for 2018 in which the emissions are increasing.

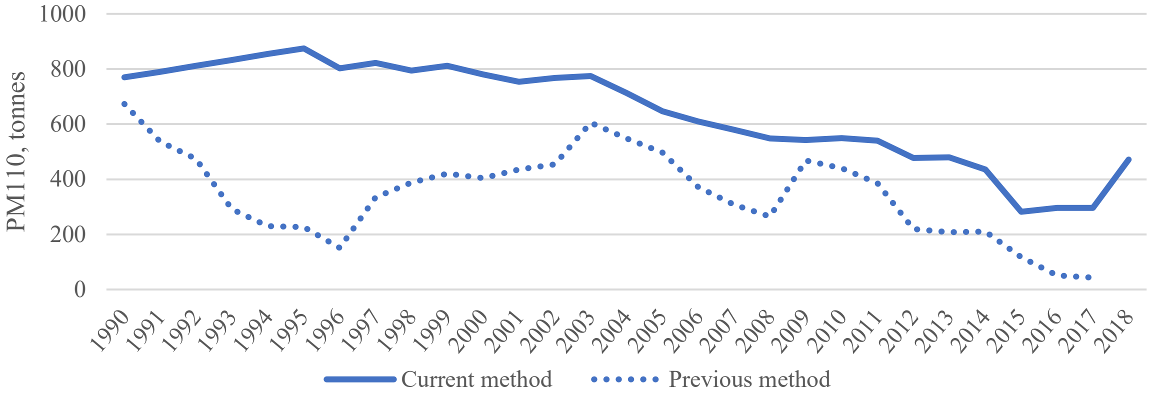

Figure 12. PM10 emissions from domestic maritime transport (commercial vessels) based on the previous and new method. Source: Statistics Sweden (2019b; 2020a).

4.1.4. Nitrogen oxide emissions

The domestic emissions of NO_X (excluding international transport) have decreased by about 19% over the period 2010-2018 and the main explanation is the reduced emissions from domestic transport (Swedish EPA, 2019g), see Figure 13. Emissions from domestic transport (excluding maritime transport) has decreased by about 33% over the period 2010-2018, but still accounted for about 34% percent of the total domestic NO_X emissions in 2018. The industry sector is the second largest domestic contributor, accounting for 22% of the total domestic NO_X emissions in 2018. Emissions from domestic maritime transport have increased by 28% over the time period and accounted for 8% of the total emissions (excluding international transport) in 2018. Emissions from international maritime transport have increased by 21% over the time period and accounted for 55% of the total emissions (including international transport) in 2018.

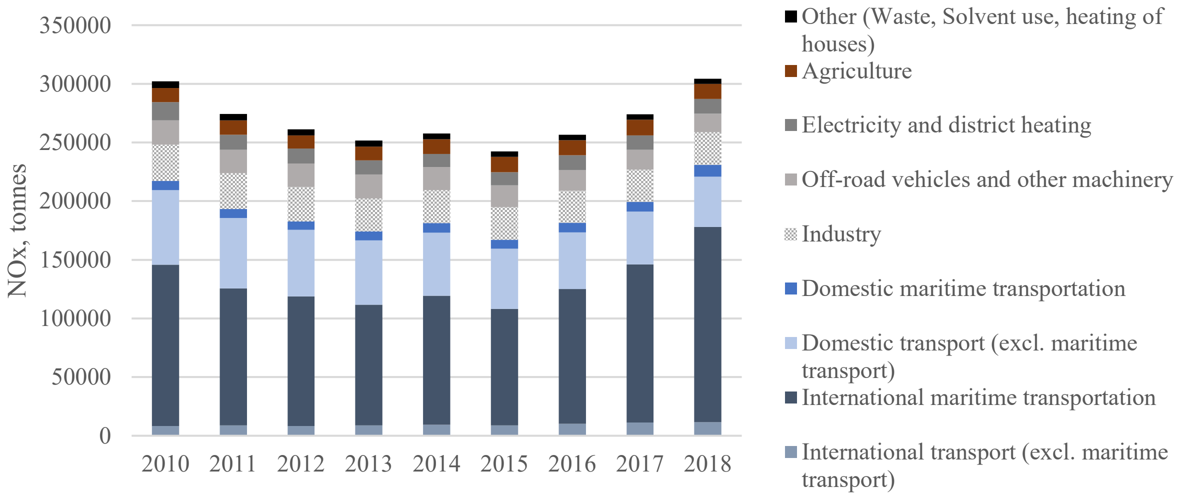

Figure 13. NO_X emissions in Sweden (including international transport) according to the new method. Source: Statistics Sweden (2020a).

Over a longer time period, 1990–2018, the total NO_X emissions from domestic maritime transport have decreased by 75 percent according to the previous method and increased by 51% according to the new method (see Figure 14).

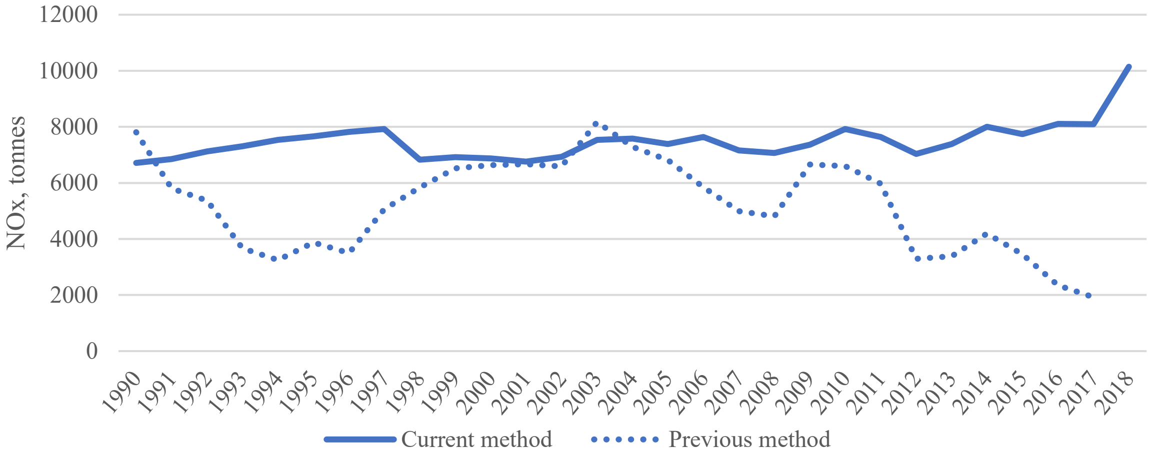

Figure 14. NO_X emissions from domestic maritime transport (commercial vessels) based on the previous and new method. Source: Statistics Sweden (2019b; 2020a).

4.1.5. Emissions from maritime transport in comparison with total emissions

To evaluate how maritime transport contributes to the four environmental quality objectives of relevance within this report, Figure 15 presents that share of total emissions from domestic and international transport in 1990, 2000, 2010 and 2018. For domestic maritime transport, the share is calculated as the share of total domestic emissions excluding international transport and, for international maritime transport, the share is calculated as the share of total domestic emissions including international transport.

For all four emission types, domestic maritime transport contributes with a relatively small share of the total emissions. For GHG emissions, the share of emissions from domestic maritime transport (excluding private recreational vessels) has been increasing, from about 0.5% in 1990 to about 1.1% in 2018. The share of SO_2 emissions from maritime transport first increased between 1990 and 2000 (from 4.5% to 10.6%), but has then been decreasing, contributing with about 1.8% of the total domestic SO_2 emissions in 2018. The share of PM_{10} emissions from domestic maritime transport has been stable at around 1% over the period 1990–2018. Finally, the share of NO_X emissions from domestic maritime transport has been increasing over the time period, from about 2.4% in 1990 to about 8% in 2018.

International maritime transport contributes with higher shares of the total emissions than domestic maritime transport. For GHG emissions, the share of emissions from international maritime transport has been increasing from about 3% in 1990 to about 13% in 2018. The share of SO_2 emissions from international maritime transport has been increasing substantially over the time period, from about 24% in 1990 to about 81% of the total domestic SO_2 emissions in 2018. The share of PM_{10} emissions from international maritime transport has also been increasing, from around 8% in 1990 to around 22% in 2018. Finally, the share of NO_X emissions from international maritime transport has been increasing considerably over the time period, from about 14% in 1990 to about 55% in 2018.

The increasing and relatively high shares of emissions from international maritime transport demonstrates that it is important to consider those emissions as well when examining Swedish targets. Even though international emissions are mainly emitted outside of Sweden, air pollutants can be transported by winds and also affect Swedish environmental objectives.

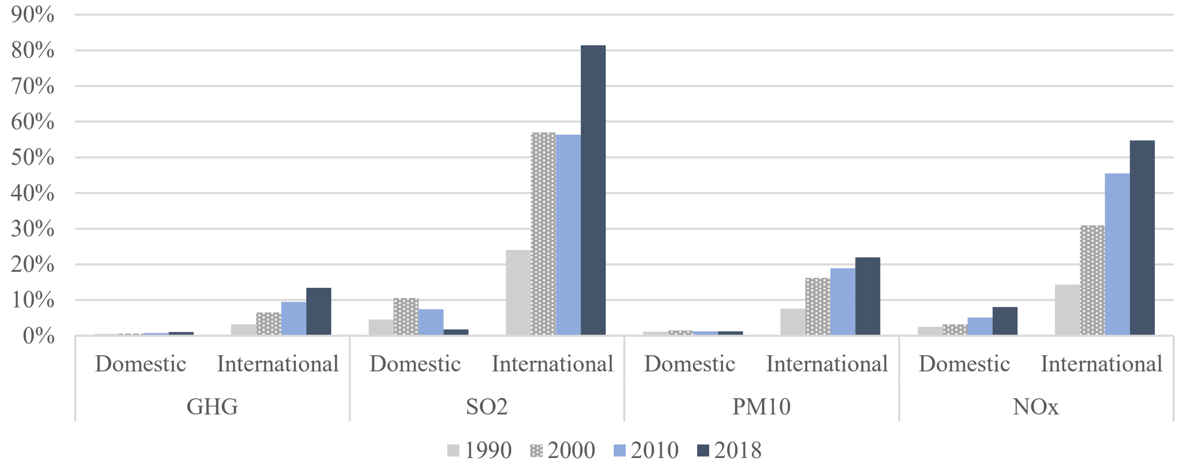

Figure 15. Share of total emissions from domestic and maritime transport in 1990, 2000, 2010 and 2018 according to the new official estimation method. Source: Statistics Sweden (2020a; 2020b).

4.2. Tonne- and passenger-kilometres

The activity of maritime transport can be described by the development of tonne-kilometres (for freight transport) and passenger-kilometres (for passenger transport).[12] Domestic transport includes journeys that have both departed and arrived in Sweden, and international transport includes journeys that either departed or arrived in Sweden. For domestic transport, the whole distance between the departure port and arrival port is included and potential journey distances that take place in non-Swedish waters are hence also included in domestic transport. For international transport, it is only the distances travelled in Swedish waters that are included (Transport Analysis, 2019a). Hence, the included geographical area for tonne- and passenger-kilometres is different to the area from which the emissions from maritime transport are estimated.

Figure 16 and Figure 17 present the development over the period 2000-2018 of tonne-kilometres for domestic and international maritime transport, respectively. In the most recent statistical publication, Transport Analysis (2019a) used a new method for estimating tonne-kilometres, illustrated by the dotted lines in the figures. The new method is based on an updated distance matrix with geographical positions based on AIS data. As illustrated in the figures, the tonne-kilometres are lower with the new method, especially for international transport.

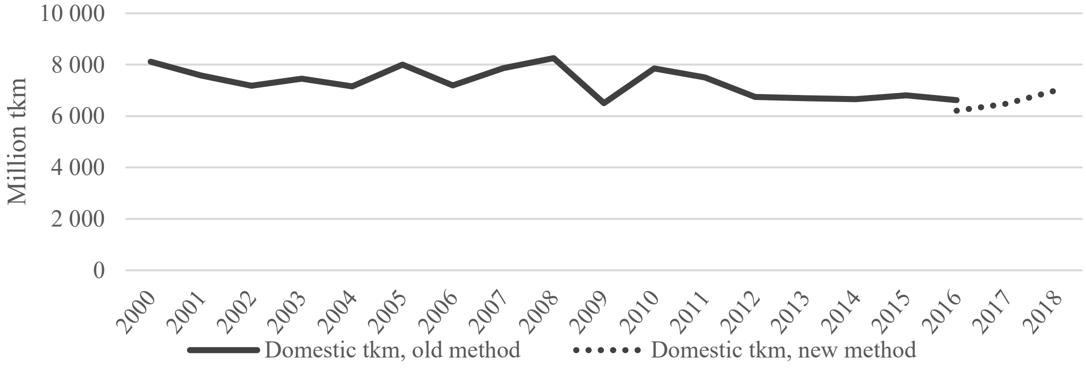

Figure 16. Tonne-kilometres for domestic maritime transport, with the old and new method. Source: Transport Analysis (2019a).

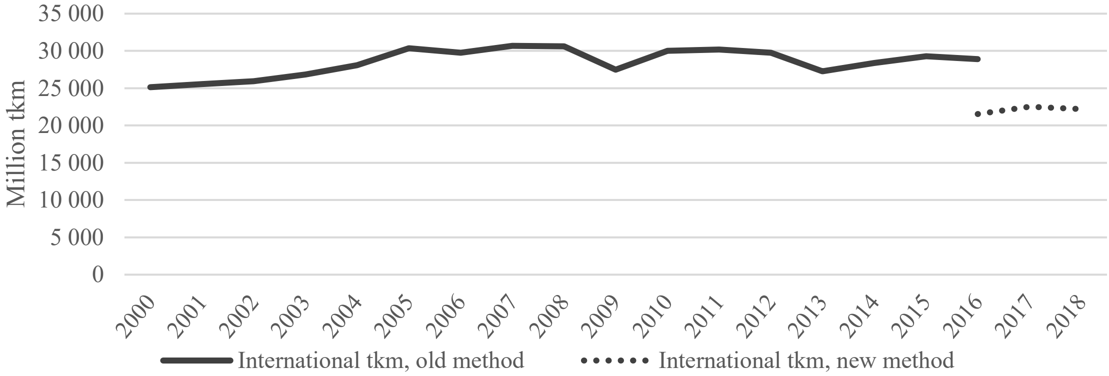

Figure 17. Tonne-kilometres for international maritime transport, with the old and new method. Source: Transport Analysis (2019a).

Figure 18 and Figure 19 present the development over the period 2000-2018 of passenger-kilometres for domestic and international maritime transport, respectively. Again, the new estimation method is

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[12] A tonne-kilometre (tkm) represents the transport of one tonne of goods by a given transport mode over a distance of one kilometre. A passenger-kilometre (pkm) represents the transport of one person by a given transport mode over the distance of one kilometre.

illustrated by the dotted lines in the figures. The figures show that the passenger-kilometres have been stable over the time period and that the new estimation method yields higher passenger-kilometres, especially for international transport.

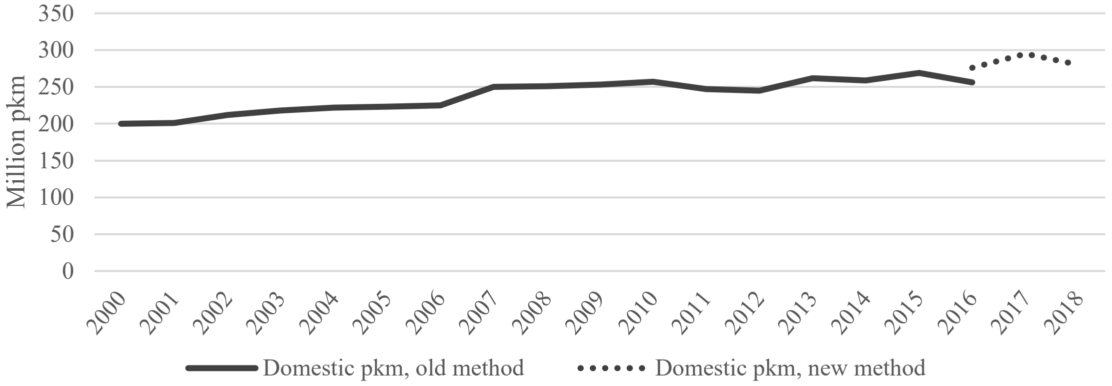

Figure 18. Passenger-kilometres for domestic maritime transport, with the old and new method. Source: Transport analysis (2019a).

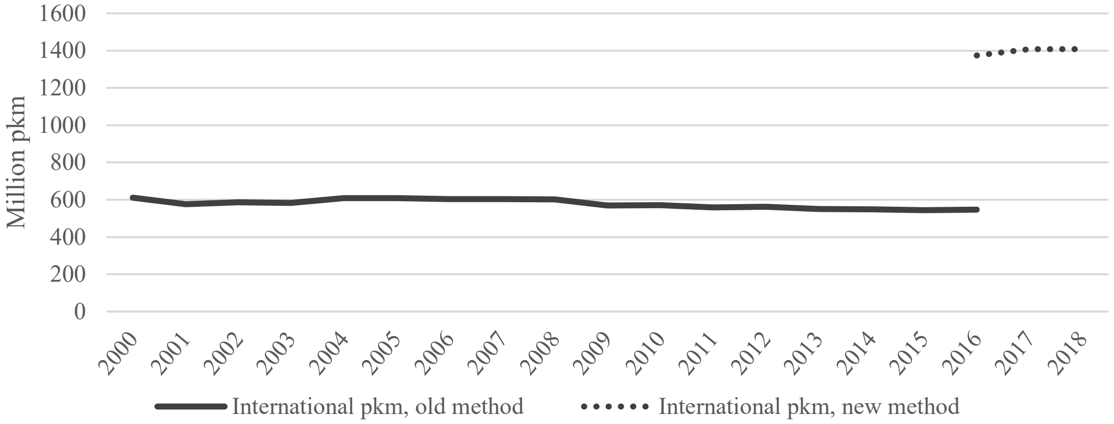

Figure 19. Passenger-kilometres for international maritime transport, with the old and new method. Source: Transport analysis (2019a).

According to the new estimation methods, the tonne-kilometres (both for domestic and international maritime transport) are lower than according to the older estimation method, whereas the passenger-kilometres (both for domestic and international maritime transport) are higher than compared to the older estimation method. For both tonne-kilometres and passenger-kilometres, the differences between the old and new method are larger for international transport than for domestic. Lower tonne-kilometres would likely indicate lower GHG emissions, and vice versa. Since the new estimation method shows lower tonne-kilometres and higher passenger-kilometres, it is difficult to estimate what the total effect on emissions would be.

4.3. Swedish shipping fleet

This section presents an overview of the Swedish shipping fleet based on official statistics. In 2018, the Swedish commercial vessel fleet consisted of about 300 vessels, of which 41% were cargo ships and 59% were passenger vessels (see Figure 20). Over the period 1990-2018, the number of Swedish cargo ships has been decreasing, while the number of Swedish passenger vessels has been more constant. In total, the Swedish flagged fleet has been decreasing over time.

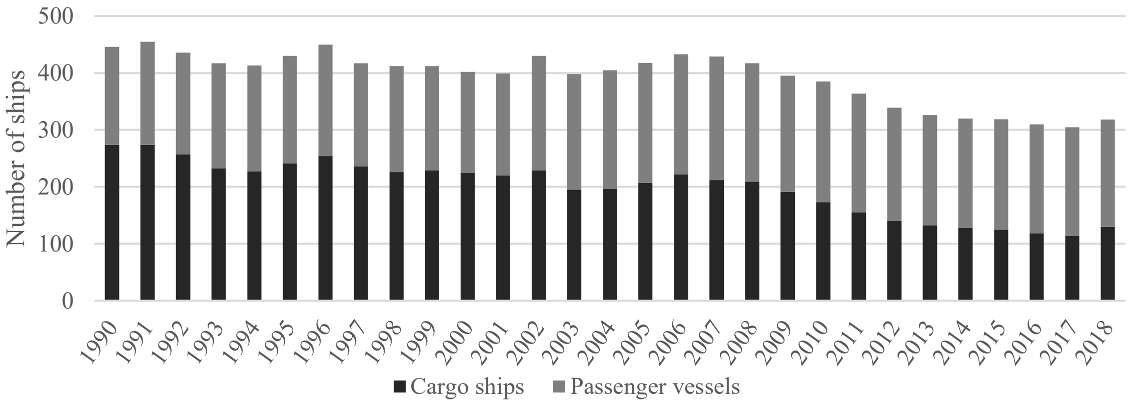

Figure 20. Swedish merchant vessels classified by cargo and passenger vessels with a gross tonnage of 100 and above. Source: Transport Analysis (2019b).

Even though the Swedish registered merchant vessel fleet has been decreasing, it does not mean that the total number of vessels under the control of Swedish operators has been decreasing. When merchant vessels chartered long-term from abroad are included, the total number of ships controlled by Swedish operators has been almost constant between 2010 and 2018. As Figure 21 shows, while Swedish registered merchant vessels have been decreasing, chartered merchant vessels from abroad have been increasing. More specifically, in 2010, the share of Swedish registered ships was 46%, which in 2018 had decreased to 40%.

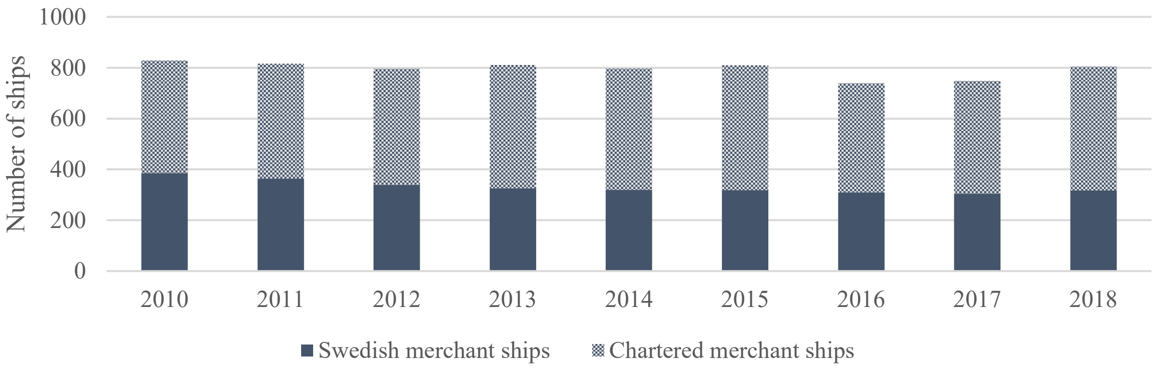

Figure 21. Swedish and chartered (from abroad) merchant vessels with a gross tonnage of 100 and above. Source: Transport Analysis (2019b).

Some vessel types are more commonly chartered from abroad than others. Of the total tanker ships controlled by Swedish operators, 86% are chartered from abroad. Other ship types commonly chartered from abroad are bulk carriers and dry cargo ships, of which 74% and 67% are chartered, respectively. The least common ship types to be chartered from abroad are other passenger ships and passenger ferries, of which 3% and 45%, respectively, are chartered from abroad.

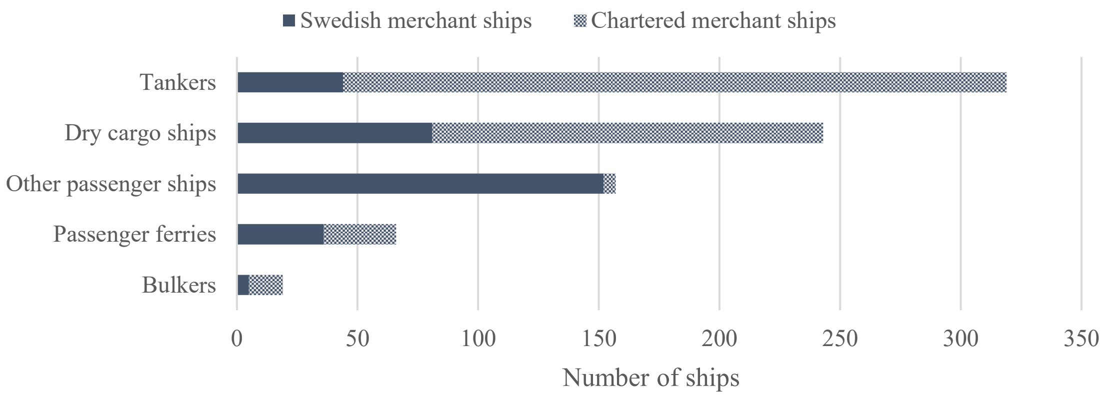

Figure 22. Swedish and chartered (from abroad) merchant vessels with a gross tonnage of 100 and above by type in 2018. Source: Transport Analysis (2019b).

5. Maritime transport and emissions based on AIS data in 2015

This section presents an overview of maritime transport in 2015, which is based on AIS data. Section 5.1 presents an estimation of fuel consumption in total and at berth. Section 5.2 identifies average vessel types in the geographical area covered in the Shipair model. Finally, section 5.3 presents estimations of emissions from maritime transport, which are based on fuel consumption estimated within the Shipair model.

5.1. Fuel consumption in 2015

5.1.1. Total fuel consumption

A ship's energy usage mainly depends on three systems: 1) main engines (MEs), which are used to move the ship in the water, 2) auxiliary engines (AEs), which are used to provide the ship with electricity, and 3) boilers, which are used to provide the ship with heat. All three systems are considered in the Shipair model and the ships' movements are categorised into different operating modes in order to determine when, and by how much, each system is used. By combining the information on the size of the engines, the operating modes, the speed of the ship and the age of the ship, the Shipair model can estimate the energy usage and fuel consumption (Windmark et al., 2017). The model does not include information about the fuel type used by ships, since there is currently no reliable method for determining or estimating this (Windmark et al., 2017).

Figure 23 shows the total fuel consumption in each sea basin, divided into three traffic types. The south sea basin contributes with the majority of the fuel consumption in the Shipair model area (about 68%), whereas the North Sea basin contributes the least (about 4%). The traffic type with the highest fuel consumption is the transit traffic, which in total accounts for 76% of all fuel consumed in the Shipair model area (see Figure 1 in section 3.1.2 for the Shipair model area).

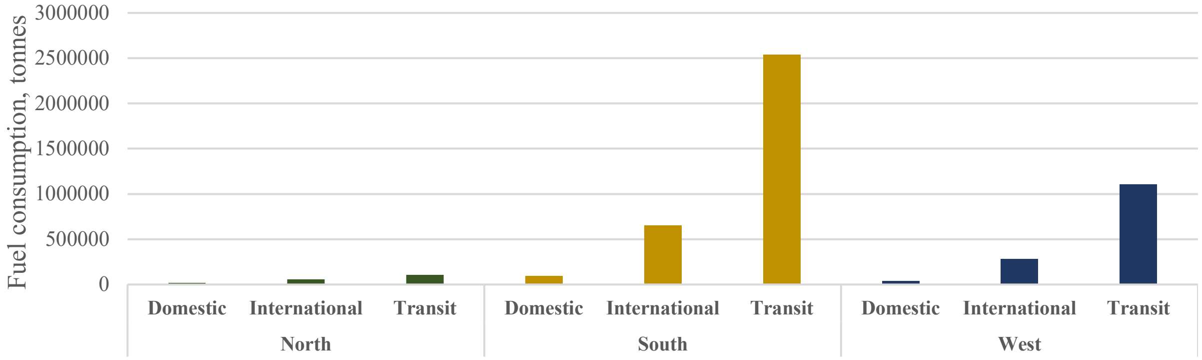

Figure 23. Fuel consumption by sea basin and traffic type (including all ship types). Source: Windmark (2019).

Figure 24 presents the total domestic fuel consumption by ship type for the whole model area. The ship type with the highest fuel consumption is RoPax, which consumes about 46% of the total domestic fuel consumption. Tanker ships account for the second highest fuel consumption, about 20%. Cargo ships, vehicle carriers, passenger ferries, bulk carriers and container ships consume about the same amount of fuel; each ship type consumes between 5-8% of the total domestic fuel consumption. The ship type consuming the least fuel is passenger cruise vessels.

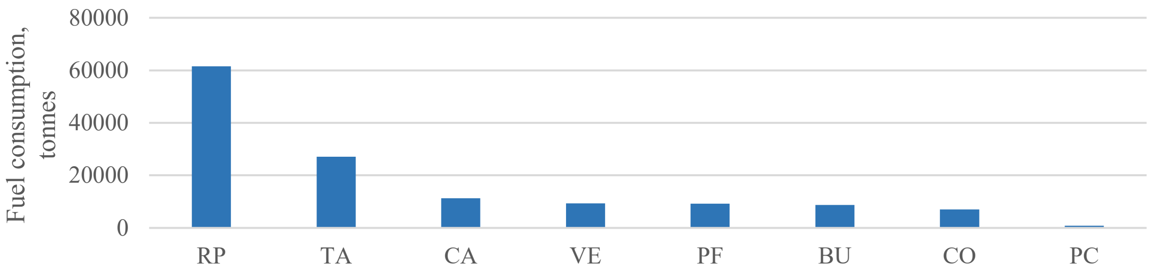

Figure 24. Domestic fuel consumption by ship type. Source: Windmark (2019).

Figure 25 presents the total fuel consumption by ship type for transit and international traffic. For international traffic, the ship type with the highest fuel consumption is RoPax, followed by tanker ships and cargo ships. Hence, the same ship types have the highest fuel consumption for both international and domestic traffic. For transit traffic, instead it is tanker ships that contribute with the highest fuel consumption, followed by RoPax, cargo ships and container ships. The ship type with the lowest fuel consumption is passenger ferries for both international and transit traffic.

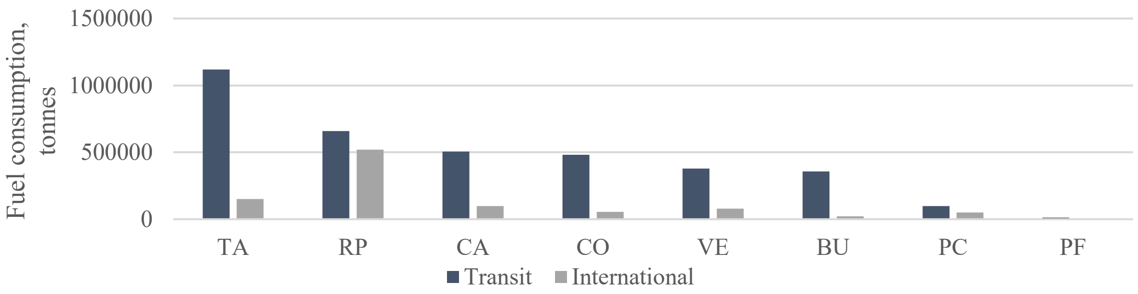

Figure 25. Fuel consumption by ship type for transit and international traffic. Source: Windmark (2019).

Figure 26 shows the fuel consumption per kilometre[13] by ship type and traffic type. Ships in transit traffic have the highest fuel consumption per kilometre, except for RoPax ships (for which the fuel consumption per kilometre is about the same across the traffic types). All ship types in domestic traffic, except cargo ships and passenger ferries, have lower fuel consumption per kilometre than for ships in transit and international traffic. Passenger cruise vessels and RoPax ships have the highest fuel consumption per kilometre, whereas cargo ships and passenger ferries have the lowest.

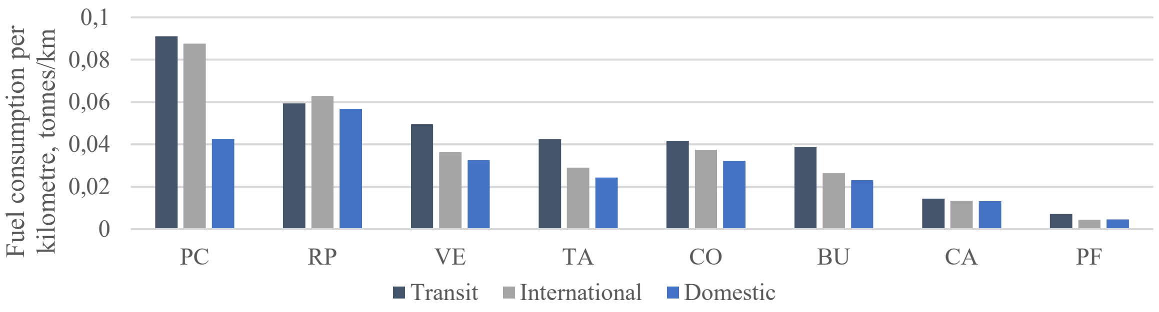

Figure 26. Fuel consumption per kilometre by ship type and traffic type (tonnes fuel / kilometre). Source: Windmark (2019).

Figure 27 presents the fuel consumption per kilometre by ship type, traffic type and engine capacity. For all ship types, the fuel consumption per kilometre is higher for ships with larger engine capacity.

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[13] This is calculated by: (total fuel consumption – fuel consumption at berth) / distance travelled

In other words, since engine capacity has a strong correlation with the size (in GT) of the ship (Windmark, 2019), the larger the ship then, on average, the higher its fuel consumption per kilometre.

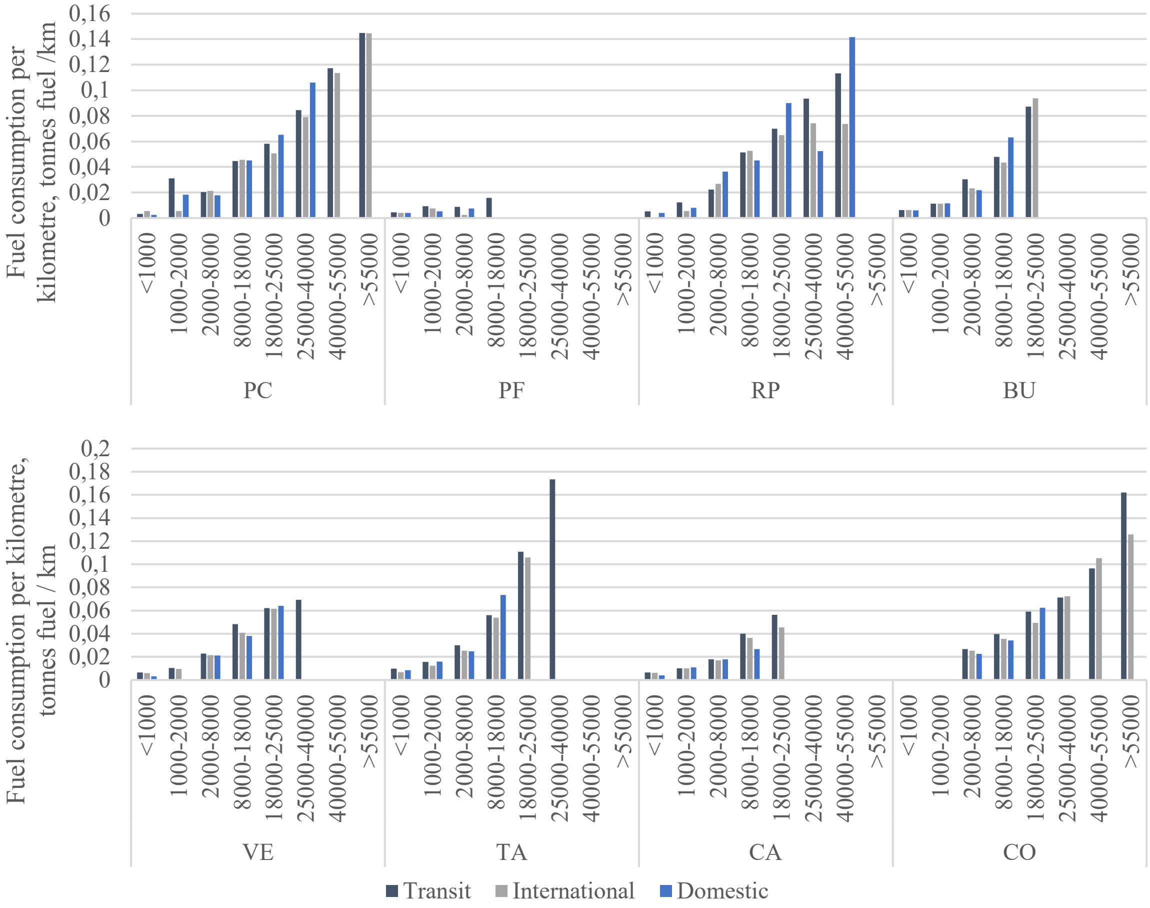

Figure 27. Fuel consumption per kilometre by ship type, traffic type and engine capacity (kW). Source: Windmark (2019).

5.1.2. Fuel consumption at berth and time at berth

In this section, transit traffic is not included since all fuel consumption at berth and time at berth for transit ships are in non-Swedish ports, which are not included in the scope of this report.

All fuel consumption at berth is assumed to come from the use of AEs (and not from the use of boilers). The estimated fuel consumption at berth is based on the usage level of the AEs, which is different for different ship types. In the Shipair model, these values are based on the literature on average AE load for different ship types. For example, a passenger ship can be expected to have a higher energy demand at berth compared to a freight ship, due to electricity usage and heating for passengers. However, in the literature, tanker ships have a higher AE load than other ship types since they are assumed to have a high energy demand for cargo handling in port (Windmark, 2019). The electricity usage for ships at berth with On-shore Power Supply (OPS) is not included in the model (Windmark et al., 2017).

Figure 28 shows the total fuel consumption at berth for domestic and international traffic by ship type. Since domestic traffic only includes ship journeys that both depart from and arrive in Sweden, all fuel in the figure has been consumed in Swedish ports. Tanker ships have the highest fuel consumption at berth, followed by RoPax ships and passenger ferries, whereas passenger cruise vessels have the lowest fuel consumption at berth. Since international traffic includes ship journeys that either departed from or arrived in Sweden, a share of the fuel has been consumed in non-Swedish ports.[14] RoPax ships and tanker ships have the highest fuel consumption at berth for international traffic, whereas passenger cruise vessels and passenger ferries have the lowest.

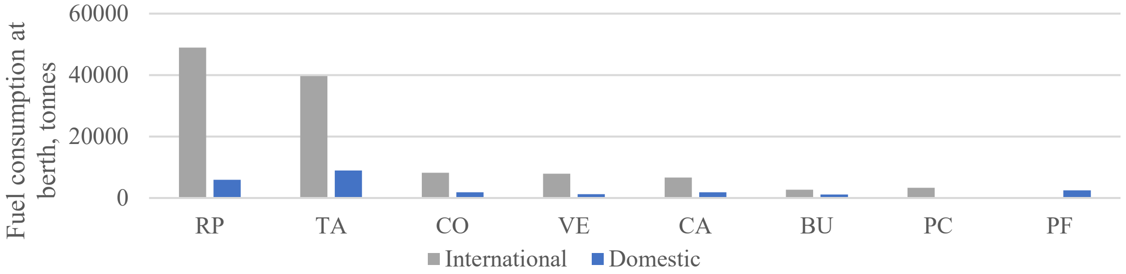

Figure 28. Fuel consumption at berth for international and domestic traffic. Source: Windmark (2019).

Figure 29 shows the domestic fuel consumption at berth and the domestic fuel consumption when ships are not at berth (i.e. the fuel consumption from all other operating modes), along with the share of fuel consumption at berth by ship type. The ship types that have the highest share of the total fuel consumption at berth are tanker ships (33% of the total fuel consumption is consumed at berth), followed by container ships and passenger ferries (both consume 27% of their total fuel at berth). RoPax ships have the lowest share (10%) and the ship types bulk carriers and vehicle carriers have the second lowest share (both consume 13% of their total fuel at berth).

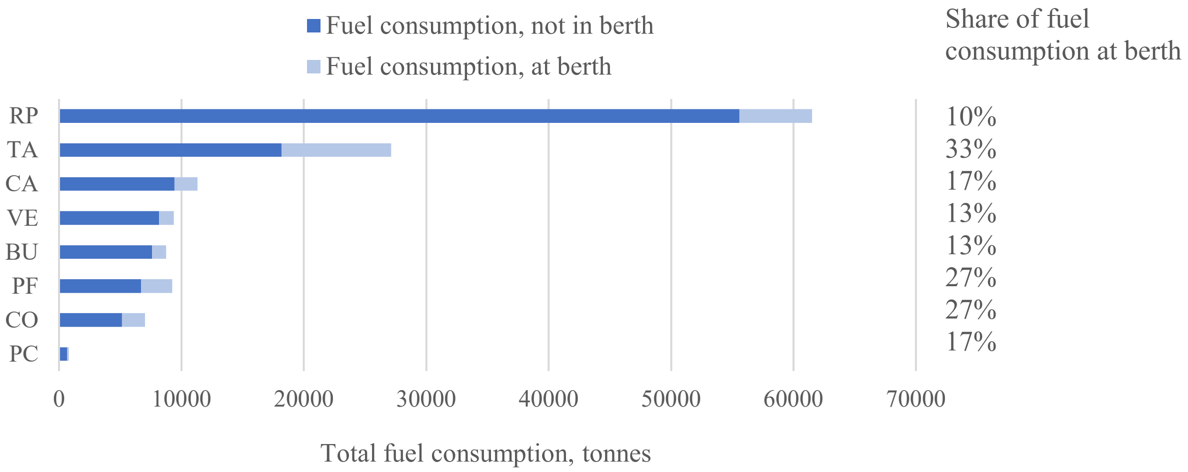

Figure 29. Fuel consumption in berth and at sea for ships in domestic traffic and the share of fuel consumption at berth. Source: Windmark (2019).

Figure 30 shows the time at berth for international and domestic traffic. International traffic has longer time at berth than domestic traffic for all ship types (except passenger ferries), which can be explained by the fact that the data also includes time at berth in international ports within the model area. Passenger ferries are likely to have longer time at berth in domestic traffic, since most passenger ferries only travel between Swedish ports and there are few passenger ferries in international traffic. The ship types with the longest time at berth are cargo ships, RoPax ships and tanker ships for international traffic. For domestic traffic, passenger ferries, RoPax, and cargo ships have the longest

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[14] In the estimation of emissions in this report, the fuel consumption at berth in Swedish ports from international traffic is estimated by: (Fuel consumption at berth for all Sweden traffic – Fuel consumption at berth for domestic traffic) / 2. This estimate hence assumes that each international journey arrives from or departs to a port within the Shipair model area. Of course, some international journeys may arrive from or depart to a port outside of the Shipair model area.

time at berth. The ship types with the shortest time at berth are vehicle carriers, container ships, bulk carriers and passenger cruise vessels, both for international and domestic traffic.

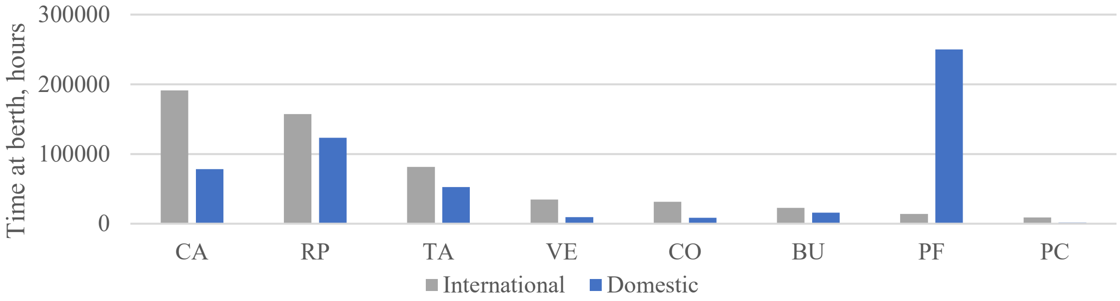

Figure 30. Time at berth for international and domestic traffic. Source: Windmark (2019).

Figure 31 shows the average fuel consumption at berth per hour[15] for international and domestic traffic. Tanker ships, passenger cruise vessels and RoPax ships have the highest fuel consumption at berth per hour for international traffic, whereas cargo ships and passenger ferries have the lowest. For domestic traffic, container ships, tanker ships and vehicle carriers have the highest fuel consumption per hour, whereas cargo ships and passenger ferries have the lowest. Ships in international traffic have higher fuel consumption per hour than in domestic traffic for all ship types.

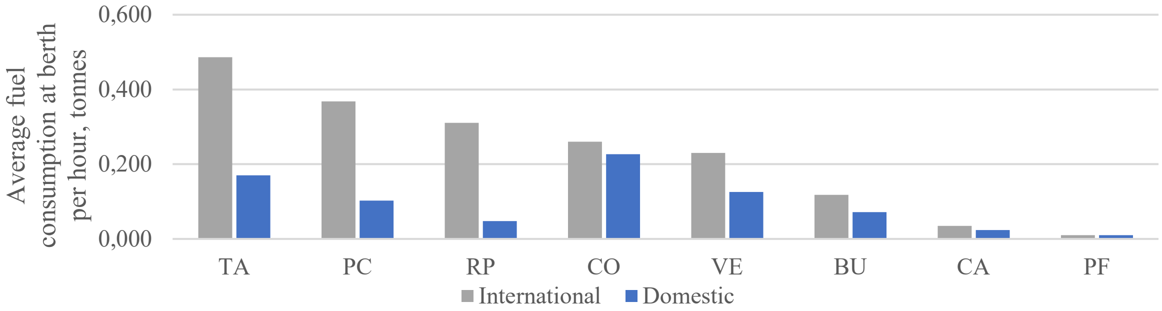

Figure 31. Average fuel consumption at berth per hour for international and domestic traffic. Source: Windmark (2019).

5.1.3. Comparison of fuel consumption between official statistics and AIS data

To put the estimated fuel consumption based on AIS data in relation to the fuel consumption from official statistics, a comparison between the two is presented for 2015 in Figure 32. However, only the fuel consumption estimated according to the previous official method is available from Statistics Sweden (2019c). Hence, the fuel consumption according to the new official method is not possible to compare with.

The grey columns show the fuel consumption according to AIS data based on Windmark (2019), for which the dark grey column shows the fuel consumption including all ship types and the light grey column shows the fuel consumption excluding the ship types of fishing vessels, service ships and other ships. The blue columns show the fuel consumption according to official statistics. The official statistics only present fuel consumption in cubic meters and to be able to compare it with the AIS data, which is presented in tonnes, the fuel consumption has to be converted from cubic meters to tonnes. For sensitivity reasons, Figure 32 presents, therefore, the fuel consumption with a low and a high conversion factor, represented by the dark and light blue columns, respectively.

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[15] This is calculated by dividing the total fuel consumption at berth with the time at berth for each ship type.

For international maritime transport, the covered geographical area is different between the AIS data used in this report and in the method used in official statistics. In the official statistics, fuel consumption from international transport, referred to as 'international bunkers', is defined as fuels bought in Sweden by Swedish or foreign-registered ships that is used for transport from Sweden to non-Swedish destinations. In the new estimation method in this report, the geographical area is based on the Shipair model area (described in section 3.1.2) which consists of three sea basins, covering Skagerrak, Kattegat and the Baltic sea. The fuel consumption is divided into two traffic types, referred to as international and transit. International includes the fuel consumed in the model area from all ship journeys that have departed or arrived in Sweden, excluding domestic traffic. Transit includes the fuel consumed in the model area from all ship journeys that have neither departed nor arrived in Sweden. Apart from the differences in which ship journeys are included in the two methods, the main difference between the methods is that the official statistics include consumed fuel to all non-Swedish destinations, whereas the new estimations only include consumed fuel within the model area. Both methods include the same types of ships. In summary, international and transit only include the fuel consumption in the Shipair model area, whereas 'international bunkers' can include the fuel consumption from journeys to international destinations outside of this area.

International maritime transport has a substantially higher fuel consumption compared to domestic maritime transport, both according to AIS data and official data. A comparison between the official data for international maritime transport, 'international bunkers', and the traffic types of international and transit shows that 'international bunkers' have higher fuel consumption than international traffic, but lower than transit traffic. However, as mentioned above, the fuel consumption between the official data and the AIS data is not directly comparable, since they include different journeys and different geographical areas.

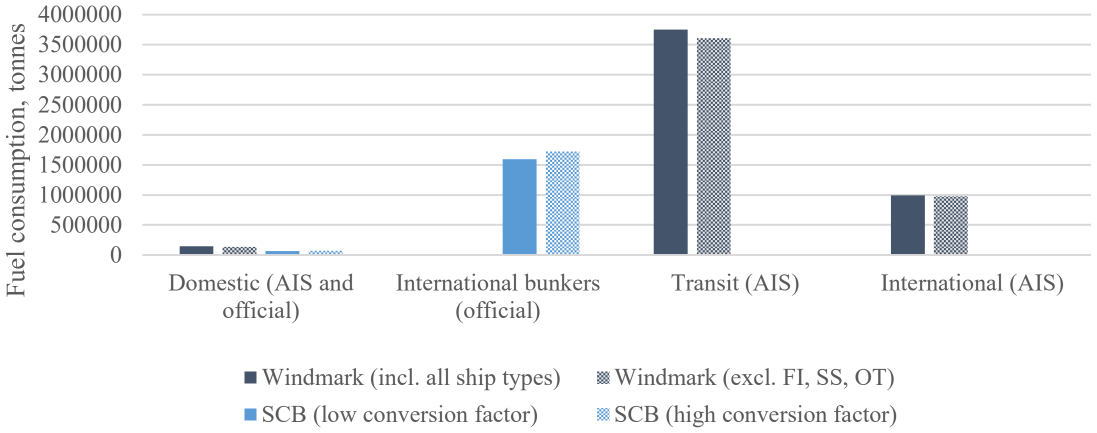

Figure 32. Fuel consumption for domestic and international maritime transport in 2015 according to AIS data and official statistics. Source: Windmark (2019), Statistics Sweden (2019c), and BP (2019) (for conversion factors of oil).

In a report by Windmark et al. (2017), which is also based on data from the Shipair model, the fuel consumption from domestic maritime transport is estimated for the period 2013-2015 (see Figure 33). The monthly estimated fuel consumption from domestic maritime transport according to AIS data is presented together with the official statistics. The fuel consumption based on the modelled method (the dotted line) is about twice as high as the fuel consumption based on official statistics (the solid line). An explanation is that a larger share of the emissions is counted as domestic rather than international maritime transport in the new modelled method (Swedish EPA, 2018a; Windmark et al., 2017). Moreover, the modelled fuel consumption follows the same trends as the fuel consumption according to official statistics until the beginning of 2015, where the trends move in different directions.

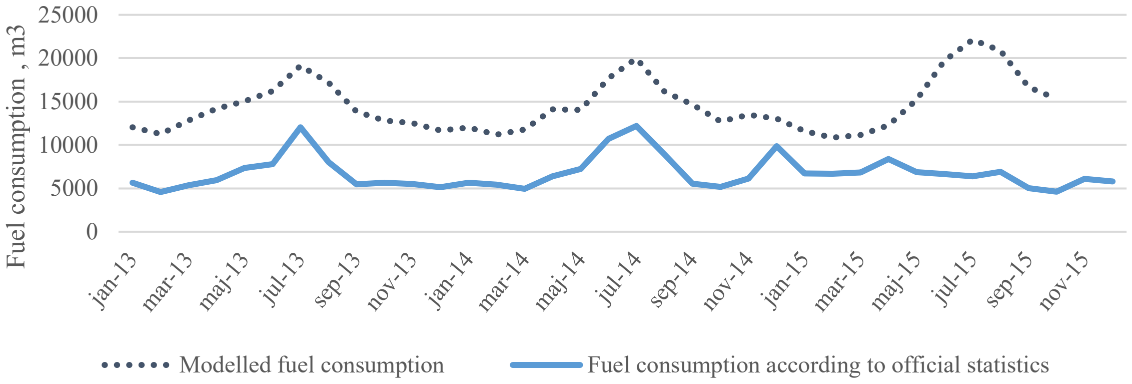

Figure 33. Monthly fuel consumption for domestic maritime transport according to official statistics and modelled estimations. Source: Windmark et al. (2017) and Statistics Sweden (2019).

5.2. Identifying average ship types

5.2.1. Ship fleet size

Table 8 presents the number of ships in the Shipair model area by ship type and traffic type. The most common ship type in the Shipair model area, for all traffic types, is cargo ships. This is followed by tanker ships and bulk carriers. The least common ship types are vehicle carriers, passenger ferries and passenger cruise vessels.

Table 8. Number of ships in the Shipair model area, by ship type and traffic type.

	Domestic	All Sweden	Transit
Cargo ship	816	1 231	2 488
Tanker ship	402	767	1 806
Bulk carrier	108	177	1 474
Container ship	87	170	342
RoPax	117	133	333
Vehicle carrier	56	175	259
Passenger ferry	84	86	153
Passenger cruise	48	78	100
Total	**1 718**	**2 817**	**6 955**

Source: Windmark (2019).

5.2.2. Average age of ships

The age of ships is relevant to examine since newer ships can be expected to have a different emissions profile and better fuel efficiency compared to older ships. It is also relevant to examine in order to get an estimate of which ship types that, on average, are older and can be expected to be replaced by newer ones.

Figure 34 shows the average age by ship type and traffic type. The oldest ship type is passenger ferries which, on average, is more than ten years older than the second oldest ship type, passenger cruise vessels. The newest ship types are container ships, tanker ships and bulk carriers. According to the figure, passenger-carrying ships are, on average, older than freight-carrying ships. Furthermore, ships in domestic and all Sweden traffic are slightly older than ships in transit traffic for all ship types, except passenger cruise vessels and container ships.

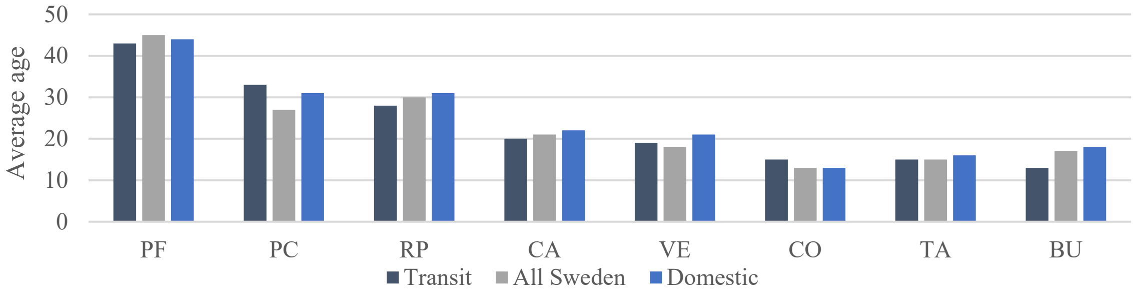

Figure 34. Average age by ship type and traffic type (including the whole model area). Source: Windmark (2019).

Figure 35 shows the average age in more detail, sorted into ship type, engine capacity and traffic type. The most notable finding from this figure is that ships with higher engine capacity are, on average, newer than ships with smaller engine capacity. In other words, since engine capacity has a strong correlation with the size of the ship (in GT) (Windmark, 2019), the larger the ship, the newer it is on average. Hence, there is a trend towards larger ships, which could reflect increasing economies of scale.

Another notable finding is that passenger cruise vessels with the smallest interval of engine capacity are considerably older compared to the other ship types. The average age is 84, 71 and 71 years old for ships in transit, all Sweden, and domestic traffic, respectively. This can be compared with the other ship types, for which almost none has a higher average age than 50 years old.

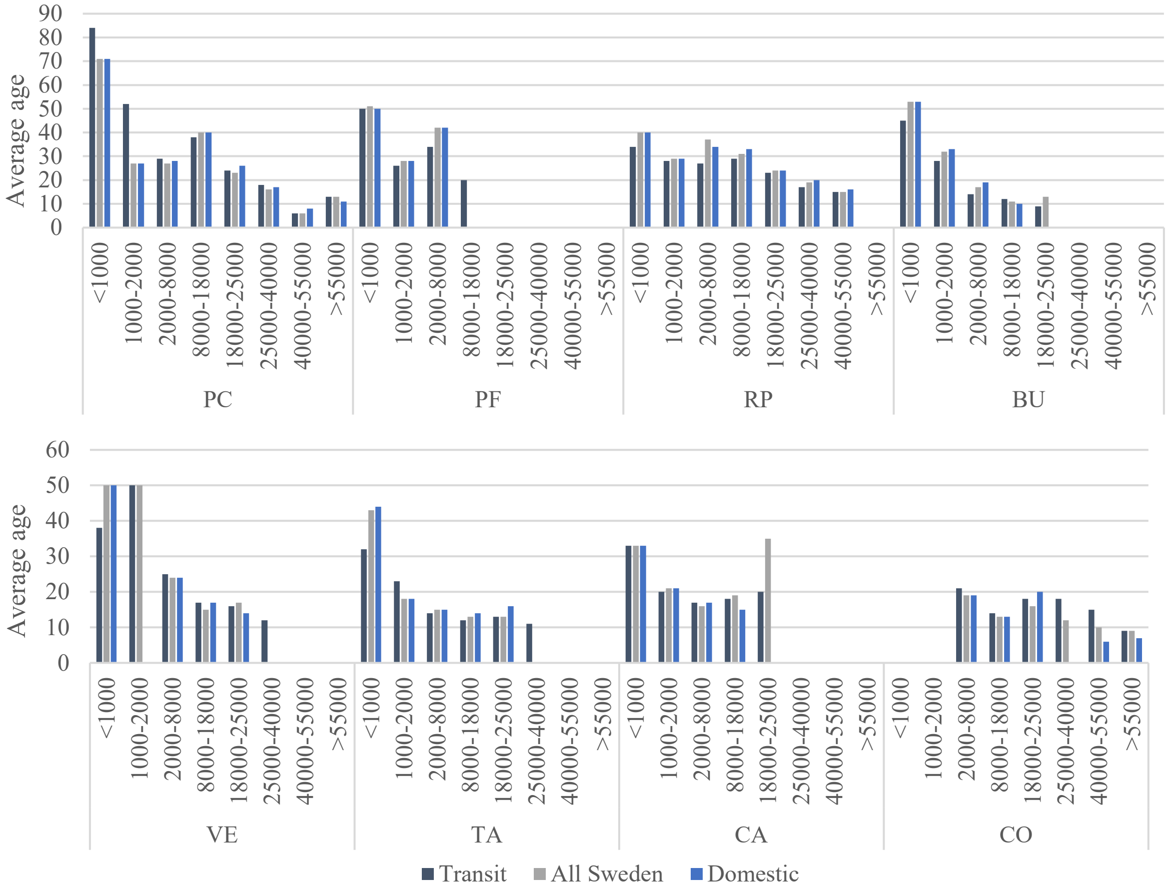

Figure 35. Average age by ship type, engine capacity (kW) and traffic type (including the whole model area). Source: Windmark (2019).

5.2.3. Design speed and average speed

Figure 36 presents the design speed and the average speed by ship type and traffic type. The design speed and the average speed are not completely comparable, since the design speed refers to the maximum speed that the ship is built for (and at which the ship is most energy efficient), whereas the average speed includes the average actual measured speed over all operating modes, such as manoeuvring into ports and sailing at sea.

The ship types with highest design speed are container ships, passenger cruise vessels, vehicle carriers, and RoPax ships. The ship type with lowest design speed is cargo ships. The design speed is almost the same for ships across traffic types. The average speed is highest for vehicle carriers, container ships, and passenger cruise vessels, whereas passenger ferries have the lowest average speed. Ships in domestic traffic have a lower average speed than ships in transit and all Sweden traffic.

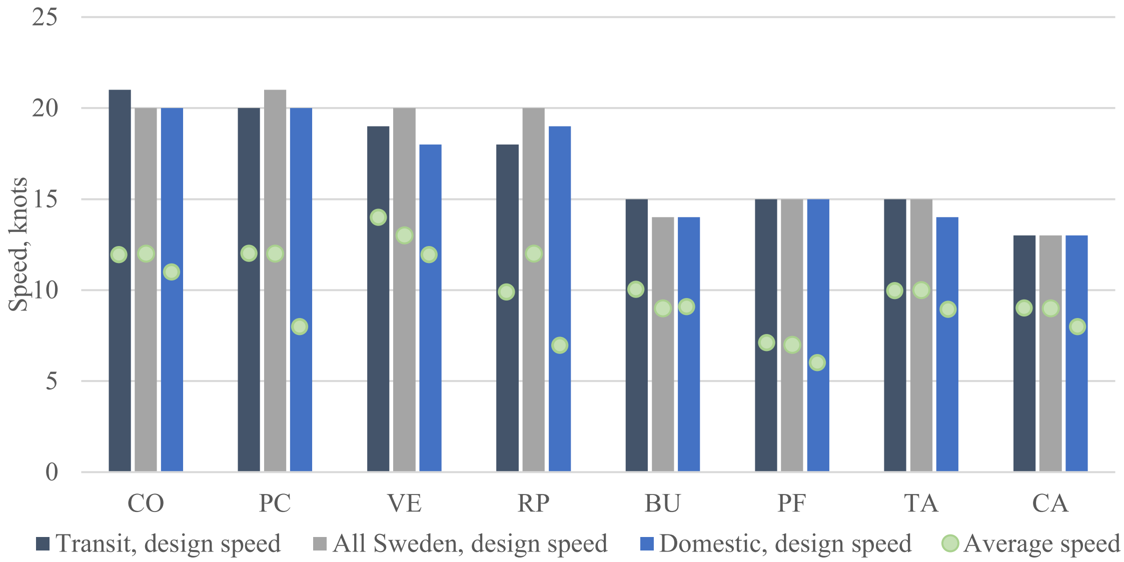

Figure 36. Design and average speed by ship type and traffic type (including the whole model area). Source: Windmark (2019).

5.2.4. Summary of vessel fleet and identification of average vessel types

The most common ship type for all traffic types, counted as number of ships, in the Shipair model area is cargo ships. This is followed by tanker ships and bulk carriers. The least common ship types are vehicle carriers, passenger ferries and passenger cruise vessels.

RoPax ships and tanker ships account for the majority of the domestic and international fuel consumption. Passenger cruise vessels and RoPax ships have the highest fuel consumption per kilometre. In transit traffic, tanker ships account for the majority of all fuel consumption, followed by RoPax ships, cargo ships and container ships. Ships in transit traffic have higher average fuel consumption per kilometre than ships in domestic and all Sweden traffic for all ship types, except RoPax, for which the average fuel consumption per kilometre is about the same for all traffic types. For all ship types, the fuel consumption per kilometre is higher for ships with larger engine capacity. Since engine capacity has a strong correlation with the size (in GT) of the ship, the larger the ship, the higher the fuel consumption per kilometres it has on average.

All ship types in international traffic have higher fuel consumption at berth per hour compared to ships in domestic traffic. A possible explanation is that ships in all Sweden traffic are larger and have higher engine capacity than ships in domestic traffic. Table 9, which presents average values of different variables, shows the average AE capacity and GT for all ship types, sorted by traffic type. The average AE is larger for all ships in all Sweden traffic (compared to ships in domestic traffic), except for the ship types of passenger cruise vessels and passenger ferries. For passenger cruise vessels, the average AE is larger in domestic traffic than in all Sweden traffic. For passenger ferries, the average AE is about the same in domestic and all Sweden traffic. Regarding the average GT, it is larger in all Sweden traffic for all ship types (compared to domestic traffic), except for bulk carriers and passenger ferries.

The oldest ship type is passenger ferries, which on average is more than ten years older than the second oldest ship type, passenger cruise vessels. The newest ship types are container ships, tanker ships and bulk carriers. On average, passenger-carrying vessels are found to be older than freight-carrying vessels. Furthermore, vessels in domestic and all Sweden traffic are slightly older than ships in transit traffic for all vessel types except passenger cruise vessels and container ships. Ships with higher engine capacity are, on average, newer than ships with smaller engine capacity. In other words, since engine capacity has a strong correlation with the size of the ship (GT), the larger the ship, the newer it is on average.

Table 9. Averages of variables from the Shipair model for domestic, all Sweden and transit traffic.

Vessel type	Traffic type	Average GT	Average ME	Average AE	Average fuel consumption, kg/km	Average fuel consumption at berth, kg/hour	Average age
Bulk carrier	Domestic	23 172	6 948	1 489	23	72	18
	All Sweden	23 078	7 011	1 526	25	99	17
	Transit	29 205	8 262	1 741	39	163	13
Cargo ship	Domestic	3 589	2 232	655	13	24	22
	All Sweden	4 116	2 562	738	13	32	21
	Transit	5 195	3 127	884	14	38	20
Container ship	Domestic	30 282	16 756	5 352	32	226	13
	All Sweden	43 922	23 450	6 435	37	253	13
	Transit	38 131	23 360	6 338	42	260	15
Passenger cruise	Domestic	40 524	24 761	3 190	43	102	31
	All Sweden	49 709	29 982	3 108	86	332	27
	Transit	43 723	26 054	2 650	91	154	33
Passenger ferry	Domestic	322	842	152	5	10	44
	All Sweden	320	830	151	5	10	45
	Transit	359	971	163	7	14	43
RoPax	Domestic	17 424	13 749	2 819	57	48	31
	All Sweden	17 844	14 088	2 919	62	195	30
	Transit	11 334	9 720	1 964	59	138	28
Tanker ship	Domestic	14 941	6 077	1 942	24	170	16
	All Sweden	20 171	7 202	2 274	28	362	15
	Transit	26 095	8 210	2 342	42	500	15
Vehicle carrier	Domestic	23 874	10 055	2 545	33	126	21
	All Sweden	41 460	12 887	3 373	36	207	18
	Transit	35 042	12 915	3 046	50	199	19

Source: Windmark (2019). The average fuel consumption (when not in berth) per kilometre (kg/km) is calculated by: (Total fuel consumption – Fuel consumption at berth) / Total distance travelled. The average fuel consumption at berth per hour (kg/hour) is calculated by: Total fuel consumption at berth / Time at berth.

5.3. Estimation of emissions from maritime transport based on AIS data

This section estimates emissions from maritime transport based on the fuel consumption presented in section 5.2, which is based on AIS data (described in section 3.1.2). The estimation method is described in section 3.2.2. The estimations are compared to the previous and current official statistics on emissions from maritime transport. A discussion of the results and their effect on the environmental quality objectives is included in section 8.

5.3.1. Emissions from domestic maritime transport

The estimated emissions of CO_2, SO_2, PM_{10} and NO_X from domestic maritime transport, referred to as "New method (AIS)" in Figure 37, are all higher than according to the previous official statistics. More specifically, all estimated emissions are at least twice as high as the previously estimated emissions in official statistics. Compared with the emissions from the current official method, the estimated emissions in this report are about the same for SO_2 and PM_{10}, but slightly lower for CO_2 and slightly higher for NO_X (see Table 10 in section 5.3.2 for more detailed results).

The new estimation method in this report and the method used in official statistics both include all fuel used for maritime journeys that both depart from and arrive in Sweden. Hence, the estimated emissions should be comparable with the emissions according to official statistics. An important difference between the two estimation methods is the emission factors. In this report, the most recently developed emission factors are used, which are updated to include aspects such as recently implemented/decided policies (e.g. SECA and NECA), several different fuel types (including relatively new low-sulphur fuels), and technology improvements of engines (Carlsson et al., 2019). Since this study uses different emission factors compared to the official statistics, sensitivity analyses with other emission factors are presented in the appendix.

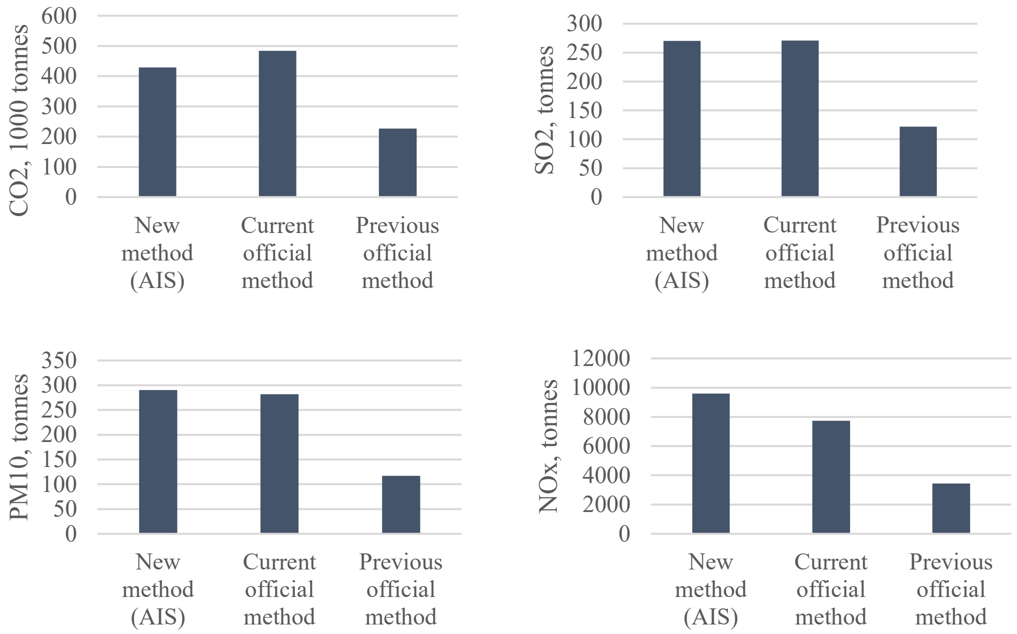

Figure 37. Emissions of CO_2, SO_2, PM_{10} and NO_X in 2015 for domestic maritime transport according to a new estimation method (based on AIS data) and according to the previous and current official method. Source: Statistics Sweden (2019a; 2019b; 2020a; 2020b) and own calculations based on Windmark (2019), SSPA (2018) and Carlsson et al. (2019).

5.3.2. Emissions from international maritime transport

For international maritime transport, the covered geographical area is different between the new estimation method and the method used in official statistics. This is discussed in more detail in section 5.1.3, but in summary, the international and transit traffic only include the fuel consumption in the Shipair model area, whereas 'international bunkers' (official statistics) also includes the fuel consumption from journeys to international destinations outside of this area. Therefore, the estimated emissions are not possible to directly compare with the official statistics.

The estimated emissions of CO_2, PM_{10} and NO_X from international maritime transport, presented in Figure 38, show that transit traffic has the highest emissions, followed by emissions from ‘international bunkers’ (both previous and current official statistics). International traffic (new method based on AIS) has the lowest estimated emissions of the traffic types in the figure. The transit traffic in the Shipair model area is hence indicated to emit more emissions than the international traffic from Sweden to all non-Swedish destinations and from international journeys within the Shipair model area. This result is expected since the transit traffic includes all traffic in the Shipair model area that do not call Swedish ports and hence includes traffic to and from all countries, except Sweden, in the Baltic sea, Skagerrak and Kattegat.

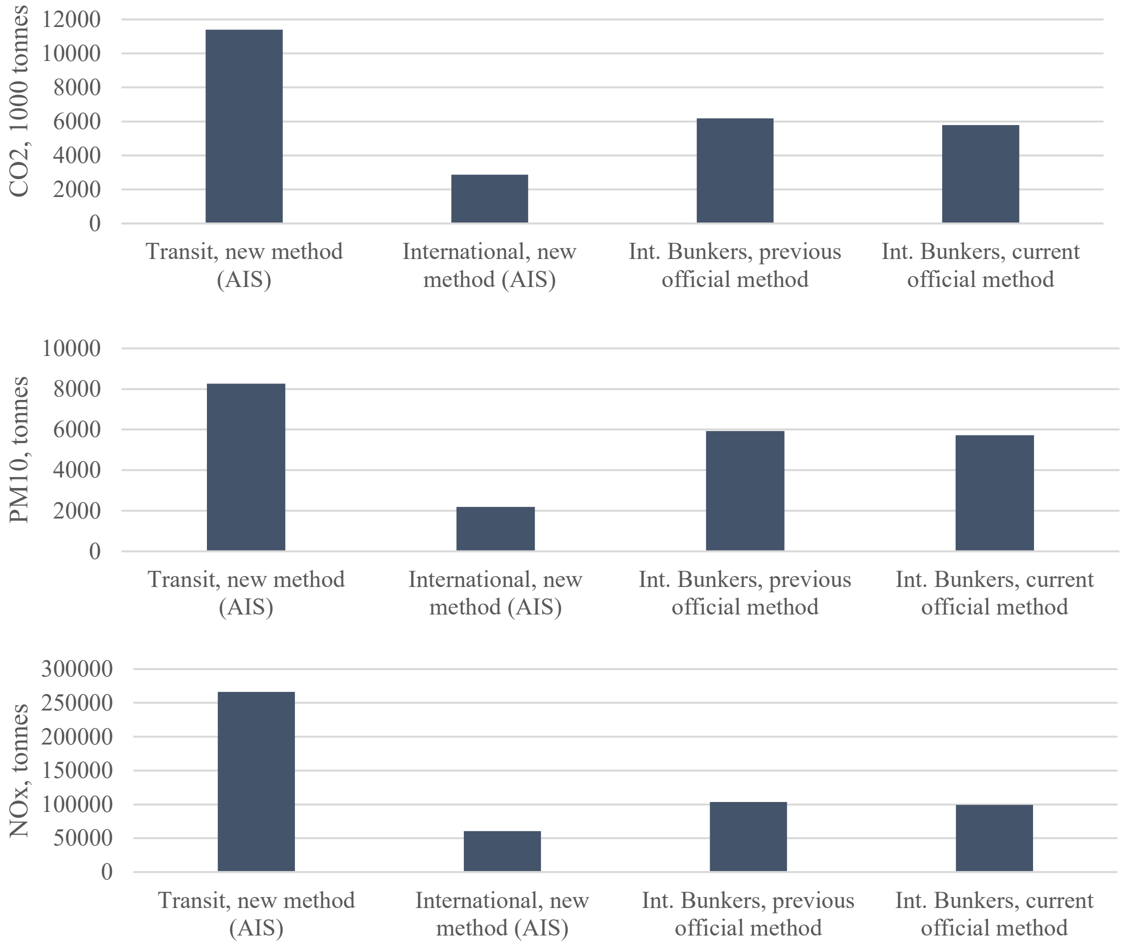

Figure 38. Emissions of CO_2, PM_{10} and NO_X in 2015 for domestic and international maritime transport according to a new estimation method (based on AIS data) and according to the previous and current official method. Source: Statistics Sweden (2019a; 2019b; 2020a; 2020b) and own calculations based on Windmark (2019), SSPA (2018) and Carlsson et al. (2019).

The distribution of estimated SO_2 emissions among the traffic types is relatively different compared to the emissions of CO_2, PM_{10} and NO_X. Even though the fuel consumption from transit traffic is higher than the fuel consumption from ‘international bunkers’ (see section 5.1.3), the SO_2 emissions from ‘international bunkers’ are substantially higher than the emissions from transit traffic, both according to the current and previous method (see Figure 39). There are a number of potential explanations for this which are discussed in section 8.

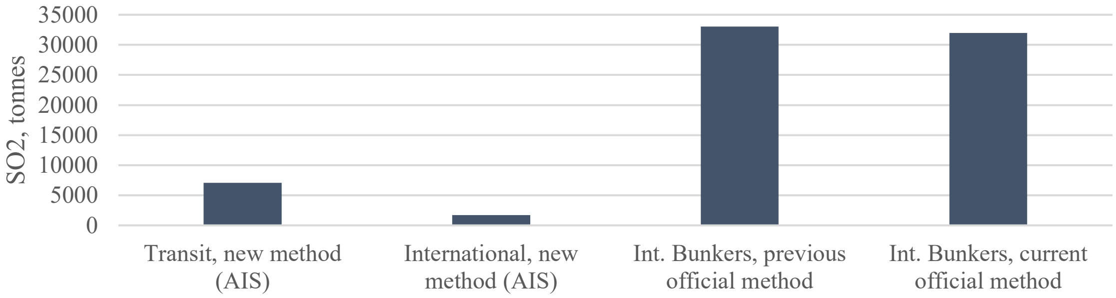

Figure 39. SO_2 emissions in 2015 for domestic and international maritime transport according to a new estimation method (based on AIS data) and according to the previous and current official method. Source: Statistics Sweden (2019a; 2019b; 2020a; 2020b) and own calculations based on Windmark (2019), SSPA (2018) and Carlsson et al. (2019).

The emissions of CO_2, SO_2, PM_{10} and NO_X from transit and international maritime transport are substantially higher than the emissions from domestic maritime transport, both according to the new estimation method and the official statistics (see Table 10). The table also presents estimated emissions separated into the two operating modes “at sea” and “at berth”. For domestic traffic, about 18% of all emissions of CO_2, SO_2 and NO_X are emitted from vessels at berth and about 8% of all PM_{10} emissions. For international traffic, about 12%, 13%, 5% and 6% of all emissions of CO_2, SO_2, PM_{10} and NO_X, respectively, are emitted from vessels at berth in Sweden. For transit traffic, about 16% of all emissions of CO_2, SO_2 and NO_X are emitted from vessels at berth and about 7% of all PM_{10} emissions.

The lower emissions of PM_{10} can be explained by the assumptions about which fuel types that are used in AEs and the corresponding emission factors. More specifically, the emission factor for MDO/MGO is lower for PM_{10} compared to emission factors for the other emissions.

Table 10. Estimated emissions of CO_2, SO_2, PM_{10} and NO_X in 2015 by operation mode and estimation method and emissions according to the previous and current official method.

		New method (AIS)			Previous official method		Current official method	
Emission type	**Operation mode**	**Transit**	**Inter-national**	**Domestic**	**Int. bunkers**	**Domestic**	**Int. bunkers**	**Domestic**
CO_2 (1000 tonnes)	At sea	9 520	2 689	353				
	At berth	1 874	188	76				
	Total	11 394	2 878	429	6 177	226	5 790	484
SO_2 (tonnes)	At sea	5 918	1 602	223				
	At berth	1 169	117	47				
	Total	7 087	1 720	270	33 046	122	31 952	271
PM_{10} (tonnes)	At sea	7 679	2 131	266				
	At berth	585	59	24				
	Total	8 263	2 190	290	5 929	117	5 723	282
NO_X (tonnes)	At sea	224 565	56 479	7 896				
	At berth	41 916	4 210	1 698				
	Total	266 481	60 689	9 593	103 356	3 452	99 280	7 737

Source: Statistics Sweden (2019a; 2019b; 2020a; 2020b) and own calculations based on Windmark (2019), SSPA (2018) and Carlsson et al. (2019).

Note: As discussed in section 5.1.3, the estimated emissions from international traffic are not possible to directly compare with the official statistics (international bunkers). The international and transit traffic only include the fuel consumption in the Shipair model area, whereas ‘international bunkers’ also includes the fuel consumption from journeys to international destinations outside of this area.

The emissions at berth from transit traffic only includes emissions in non-Swedish ports in the Shipair model area since transit traffic, by definition, does not call at Swedish ports. It is further important to clarify that the emissions at berth in Swedish ports from international traffic is an estimate which is based on fuel consumption that has not been estimated within the Shipair model. The fuel consumption at berth in Swedish ports from international traffic is instead estimated by: (Fuel consumption at berth for all Sweden traffic – Fuel consumption at berth for domestic traffic) / 2. Hence, this estimate assumes that each international journey arrives from, or departs to, a port within the Shipair model area. Some international journeys may, however, arrive from, or depart to, a port outside of the Shipair model area.

6. Future development

This section describes forecasts related to the future development of maritime transport, which will be used as input to the BAU scenarios in section 7.

6.1. Forecast of tonne- and passenger-kilometres

6.1.1. Freight transport

The Swedish Transport Administration (2018a) presents, on behalf of the government, forecasts of the development of freight transport and tonne-kilometres. The most recently published forecast presents the expected development of freight transport to the year 2040, using 2012 as the base year. Domestic tonne-kilometres of maritime transport is forecasted to increase by 1.9% per year between 2012 and 2040, while international tonne-kilometres is forecasted to increase by 2.2% per year.[16] These forecasts are represented by the dashed lines in Figure 40.

The Swedish Transport Administration (2018a) has based the demand for freight transport on a survey of commodity flows made in 2004/2005, in combination with statistics of industry development and foreign trade. Furthermore, a number of assumptions have been made when developing the forecasts, for example regarding economic growth, the valuation of goods and the development of foreign trade. The main scenario (an increase by 1.9% per year) is based on a substantial increase in demand for freight transport, resulting in an increase of tonne-kilometres that is considerably higher than the historical long-term trend (Swedish Transport Administration, 2018a). According to the Swedish Transport Administration (2018a), this increase is mainly the result of basing the scenario on the long-term forecast for economic growth in the "Long-term survey of the Swedish economy" from the Swedish Ministry of Finance.

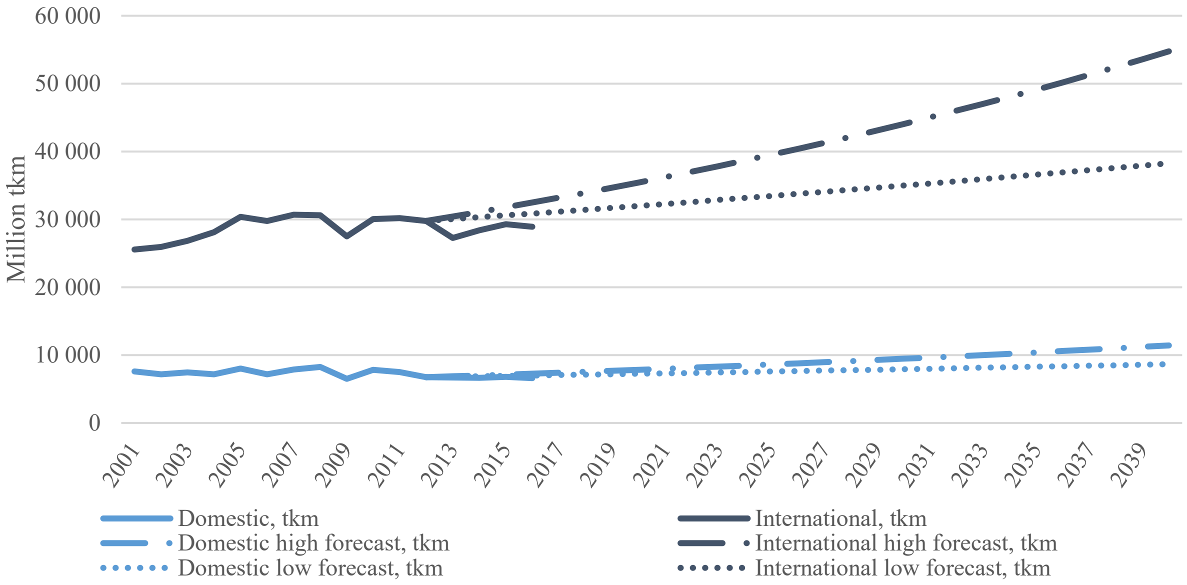

Figure 40. The historical development of tonne-kilometres along with the high and low forecasts of tonne-kilometres for domestic and international maritime transport. Source: Swedish Transport Administration (2018a), Transport analysis (2019a).

A sensitivity analysis is also made by the Swedish Transport Administration (2018a), in which the growth of tonne-kilometres is instead based on the historical trend of tonne-kilometres over the period

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[16] The international value is partly based on the Swedish Transport Administration (2018a) and partly on calculations by Magnus Johansson, VTI.

1984-2012. In this scenario, the estimated increase of tonne-kilometres is instead 0.9% per year between 2012 and 2040, which is represented by the dotted lines in Figure 40. The figure also includes the historical tonne-kilometres for maritime transport. A notable finding from the figure is that the development of tonne-kilometres over the period 2012-2018 is not in line with either of the forecasts, but is instead lower, especially for international maritime transport.

6.1.2. Passenger transport

There are no forecasts of passenger-kilometres available for maritime transport in Sweden (at least to the knowledge of the authors). Therefore, this report uses the historical trend of passenger-kilometres as an estimate for the future development of passenger transport. The trends for domestic and international passenger-kilometres show an increasing trend for domestic transport and a decreasing trend for international transport (see Figure 41). More specifically, over the period 2000-2016, the passenger-kilometres have, on average, been increasing by 1.6% per year for domestic transport and decreasing by 0.7% per year for international transport (excluding the years of 2017 and 2018 due to a new estimation method).

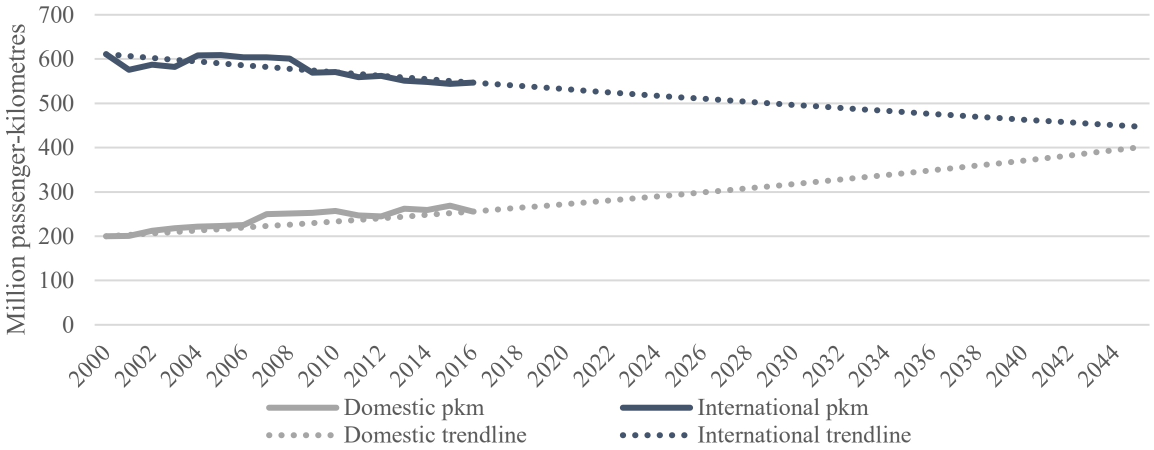

Figure 41. Development of domestic and international passenger-kilometres over the period 2000-2016 and a linear trendline until 2045 following the previous trend. Source: Transport analysis (2019a).

For sensitivity analysis, this report also uses the historical development of the number of passengers as an estimate for its future development. Figure 42 shows the number of cruise passengers visiting Sweden over the period 2004-2018, including both domestic and international journeys, and a linear trendline until 2030 (based on the trend over the period 2004-2018). Between 2004 and 2018, the number of cruise passengers has, on average, been increasing by 4.5% per year.

Figure 43 shows the total number of passengers over the period 2004-2018, excluding cruise passengers, and a linear trendline until 2030 (based on the trend over the period 2004-2018). Between 2004 and 2018, the number of passengers has, on average, been decreasing by 0.9% per year. Both figures include domestic and international journeys. For domestic journeys, the passengers are counted twice, once on departure and once on arrival.

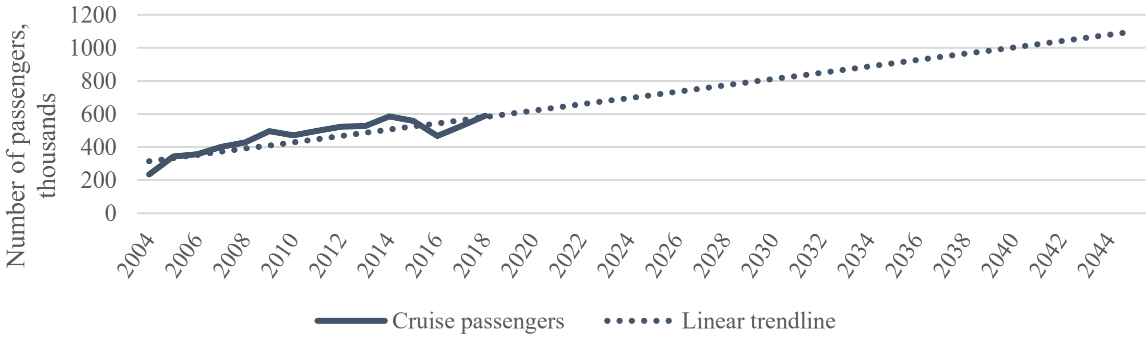

Figure 42. Development of number of cruise passengers over the period 2004-2018 and a linear trendline until 2045 following the previous trend. Source: Transport analysis (2019c).

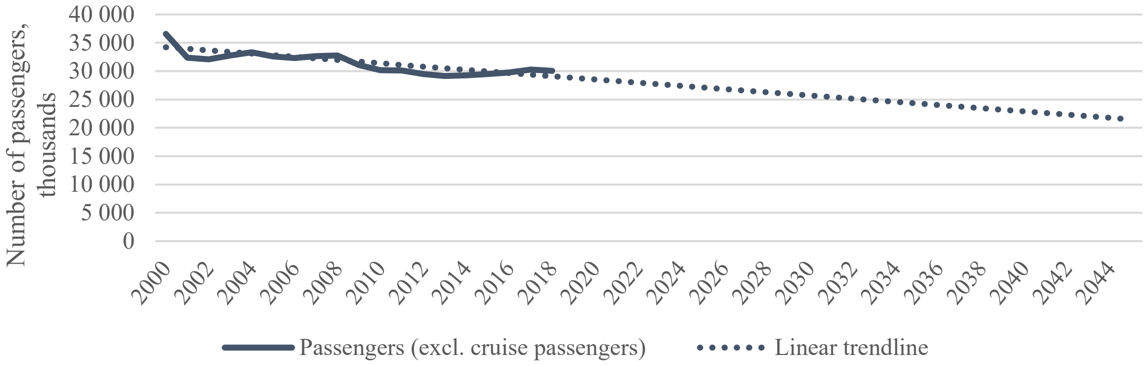

Figure 43. Development of number of passengers (excluding cruise passengers) over the period 2004-2018 and a linear trendline until 2045 following the previous trend. Source: Transport Analysis (2019c).

6.2. Forecast of energy efficiency improvements

Two relevant measures affecting maritime energy efficiency improvements are the Energy Efficiency Design Index (EEDI) for new ships and the Ship Energy Efficiency Management Plan (SEEMP) for all ships, which came into force in 2011 with the adoption of amendments to MARPOL Annex VI, resolution MEPC.203(62) (IMO, 2011). The EEDI is a mandatory measure for new ships which is aimed at promoting the use of more energy efficient equipment and engines. It requires a minimum energy efficiency per capacity mile for different ship types and sizes. More specifically, it requires most new ships to be 10% more efficient by 2015, 20% by 2020, and 30% from 2025 and onwards (IMO, 2015). The SEEMP is an operational measure which requires all shipowners to manage ship and fleet efficiency performance over time. The operational performance can be increased by, for example, improving the voyage planning or by doing more frequent propeller cleaning (IMO, 2015).

In a maritime forecast by DNV GL (2018), it is estimated that the fuel consumption per tonne-mile will decline 30% on average by 2050, compared to 2018 levels, due to energy-efficiency measures, such as hull and machinery improvements and speed reduction. This forecast assumes that the IMO target of a reduction in GHG emissions from international maritime transport of at least 50% by 2050, compared to the levels in 2008, will be reached. Another forecast is made by IMO (2015) in which it is forecasted that, without any additional implemented measures, the efficiency improvement will be 40% higher in 2050 relative to 2012 levels. For assumptions about energy efficiency improvements in the BAU scenarios, this report uses the forecast by DNV GL (2018) and the forecast by IMO (2015).

6.3. Forecast of alternative fuels

For assumptions about fuel types in the BAU scenarios, this report uses a forecast by the Swedish Energy Agency (2019) and a forecast by DNV GL (2018).

In scenarios by the Swedish Energy Agency (2019) about the future Swedish energy usage, it is forecasted that the fuel mix used by maritime transport will not change between 2018 and 2050. The forecast assumes that there are (and will not be) policy instruments strong enough to give incentives for fuel switches or reductions. Assuming that the fuel mix will not change, the fuel mix for 2015 by SSPA (2018) will therefore be used as a base in the BAU scenarios until 2045.

In a maritime forecast by DNV GL (2018), a forecast of the future fuel mix for short-sea shipping is presented for the period 2015-2050 (see Table 11). The fuel mix is divided into four fuel types; carbon-neutral fuels, HFO/MGO, LNG and electricity. The carbon-neutral fuels refer to fuels or energy systems that have no net GHG emissions (from well-to-propeller), for example, biofuels, hydrogen, ammonia, renewable, nuclear, or using carbon capture and storage. The usage of electricity includes both the charging of batteries used for ship propulsion and on-shore power supply. In the forecast by DNV GL (2018), the category of "carbon-neutral fuels" does not include the shares of the different fuel types, which hence limits the possibility estimate emissions from each fuel type. For simplicity, carbon-neutral fuels will therefore be assumed to result in zero emissions in the estimations in this report, which hence may result in an overestimated reduction of emissions.

Table 11. Forecasted fuel mix for short-sea shipping for 2030, 2045 and 2050 (based on the development in figure 6.3.1 in DNV GL (2018)).

Fuel types	**2030**	**2045**	**2050**
Carbon-neutral fuels	7%	28%	38%
HFO/MGO	79%	45%	27%
LNG	12%	23%	23%
Electricity	2%	5%	11%

Source: DNV GL (2018).

7. BAU scenarios

This section estimates BAU scenarios of emissions from domestic and international maritime transport until 2030 and 2045. Section 7.1 provides an overview of the assumptions used in the scenarios (the method is described in section 3.2.2). Section 7.2 and 7.3 present the domestic and international BAU scenarios, respectively. Section 7.4 provides a lifecycle analysis with the emissions from LNG.

7.1. Assumptions

There are several factors that can be expected to affect the future development of emissions from maritime transport. The demand for maritime transport, energy efficiency improvements, adoption of alternative fuels are some examples (which are described in section 6). There are of course numerous other factors that could affect the development of emissions from maritime transport, such as implementation of new policy instruments, economic growth, trade patterns, fuel prices, vessel speed, innovations of fuel types or energy efficiency improvements. However, since this study assumes a development according to business as usual, such factors are not taken into consideration in the BAU scenarios. Due to relatively large differences in forecasts about the demand for maritime transport, energy efficiency improvements, and adoption of alternative fuels, this study provides four BAU scenarios for estimation of emissions until 2030 and 2045.[17]

1. **Base scenario:** Including forecasted transport demand and forecasted energy efficiency improvement. Scenario (1) is the highest scenario.
2. **Scenario with higher energy efficiency improvement:** Including forecasted transport demand and high energy efficiency improvement.
3. **Scenario with lower transport demand:** Including low freight transport demand, passenger demand based on the historical trend of number of passengers, and high energy efficiency improvement.
4. **Scenario with lower transport demand and fuel switch:** Including low freight transport demand, passenger demand based on the historical trend of number of passengers, high energy efficiency improvement, and a fuel switch over time. Scenario (4) is the lowest scenario.

Table 12 summarises the assumptions used in this report to estimate emissions in BAU scenarios. The freight transport demand in the scenario (1) and (2) is based on a forecast of tonne-kilometres by the Swedish Transport Administration (2018a) in which the tonne-kilometres are expected to increase by 1.9% and by 2.2% per year between 2012-2040 for domestic and international traffic, respectively.[18] In scenario (3) and (4), a lower forecast of tonne-kilometres by the Swedish Transport Administration (2018a) is used, in which both domestic and international traffic is assumed to increase by 0.9% per year between 2012-2040. In all scenarios, the yearly changes are assumed to continue until 2045.

The future development of passenger transport demand in scenario (1) and (2) is based on the historical trend of passenger-kilometres, which is described in section 6.1.2.[19] The passenger transport demand is assumed to increase by 1.6% per year for domestic traffic and decrease by 0.7% per year

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[17] The reason for why all four scenarios are referred to as “Business-as-usual” scenarios, despite having different assumptions, is that the Swedish forecasts indicate different trends and predictions about the future. As the authors of this report cannot assess or judge which of the forecasts that most likely would correspond to business-as-usual, four BAU scenarios were included in order to demonstrate these differences.

[18] The ship types included in the freight transport category are cargo ships, tanker ships, bulk carriers, container ships, RoPax ships, and vehicle carriers. Even though RoPax ships are used both for passenger and freight transportation, they are included in this category since they are included in the freight transport forecast and hence should be assumed to have the same future development as freight transports.

[19] The ship types included in the passenger transport category are passenger cruise vessels and passenger ferries.

for international traffic. In scenario (3) and (4), the historical trend of number of passengers on passenger cruise vessels and passenger ferries are used, which also is described in section 6.1.2. The transport demand is assumed to increase by 6.8% for passenger cruise vessels and decrease by 1.1% for passenger ferries, both for domestic and international traffic.

Table 12. Assumptions used in BAU scenario and in sensitivity analyses.

Factor	Traffic type	Assumptions			
		1. Base scenario	2. Scenario with higher energy efficiency improvement	3. Scenario with lower transport demand	4. Scenario with lower transport demand and fuel switch
Freight transport demand	Domestic	**1.9% per year** Based on forecast of tkm by the Swedish Transport Administration (2018a)		**0.9% per year** Based on a lower increase of tkm according to the lower forecast by the Swedish Transport Administration (2018a)	
	International	**2.2% per year** Based on forecast of tkm by the Swedish Transport Administration (2018a) [a]		**0.9% per year** Based on a lower increase of tkm according to the lower forecast by the Swedish Transport Administration (2018a)	
Passenger transport demand	Domestic	**1.6% per year** Based on trends of the historical development of pkm.		**6.8% cruise,** **- 1.1% ferry per year** Based on historical development of number of passengers	
	International	**- 0.7% per year** Based on trends of the historical development of pkm		**6.8% cruise,** **- 1.1% ferry per year** Based on historical development of number of passengers	
Energy efficiency improve-ment	Domestic and International	**1% per year** Based on forecast by DNV GL (2018) [b]	**1.4% per year** Based on forecast by IMO (2015) [c]		
Fuel types	Domestic and International	No change according to forecast by the Swedish Energy Agency (2019)			Changed fuel mix over time according to DNV GL (2018) [d]
Emission factors	Domestic and International	Based on Carlsson et al. (2019)			

[a] The international value is partly based on the Swedish Transport Administration (2018a) and partly on calculations by Magnus Johansson, VTI.

[b] DNV GL (2018) forecasts that the fuel consumption per tonne-mile will decline by 30%, on average, for the period 2015-2050 (corresponding to 1% per year).

[c] IMO (2015) forecasts 40% improvement for the period 2012-2050 (corresponding to 1.4% per year).

[d] See section 6.3 for the fuel mix.

The energy efficiency improvement used in scenario (1) is based on DNV GL (2018), in which it is forecasted that the fuel consumption per tonne-mile will decrease by 30% for the period 2015-2050. This corresponds to an energy efficiency improvement of about 1% per year which, hence, is assumed to reduce the fuel consumption by the same percentage per year. In the other three scenarios, a higher energy efficiency improvement by IMO (2015) is used, in which it is forecasted that there will be a 40% energy efficiency improvement for the period 2012-2050. This corresponds to an energy efficiency improvement of about 1.4% per year which, hence, is assumed to reduce the fuel consumption by the same percentage per year.

For the estimation of fuel consumption at berth, the same transport demand and energy efficiency improvement is used as at sea.

In scenarios (1), (2) and (3), the same fuel mix is assumed over the whole time period. This assumption is based on a forecast by the Swedish Energy Agency (2019) in which it is estimated that the fuel mix used by maritime transport will not change between 2018 and 2050. In scenario (4), a fuel mix by DNV GL (2018) is used, which is described in section 6.3.

In all four scenarios, the emission factors are based on Carlsson et al. (2019) – see Table 6 and Table 7 in section 3.2. For the period 2015-2024, the emission factors for 2017 are used, for 2025-2039, the emission factors for 2025 are used, and for 2040-2045, the emission factors from 2040 are used. The emission factors for MEs are used, both for the estimation of emissions at sea and at berth. The emission factors of HFO/IFO and MGO/MDO for NO_X (see Table 7) are substantially reduced over time. This can be explained by the decided introduction of NECA in 2021, which will require all new vessels to comply with the Tier III standards for engines. In Carlsson et al. (2019), it is assumed that vessels have an average life length of 25 years and with the replacement of ships over time, this will increase the share of vessels complying with Tier III levels. More specifically, this is assumed to result in 20% of all vessels complying with Tier III in 2025, and 76% of all vessels complying with Tier III in 2040. In 2046, it is assumed that all vessels will comply with Tier III (Carlsson et al., 2019).

In scenario (4) with the fuel switch, the fuel types of electricity and carbon-neutral fuels are assumed to have zero emissions. However, although carbon-neutral fuels should not contribute to CO_2 emissions, they may still contribute to emissions of SO_2, PM_{10} and NO_X.[20] Hence, these emissions are likely to be underestimated in this scenario. Furthermore, to what extent electrified ships contribute to emissions depends on how the electricity is produced.

As described in section 6.3, the fuel types in DNV GL (2018) are different from those included in Carlsson et al. (2019) and in SSPA (2018). More specifically, the fuel types of HFO and MGO are combined into one category in scenario (4) with a changed fuel mix, whereas these are separated in the other scenarios. Since the emission factors for HFO and MGO are different in Carlsson et al. (2019), the average value of those emission factors was used in the estimation of emissions in scenario (4).

The emission factors in Carlsson et al. (2019) represent the emissions from a tank-to-propeller (TTP) perspective. Hence, potential emissions from the well-to-tank (WTT) perspective are not included in the BAU scenarios. However, when it comes to emissions from LNG, the total emissions of CO_2-equaivalents can be expected to be significantly higher when including the WTT perspective, due to methane slip. Therefore, a life cycle estimation is presented in section 7.4, in which the emissions of methane are included.

Other factors that have been discussed in this report, and that can be expected to have an effect on the future development of emissions from maritime transport, are vessel types in the fleet, fleet size, vessel age, vessel size and vessel speed. However, the effect from the replacement of ships and the trend towards larger ships are assumed to be captured by the energy efficiency improvement values. In BAU scenarios, vessel speed is assumed to not change. Moreover, the effects of implemented or decided measures and policy instruments, such as SECA and NECA, are also assumed to be captured by the energy efficiency improvement values.

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[20] As mentioned in section 6.3, the assumption about zero emissions from "carbon-neutral fuels" will be resulting in an overestimated reduction of emissions. The assumption was made due to the fact that the category of "carbon-neutral fuels" in the forecast by DNV GL (2018) does not include the shares of different fuel types, which hence limits the possibility estimate emissions from each fuel type.

7.2. Domestic BAU scenarios

The estimated BAU scenarios for the emissions of CO_2, SO_2, PM_{10} and NO_X until 2030 and 2045 are presented in Table 13. The table includes the four BAU scenarios and separates emissions emitted at sea and at berth. Figure 44 presents an overview of the estimated emissions, based on the results in Table 13, by showing the highest and lowest estimation results.

The estimated emissions of CO_2, SO_2, and PM_{10} have similar developments until 2030 and 2045 (see Figure 44). However, scenario (1), represented by black lines, and scenario (4), represented by grey lines, indicate quite different development paths for the emissions. The estimated emissions from the highest scenario indicate increasing emissions over time, while the lowest scenario indicate decreasing emissions over time. Scenario (1) indicates an increase of emissions by about 28% for the period 2015-2045 for CO_2, SO_2 and PM_{10}. NO_X emissions are instead indicated to decrease by about 55% for the period 2015-2045 in scenario (1). In scenario (4), all emissions are indicated to decrease. More specifically, for the period 2015-2045, the emissions are indicated to decrease by 45% for CO_2, 62% for SO_2, 58% for PM_{10} and 85% for NO_X emissions. The relatively large difference between the highest and lowest scenario can be explained by the variations in the Swedish forecasts that the estimations are based upon, which indicate different trends and predictions about the future.

The development of the estimated emissions of NO_X is different from the other emissions. This can be explained by the decreasing emission factors of NO_X over time, which is due to the decided implementation of NECA in 2021 (described in section 7.1 and discussed in section 8). Hence, assuming that all new vessels comply with Tier III standards for engines, the NO_X emissions will decline over time as older ships are replaced by newer ones. The change in the trend for NO_X emissions after 2030, which can be seen in Figure 44, can be explained by the assumptions about NECA made in Carlsson et al. (2019). It is assumed that NECA will contribute to compliance with Tier III standards, hence affecting emission factors over time.

The majority of the emissions are emitted at sea and between 8-18% of the total emissions are emitted at berth. More specifically, of the total emissions of CO_2, SO_2 and NO_X, about 17-18% are emitted at berth and of the total emissions of PM_{10}, about 8% are emitted at berth. The share of emissions emitted at berth is almost the same over time, whereby only a small reduction of the shares can be observed.

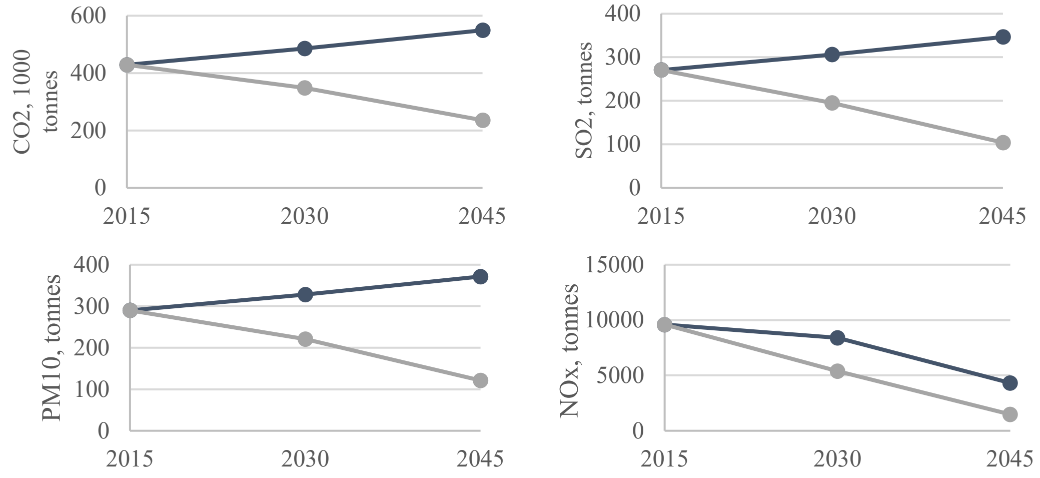

Figure 44. High and low estimations of domestic emissions of CO_2, SO_2, PM_{10} and NO_X until 2030 and 2045. Source: Own calculations based on information and data described in section 7.1.

The reduction of emissions in scenario (4) can be expected to be overestimated due to the assumptions made in the estimation method. First, the fuel types of electricity and carbon-neutral fuels are assumed to have zero emissions. However, although carbon-neutral fuels should not contribute to CO_2 emissions, they may still contribute to emissions of SO_2, PM_{10} and NO_X. Hence, these emissions are likely underestimated in scenario (4) in Table 13 and Figure 44. Second, the fuel switch includes an increased share of LNG (see section 6.3). Taking the methane slip from LNG usage into account, the total GHG emissions (in CO_2-equivalents) are higher than in the BAU estimations (see section 7.4). To conclude, all the emissions in scenario (4) would be higher if these factors were included in the estimation. Even though the estimated emissions in this scenario can be expected to be underestimated, it is still relevant to include it in the report since it shows the difficulties in reaching the targets. Even if there would be low future transport demand, high energy efficiency improvements and changed fuel mix towards fuels with less emissions, polluting emissions would still be high and the target of reduced CO_2 emissions would not be reached.

Table 13. Domestic estimations of CO_2, SO_2, PM_{10} and NO_X for four scenarios until 2030 and 2045.

Scenario	Pollutant	2015	2030	2045
1. Base scenario	CO_2 at sea, 1000 tonnes	353	399	452
	CO_2 at berth, 1000 tonnes	76	86	97
	SO_2 at sea, tonnes	223	253	286
	SO_2 at berth, tonnes	47	54	61
	PM_{10} at sea, tonnes	266	301	341
	PM_{10} at berth, tonnes	24	27	30
	NO_X at sea, tonnes	7 896	6 922	3 564
	NO_X at berth, tonnes	1 698	1 468	754
2. Scenario with higher energy efficiency improvement	CO_2 at sea, 1000 tonnes	353	378	406
	CO_2 at berth, 1000 tonnes	76	81	87
	SO_2 at sea, tonnes	223	239	257
	SO_2 at berth, tonnes	47	51	54
	PM_{10} at sea, tonnes	266	286	306
	PM_{10} at berth, tonnes	24	25	27
	NO_X at sea, tonnes	7 896	6 557	3 444
	NO_X at berth, tonnes	1 698	1 390	677
3. Scenario with lower transport demand	CO_2 at sea, 1000 tonnes	353	324	302
	CO_2 at berth, 1000 tonnes	76	69	64
	SO_2 at sea, tonnes	223	205	191
	SO_2 at berth, tonnes	47	43	40
	PM_{10} at sea, tonnes	266	245	228
	PM_{10} at berth, tonnes	24	21	20
	NO_X at sea, tonnes	7 896	5 616	2 380
	NO_X at berth, tonnes	1 698	1 178	495
4. Scenario with lower transport demand and fuel switch	CO_2 at sea, 1000 tonnes	353	288	195
	CO_2 at berth, 1000 tonnes	76	60	41
	SO_2 at sea, tonnes	223	161	86
	SO_2 at berth, tonnes	47	34	18
	PM_{10} at sea, tonnes	266	204	111
	PM_{10} at berth, tonnes	24	17	10
	NO_X at sea, tonnes	7 896	4 492	1 236
	NO_X at berth, tonnes	1 698	890	244

Source: Own calculations based on information and data described in section 7.1.

Figure 45 illustrates the estimation of future CO_2 emissions and the target for GHG emissions. Scenario (1), represented by the black solid line, and scenario (2), represented by the green line, both show increased emissions of CO_2 over the time period. The lowest scenarios instead indicate reduced emissions of CO_2 over the time period; scenario (3), represented by the grey line, only indicates a relatively small reduction of CO_2 emissions, whereas scenario (4), represented by the orange line, indicates a larger reduction of emissions. However, if all GHG emissions would have been included in the estimations, the estimated emissions would be underestimated due to the methane slip from LNG (see section 7.4 for more details).

Figure 45 also includes the GHG reductions needed to reach the target of reducing GHG emissions from domestic transport by 70% by 2030 compared to 2010 levels and the target of zero net GHG emissions by 2045, which are represented by the dashed line. It should be noted that the target includes all GHG emissions, whereas the BAU estimations only includes CO_2 emissions. Hence, if emissions of other GHGs were included in the estimations, the estimated emissions would be even further away from the targets.

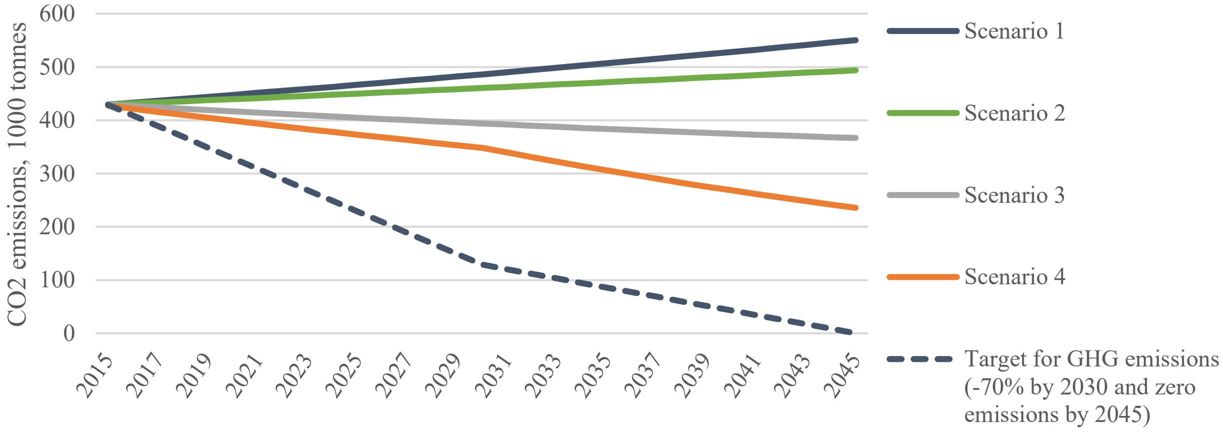

Figure 45. Domestic estimations of CO_2 emissions for four scenarios until 2045 and the target for GHG emissions. Source: Own calculations based on information and data described in section 7.1.

7.3. International BAU scenarios

The estimated BAU scenarios for international maritime transport emissions of CO_2, SO_2, PM_{10} and NO_X until 2030 and 2045 is presented in Table 14. The table includes the four BAU scenarios and separates emissions at sea and at berth. Figure 46 presents an overview of the estimated emissions based on the results in Table 14 by presenting the highest and lowest estimation results.

The estimated emissions of CO_2, SO_2 and PM_{10} have similar developments until 2030 and 2045 (see Figure 46). The trends are also similar to those of the domestic BAU scenarios, presented in section 7.2. As can be seen in Figure 46, scenario (1), represented by black lines, and scenario (4), represented by grey lines, indicate quite different developments of the emissions. Scenario (1) indicates increasing emissions over time, while scenario (4) indicates decreasing emissions over time. More specifically, scenario (1) indicates an increase of emissions by about 37% for the period 2015-2045 for CO_2, SO_2 and PM_{10}. NO_X emissions are instead indicated to decrease by about 51% for the period 2015-2045 in scenario (1). In scenario (4), all emissions are indicated to decrease. More specifically, for the period 2015-2045, the emissions are indicated to decrease by 31% for CO_2, 49% for SO_2, 50% for PM_{10} and 79% for NO_X emissions.

The development of the estimated emissions of NO_X is different from the other emissions. As mentioned in section 7.2, this can be explained by the decreasing emission factors of NO_X over time, which is due to the decided implementation of NECA in 2021 (described in section 7.1). Hence, assuming that all new ships comply with Tier III standards for engines, the NO_X emissions will decline over time as older ships are replaced by newer ones.

The majority of the emissions are emitted at sea and between 2-7% of the total emissions are emitted at berth. In scenarios (1), (2) and (3), the shares of emissions emitted at berth do not change over time, but in scenario (4), the share of emissions emitted at berth decreases slightly.

As mentioned in section 7.2, the BAU scenarios do not take other GHG emissions than CO_2 into account. Since the usage of LNG, which is a fuel type assumed to be used in all four scenarios, contributes to leakage of methane, the GHG emissions (in CO_2-equivalents) are higher when taking this into account – see section 7.4 for more details. Furthermore, the emissions of SO_2, PM_{10} and NO_X can be expected to be underestimated in scenario (4), due to assumptions about the fuel switch, which is discussed further in section 8.

Table 14. International estimations of CO_2, SO_2, PM_{10} and NO_X for four scenarios until 2030 and 2045.

Scenario	Pollutant	2015	2030	2045
1. Base scenario	CO_2 at sea, 1000 tonnes	2 689	3 138	3 687
	CO_2 at berth, 1000 tonnes	188	222	262
	SO_2 at sea, tonnes	1 602	1 870	2 197
	SO_2 at berth, tonnes	117	138	164
	PM_{10} at sea, tonnes	2 131	2 487	2 922
	PM_{10} at berth, tonnes	59	69	82
	NO_X at sea, tonnes	56 479	51 275	27 758
	NO_X at berth, tonnes	4 210	3791	2 037
2. Scenario with higher energy efficiency improvement	CO_2 at sea, 1000 tonnes	2 689	2 973	3 308
	CO_2 at berth, 1000 tonnes	188	210	235
	SO_2 at sea, tonnes	1 602	1 771	1 971
	SO_2 at berth, tonnes	117	131	147
	PM_{10} at sea, tonnes	2 131	2 356	2 622
	PM_{10} at berth, tonnes	59	66	73
	NO_X at sea, tonnes	56 479	48 574	25 612
	NO_X at berth, tonnes	4 210	3 591	1 828
3. Scenario with lower transport demand	CO_2 at sea, 1000 tonnes	2 689	2 676	2 883
	CO_2 at berth, 1000 tonnes	188	181	182
	SO_2 at sea, tonnes	1 602	1 595	1 718
	SO_2 at berth, tonnes	117	113	113
	PM_{10} at sea, tonnes	2 131	2 121	2 285
	PM_{10} at berth, tonnes	59	56	57
	NO_X at sea, tonnes	56 479	43 649	21 533
	NO_X at berth, tonnes	4 210	3 090	1 410
4. Scenario with lower transport demand and fuel switch	CO_2 at sea, 1000 tonnes	2 689	2 405	1 881
	CO_2 at berth, 1000 tonnes	188	158	116
	SO_2 at sea, tonnes	1 602	1 345	830
	SO_2 at berth, tonnes	117	89	51
	PM_{10} at sea, tonnes	2 131	1 699	1 074
	PM_{10} at berth, tonnes	59	46	28
	NO_X at sea, tonnes	56 479	37 310	11 862
	NO_X at berth, tonnes	4 210	2 334	696

Source: Own calculations based on information and data described in section 7.1.

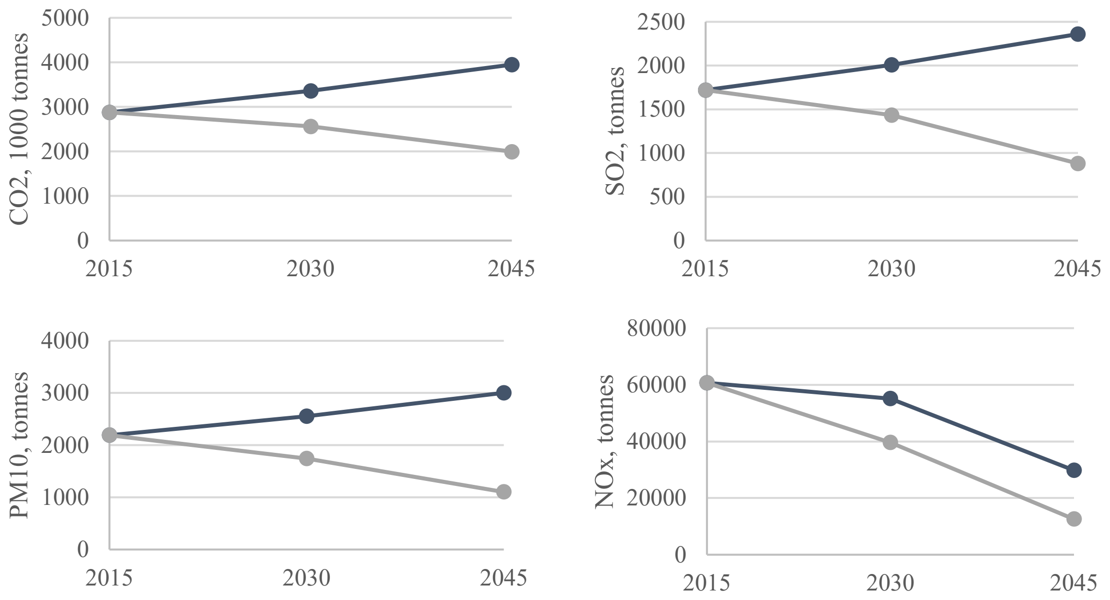

Figure 46. High and low estimations of international emissions of CO_2, SO_2, PM_{10} and NO_X until 2030 and 2045. Source: Own calculations based on information and data described in section 7.1.

7.4. BAU estimations with a lifecycle perspective

The estimated emissions of CO_2 in the BAU scenarios in section 7.2 and 7.3 do not include any other GHG emissions that the combustion of marine fuels can contribute to. More specifically, by utilising LNG, which primarily consists of methane (CH_4), there can be a significant leakage of methane along the process of extraction, transport, bunkering and combustion, which is referred to as methane slip (Brynolf et al., 2014). Emissions of methane are important to include in analyses of GHG emissions since it has a global warming potential (GWP) that is 34 times higher than that for CO_2 over a 100-year perspective (Myhre et al., 2013). Therefore, this section presents emissions of CO_2-equivalents from the estimated usage of LNG in the BAU scenarios estimated in section 7.2 and 7.3.

To calculate GHG emissions from the use of LNG, emissions factors of CO_2 and CH_4 for a TTP and WTP perspective are used, which are based on Brynolf et al. (2014). The WTP emission factors include emissions from the whole lifecycle of LNG, including extraction, production, transport, bunkering and combustion, whereas the TTP emission factors include emissions emitted during the combustion in marine engines for ship propulsion (Brynolf et al., 2014). The emission factors are expressed in grams per MJ LNG, and since the data on the fuel consumption of LNG is expressed in tonnes, some conversions were required to estimate the emissions. First, the fuel consumption of LNG is converted from tonnes to MJ by multiplying the energy content of marine LNG with tonnes of LNG. The value for the energy content is based on Gilbert et al. (2018) and is expressed as MJ per kg fuel. Second, by multiplying the emission factors by the fuel energy content, the emissions of CO_2 and CH_4 are estimated. Third, to express the CH_4 emissions as CO_2-equivalents, the estimated emissions of CH_4 are multiplied with a GWP-value based on Myhre et al. (2013).[21] The results for domestic and international traffic are presented in Table 15 and Table 16, respectively. For comparison, the tables also include CO_2 emissions from LNG based on the BAU estimations in section 7.2 and 7.3, for which emission factors from Carlsson et al. (2019) are used.

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[21] The following values have been used in the estimations: The TTP emission factors are: 54 CO_2 g/MJ fuel and 0.71 CH_4 g/MJ fuel. The WTP emission factors are: 62.3 CO_2 g/MJ fuel and 0.743 CH_4 g/MJ fuel. The value for the energy content of marine LNG is 48.6 MJ/kg fuel. The GWP-value for CH_4 is 34.

For domestic traffic, GHG emissions are only calculated for scenario (4), since it is the only domestic scenario in which the use of LNG is included. As shown in Table 15, the GHG emissions (in 1000 tonnes CO_2-equivalents) are higher when emissions of CH_4 are included. More specifically, when the methane slip is excluded from the estimation, LNG combustion is estimated to contribute 41 (71) thousand tonnes CO_2 emissions in 2030 (2045). When the methane slip is included in the estimation, the use of LNG from a TTP perspective is instead estimated to contribute 56 (99) thousand tonnes CO_2-equivalents in 2030 (2045). From a WTP perspective, the use of LNG is estimated to contribute 63 (111) thousand tonnes CO_2-equivalents in 2030 (2045). Hence, when taking the lifecycle perspective into account (WTP), the estimation indicates about 54% higher GHG emissions in 2030 and about 56% higher GHG emissions in 2045.

To put this in perspective, this means that the total domestic emissions of CO_2-equivalents in 2045 in scenario (4) amount to 276 thousand tonnes using the WTP estimate, or 264 thousand tonnes using the TTP estimate. This can be compared to the 236 thousand tonnes CO_2 emissions when using the TTP estimate without CH_4. Consequently, when taking the methane slip into account, the total GHG emissions in 2045 are expected to be about 17% higher when using the WTP perspective and about 12% higher when using the TTP perspective.

Table 15. Estimated emissions (in 1000 tonnes) from domestic usage of LNG in scenario 4 (sensitivity analysis with changed fuel mix) in 2030 and 2045.

Emission type	2030	2045
CO_2 emissions (TTP)	41	71
TTP (CO_2-equivalents)	56	99
WTP (CO_2-equivalents)	63	111

Source: Own calculations based on Windmark (2019), DNV GL (2018), Brynolf et al. (2014), Gilbert et al. (2018), Myhre et al., (2013) and Carlsson et al. (2019).

For international traffic, GHG emissions are calculated for all four scenarios since they all include the use of LNG. As shown in Table 16, the GHG emissions (in 1000 tonnes CO_2-equivalents) are higher when emissions of CH_4 are included. In all scenarios, the GHG emissions are estimated to be between 54-55% higher in 2030 and 2045 when taking the lifecycle perspective into account (WTP).

The total international emissions of CO_2-equivalents in 2045 in scenario (1) would amount to 4070 thousand tonnes using the WTP estimate, or 4033 thousand tonnes using the TTP estimate. This can be compared to the 3949 thousand tonnes CO_2 emissions when using the TTP estimate without CH_4. Hence, when taking the methane slip into account, the total GHG emissions are about 3% higher when using the WTP perspective and about 2% higher when using the TTP perspective in scenario (1).

In scenario (4) in 2045, the total international emissions of CO_2-equivalents would amount to 2329 thousand tonnes using the WTP estimate, or 2228 thousand tonnes using the TTP estimate. This can be compared to the 1997 thousand tonnes of CO_2 emissions when using the TTP estimate without CH_4. Hence, when taking the methane slip into account, the total GHG emissions are about 17% higher when using the WTP perspective and about 12% higher when using the TTP perspective.

To put the estimated emissions from LNG into perspective, Figure 47 combines the estimations in Table 16 with the estimations in Table 14, along with the Swedish GHG targets and the IMO's GHG target. The three black lines in the figure represent the estimated BAU emissions in scenario (1); the solid line shows the TTP CO_2 emissions, the dashed line shows the TTP CO_2-equivalent emissions, and the dotted line shows the WTP CO_2-equivalent emissions. The three grey lines in the figure represent the estimated BAU emissions in scenario (4); the solid line shows the TTP CO_2 emissions, the dashed line shows the TTP CO_2-equivalent emissions, and the dotted line shows the WTP CO_2-equivalent emissions. The dotted red line represents IMO's target of reducing GHG emissions from international maritime transport by 50% by 2050, compared to the levels in 2008 (IMO, 2018). The green dotted line represents the Swedish targets of reducing GHG emissions from domestic transport by 70% by 2030 compared to 2010 levels and the target of zero net GHG emissions by 2045. However, due to data unavailability, 2015 is used as the base year for both the Swedish target and the IMO's target. It should be noted that international traffic is not covered within the Swedish GHG targets. A discussion of the results is provided in section 8.

Table 16. Estimated emissions (in 1000 tonnes) from the use of LNG in international traffic in 2030 and 2045.

Scenario	Emission type	2030	2045
1. Base scenario	CO_2 emissions (TTP)	188	221
	TTP (CO_2-equivalents)	260	305
	WTP (CO_2-equivalents)	291	342
2. Scenario with higher energy efficiency improvement	CO_2 emissions (TTP)	178	198
	TTP (CO_2-equivalents)	246	274
	WTP (CO_2-equivalents)	276	307
3. Scenario with lower transport demand	CO_2 emissions (TTP)	160	173
	TTP (CO_2-equivalents)	222	239
	WTP (CO_2-equivalents)	248	267
4. Scenario with lower transport demand and fuel switch	CO_2 emissions (TTP)	299	605
	TTP (CO_2-equivalents)	412	836
	WTP (CO_2-equivalents)	462	937

Source: Own calculations based on Windmark (2019), DNV GL (2018), Brynolf et al. (2014), Gilbert et al. (2018), Myhre et al., (2013), and Carlsson et al. (2019).

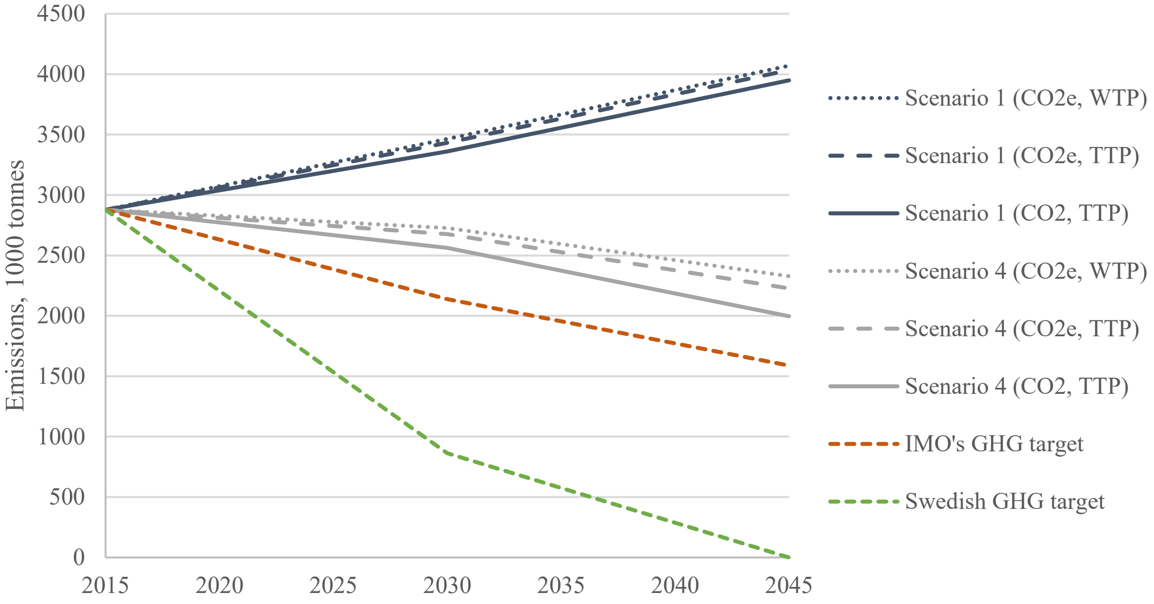

Figure 47. Estimation of international emissions of CO_2 and CO_2-equivalents for scenario 1 and 4 (TTP and WTP perspective), together with the Swedish GHG targets and IMO's GHG target. Source: Own calculations based on Windmark (2019), DNV GL (2018), Brynolf et al. (2014), Gilbert et al. (2018), Myhre et al., (2013), and Carlsson et al. (2019).

8. Discussion

This section presents a discussion of the results from the report, divided into the different purposes of the report.

Overview of vessel fleet

One purpose of this report has been to provide an overview of Swedish maritime transport and to identify characteristics of the Swedish shipping fleet. The findings from the AIS data suggest that the freight ship types are more common than passenger ship types, counted in terms of number of ships. Furthermore, even though RoPax ships are not the most common ship type, they account for the majority of the total domestic and international fuel consumption. This can likely be explained by the fact that it is one of the ship types with the highest fuel consumption per kilometre, in combination with being the ship type that calls at Swedish ports most often, which has been found in a report by Vierth and Johansson (2020). The results further suggest that ships in transit traffic generally have higher average fuel consumption per kilometre than ships in domestic and international traffic. Since there is a correlation between high engine capacity and high fuel consumption per kilometres, this result could potentially be explained by transit ships, on average, having higher engine capacity and/or being larger (in terms of GT) than ships in domestic and international traffic. Regarding ships' average age, ships in domestic and international traffic are, on average, slightly older than ships in transit traffic and ships with higher engine capacity are, on average, newer than ships with smaller engine capacity. Passenger-carrying vessels are found to be older than freight-carrying vessels.

These findings are different from the official statistics, since they show characteristics of ship types in the geographical area surrounding Sweden (that is, in the Shipair model area, covering the Baltic sea, Kattegat and Skagerrak), rather than just the ship types that are registered under the Swedish flag. When designing policy instruments, it is useful to understand which ship types are most common and how often they visit the area.

Estimated emissions from maritime transport in 2015

The second purpose of the report was to estimate emissions from maritime transport in 2015 by using AIS data and to compare the results with the official statistics. For domestic maritime transport, the results suggest that the emissions of CO_2, SO_2, PM_{10} and NO_X are at least twice as high as estimated emissions in official statistics based on the previous official estimation method. Compared with the emissions estimated by the new official method, the estimated emissions in this report are about the same for SO_2 and PM_{10}, but slightly lower for CO_2 and slightly higher for NO_X. Since both methods are based on AIS data and include the same ship types, journeys and geographical areas, the two estimations should be of approximately the same magnitude. The main difference between the methods are the emission factors applied in the estimations. Hence, the difference in the estimated emissions from NO_X can be explained by the use of disaggregated emission factors by ship size in the estimation method applied in this report, while aggregated emission factors for all ship sizes have been used in the official statistics (see appendix).

For international and transit traffic, the estimated emissions of CO_2, SO_2, PM_{10} and NO_X are substantially higher than the emissions from domestic maritime transport, both according to the official statistics and the estimation method used in this report. However, the estimated emissions from international traffic in this report are not possible to directly compare with the official statistics, due to differences in the types of journeys and geographical areas included in the estimation methods. The data for international and transit traffic include only the fuel consumption in the Shipair model area, whereas the international traffic in the official statistics includes the fuel consumption from journeys to international destinations which can be situated outside of this area. Furthermore, the data used in this report for international traffic include journeys departing from or arriving in Sweden, whereas the official statistics only include journeys departing from Sweden.

Of the estimated emissions of CO_2, PM_{10} and NO_X, transit traffic has the highest emissions, followed by emissions from 'international bunkers' (which are based on previous and current official statistics). International traffic (estimated in this report based on AIS data) has the lowest estimated emissions among these categories of international traffic types. The international traffic types contributing to SO_2 emissions are relatively different compared to the other emissions. Even though the fuel consumption from transit traffic is higher than the fuel consumption from 'international bunkers', the SO_2 emissions from 'international bunkers' are substantially higher than the emissions from transit traffic, both according to the current and previous method. There are a number of potential explanations for this. First, in the estimation method in this report, a relatively high share of newer fuel types with lower sulphur content is assumed (41% of the total fuel consumption is assumed to be ULSFO). In the official statistics, the same distinction between high and low sulphur fuels is not included. Instead, the fuel consumption of petroleum products is sorted into three types: diesel, eo1 and eo2-6 (Swedish EPA, 2017). However, even though a distinction is made between high and low sulphur HFO, the emission factors do not take the use of ULSFO or scrubbers into account. The estimated emissions of SO_2 from international and transit traffic are, therefore, likely overestimated, and the difference between the estimated emissions in this report and the emissions from 'international bunkers' is likely even larger. Second, the high level of SO_2 emissions from 'international bunkers' may also be explained by the fact that it includes ship journeys to non-Swedish destinations outside of SECA, where the use of high-sulphur fuels and/or more limited use of scrubbers may have been the case in 2015.

The main advantages of the estimation method used in this report compared to the method used in the official statistics are that 1) it comprises all sea transport in the Shipair area and allows a classification of the traffic types domestic, international and transit. More specifically, the newly updated official statistics only estimate emissions from international ship journeys departing from Sweden, whereas the AIS data used in this report include journeys both departing from and arriving in Sweden. 2) The official statistics include international journeys to all non-Swedish destinations, whereas the data used in this report cover a specific geographical area surrounding Sweden, which provides more information about where the emissions are emitted. Furthermore, transit traffic is currently not included in the official statistics, and since emissions from all traffic surrounding Sweden may affect the Swedish environmental quality objectives, it is important to consider the effects from that traffic type. 3) The dataset makes it possible to separate emissions emitted at sea and at berth. Information about the amount/share of the emissions at berth can facilitate the analysis of the potential that policy instruments can have on emissions reduction.

There are also some aspects of this report's estimation method that could be improved: 1) Even though the fuel mix is based on the currently most detailed estimate of fuel types used for Swedish maritime transport (by SSPA, 2018), the estimate could be improved by being based on the amount of sold fuel or if it was estimated within the Shipair model. Currently, the official statistics of sold fuel only include three categories of fuel types and there is no information about the fuel mix used for different ship types or traffic types. Hence, the official statistics are currently less suitable to use when estimating emissions. 2) The estimation of emissions could be improved if the AIS data would have an even higher level of detail and, for example, include more operational modes of ships, such as manoeuvring. 3) Forecasts of passenger transport would be useful when estimating future emissions from passenger ships (since in this report, it was simply assumed to follow the historical trend). 4) Emission factors that take the use of scrubbers into account would be useful since all HSFO use should be complemented with scrubbers in the SECA since 2015 and globally since 2020 due to the introduction of the Global Sulphur Cap.

An important difference between the two estimation methods is the emission factors. In this report, the most recently developed emission factors are used, which are updated to include aspects such as recently implemented/decided policies (such as SECA and NECA), several different fuel types, and technology improvements of engines (Carlsson et al., 2019). Since this study uses different emission factors compared to the official estimation method, sensitivity analyses with other emission factors are presented in the appendix. The sensitivity analyses with alternative emission factors show that the estimated emissions of CO_2 are similar to the base scenario, whereas the estimated emissions of SO_2, PM_{10} and NO_X are more varying. However, the variation can be explained by the fact that the alternative emission factors do not take the effects of SECA or NECA into account. Based on the results of the sensitivity analyses, the emission factors used in the base-cases in this report are found to be the most suitable and accurate to use for the purposes of this report.

BAU scenarios of emissions from maritime transport and effects on the Swedish environmental quality objectives

The most central purposes of this report were to provide BAU scenarios for the future development of emissions from maritime transport and to examine how the estimated future emissions would contribute to the achievement of the four Swedish environmental quality objectives of relevance.

The specified targets of the four environmental quality objectives are set in different ways and it is therefore not possible to assess the effects of the estimated emissions on the environmental quality objectives in the same way. To follow up on the GHG targets within the objective *Reduced climate impact* is relatively straightforward since the targets are set as reductions in percentages over certain time periods. The objectives of *Clean air, Natural acidification only* and *Zero eutrophication*, which are related to the emissions of SO_2, PM_{10} and NO_X, are either specified in a more general way or have targets of the maximum concentration (micrograms per cubic metre) of air pollutants in the air. A quantitative follow up of these objectives is therefore not possible within the scope of this report, which is why these are evaluated by using a more general discussion.

Regarding the objective of *Reduced climate impact*, the estimated BAU scenarios until 2045 indicate increased CO_2 emissions in the highest scenario (1) and decreased CO_2 emissions in the lowest scenario (4), both for domestic and international traffic. However, the estimated BAU scenarios only include CO_2 emissions and no other greenhouse gases that the combustion of marine fuels can contribute to. More specifically, by utilising LNG, there can be a significant leakage of methane, referred to as methane slip, which has a global warming potential that is 34 times higher than that for CO_2 over a 100-year perspective (Myhre et al., 2013).

For domestic traffic, the effect of the methane slip is only relevant in the lowest scenario (4), since it is the only scenario in which the use of LNG is included. When the methane slip from LNG is included, the total domestic emissions of CO_2-equivalents in 2045 are about 12% higher when using a TTP perspective, compared to not including the methane slip. For international traffic, the effect of the methane slip is relevant for all four scenarios, since they all include the use of LNG.[22] In the highest scenario (1), the total domestic emissions of CO_2-equivalents in 2045 are about 2% higher when using a TTP perspective. The corresponding value for the lowest scenario (4) is about 12% higher emissions compared to not including the methane slip.

Even when the methane slip is not considered, neither domestic nor international traffic can be expected to reach the GHG targets – see Figure 45 and Figure 47 for domestic and international traffic, respectively. More specifically, in the lowest BAU scenario (1), CO_2 emissions from domestic traffic are expected to decrease by 19% by 2030 and by 45% by 2045. When including the effects of the methane slip, the total GHG emissions would instead decrease by 15% by 2030 and 39% by 2045 (using the TTP perspective). When comparing these potential reductions to the Swedish GHG targets of reducing emissions by 70% by 2030 (compared to 2010 levels) and achieving zero net emissions by

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[22] This is based on an estimated fuel mix according to a study by SSPA (2018), in which international traffic uses LNG but domestic traffic does not.

2045, it is clear that these targets will not be achieved by continuing with business as usual.[23] For international traffic, CO_2 emissions are expected to decrease by 11% by 2030 and by 31% by 2045 in the lowest BAU scenario. When including the effects of the methane slip, the total GHG emissions would instead decrease by 7% by 2030 and 23% by 2045 (using the TTP perspective). Comparing these emissions reductions with the international IMO target of reducing emissions by 50% by 2050 (compared to 2008 levels) or by the Swedish GHG targets (even though the emissions are not covered by those targets), it is clear these will not be achieved by continuing with business as usual.

Regarding the objectives of *Clean air, Natural acidification only* and *Zero eutrophication*, Swedish EPA (2019a) has previously estimated that these objectives will not be possible to achieve by 2020 (which is the “target year” used in their analysis). Swedish EPA (2019a) made this evaluation before the official statistics were updated. Hence, considering the fact that the new estimated emissions of SO_2, PM_{10} and NO_X are at least twice as high as the previous estimations, achieving the objectives can be expected to be even further away. Furthermore, the estimations of international and transit traffic in this report show that these traffic types contribute considerably higher levels of emissions than domestic traffic. As illustrated in section 4, international maritime transport contributes higher shares of the total emissions compared to domestic maritime transport. Furthermore, the shares from international maritime transport have been increasing over time (over the period 1990-2018), especially for emissions of SO_2 and NO_X (for SO_2, the share has increased from about 24% in 1990 to about 81% of the total domestic SO_2 emissions in 2018 and the share of NO_X emissions has increased from about 14% in 1990 to about 55% in 2018). The increasing and relatively high shares of emissions from international maritime transport demonstrates that it is important to also consider those emissions when examining Swedish targets. Even though emissions from international and transit traffic are mainly emitted outside of Sweden, air pollutants can be transported by winds and also affect Swedish environmental objectives.

An advantage of examining emissions from the fuel consumed in the Shipair model area is that it facilitates the analyses of the effects of the estimated emissions, at least for the emissions that mainly have local or regional effects (SO_2, PM_{10} and NO_X). In contrast, emissions from fuel consumed in non-Swedish destinations at sea outside of the model area is less likely to have an impact on the Swedish environmental quality objectives of interest in this report, except for emissions of CO_2 which have global effects. The fact that SO_2 emissions from transit and international traffic (in the model area surrounding Sweden) are estimated to be much lower than according to official statistics (which includes emissions to all non-Swedish destinations) is hence positive for the environmental quality objectives. It indicates that maritime traffic surrounding Sweden emits less SO_2 emissions than marine traffic travelling outside of the model area used in this report, which likely could be explained by SECA.

Future emissions from transit traffic are not estimated in this report since there are no forecasts of the future traffic in the model area. However, as the estimated emissions in 2015 from transit traffic are substantially higher compared to emissions from domestic and international traffic (except for SO_2), the transit traffic is important to consider when evaluating the Swedish environmental quality objectives. Here we see a need for further research.

In the scenarios with fuel switch (4), the fuel types of electricity and carbon-neutral fuels are assumed to have zero emissions. However, although carbon-neutral fuels should not contribute to CO_2 emissions, they may still contribute to emissions of SO_2, PM_{10} and NO_X. Therefore, even though the estimated emissions in this scenario can be expected to be underestimated, it is still relevant to include it in the report, since it shows the difficulties in reaching the targets. Even if there would be low future

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[23] The 2030-target covers emissions at the TTP-perspective, whereas the 2045-target covers emissions at the WTP-perspective. Both targets cover all GHG emissions and are defined as reductions of emissions of CO_2-equivalents.

transport demand, high energy efficiency improvements and a changed fuel mix towards less polluting fuels (with underestimated emissions due to unavailability of emissions factors), polluting emissions would still be high and the target of reduced CO_2 emissions would not be reached.

Both in domestic and international traffic, all four scenarios indicate decreasing emissions of NO_X until 2030 and 2045 and the development over time is hence different from the trends of other emissions. The reduction of NO_X emissions is based on assumptions made in Carlsson et al. (2019) regarding the introduction of NECA, which explains the different trend for NO_X emissions compared to other emissions. In Carlsson et al. (2019), it is assumed that vessels have an average life length of 25 years and with the replacement of ships over time, this will increase the share of vessels complying with Tier III levels. More specifically, this is assumed to result in 20% of all vessels complying with Tier III in 2025 and 76% of all vessels complying with Tier III in 2040. In 2046, it is assumed that all vessels will comply with Tier III (Carlsson et al., 2019). However, the identification of vessel types in this report shows that some ship types have higher average age than 25 years. This could indicate that the replacement of ships over time can be slower than 25 years for some ship types, and the reduction of NO_X would in turn be slower than according to the estimated BAU scenarios. Furthermore, since ships complying with Tier III standards can be expected to be more expensive than other ships, there may be a tendency for shipowners to postpone investments in new ships and instead continue using ships a longer time. One recommendation is, therefore, to examine whether NECA would benefit from being complemented with additional policy instruments or measures that incentivise shipowners to replace ships.

Freight transport demand is forecasted to increase at a higher rate than the historical long-term trend (Swedish Transport Administration, 2018a). The forecast is based on a survey of commodity flows made in 2004/2005, in combination with statistics on industry development and foreign trade. However, exactly which assumptions this forecast are based upon is not clear from the report by the Swedish Transport Administration (2018a). The level of detail in the forecast would hence benefit from being improved. Furthermore, when comparing the actual tonne-kilometres with the forecasted tonne-kilometres in Figure 40 (in section 6.1), it indicates that the actual tonne-kilometres over the period 2012-2016 has increased at a slower rate than the higher forecast (of 1.9% increase for domestic and 2.2% increase for international transport). Hence, if future transport demand is lower than forecasted, it will likely result in lower emissions, which scenario (3) and (4) indicate.

As described in the appendix, there are global forecasts that indicate a reducing growth rate of demand for maritime transport over time. Therefore, sensitivity analyses based on global forecasts with reducing growth rates over time are estimated for emissions of CO_2 for domestic and international maritime transport (using a forecast of first increasing, then decreasing growth rates over time, in combination with the assumptions of high energy efficiency improvements and no fuel switch). For domestic traffic, the analysis indicates that the CO_2 emissions in 2045 would be lower than the emissions in scenario (2), but higher than the emissions in scenario (3). For international traffic, the analysis indicates that CO_2 emissions would be lower than scenario (3), but higher than in scenario (4). Hence, the results suggest that reducing sea transport demand over time contributes to the reduction of emissions of CO_2, but also that a fuel switch towards carbon-neutral fuels would have a higher effect.

Despite the introduction of SECA in 2015, the SO_2 emissions are indicated to increase in scenario (1) and (2) for domestic maritime transport and in scenarios (1), (2) and (3) for international maritime transport. This can mainly be explained by the increase in transport demand, in combination with the assumption of no fuel switch and the fact that the emission factors do not take the use of scrubbers into account, in these scenarios. The assumption about no changed fuel mix over time, based on a forecast by the Swedish Energy Agency (2019) is, however, relatively unlikely. For example, SECA will likely have an effect on the fuel types used (SSPA, 2018) and the Global Sulphur cap 2020 will likely affect the fuel types used in international traffic. Furthermore, there are currently (February 2020) ships in domestic traffic using LNG for propulsion (Svensson, 2019), hence illustrating that the fuel mix has already changed compared to the fuel mix in 2015. Scenario (4) with fuel switch is therefore likely a better estimate of the SO_2 emissions.

The updated official estimation method, which partly is based on AIS data, has improved the quality of the official statistics of emissions from maritime transport. To improve the quality even further, the following aspects should be considered: 1) Since there are fuel types that are currently used (in 2020) within the maritime transport sector, but that are not included in the official statistics, the level of detail regarding which fuel types that are used could be improved. 2) The method for developing emission factors could be described in more detail. Furthermore, emissions factors for other fuel types should be developed, for example for LNG with a lifecycle perspective and for HSFO in combination with scrubbers. 3) For the estimations of NO_X emissions, the official statistics do not include information about ships' compliance with Tier III standards. Instead, the fuel consumption of different fuels is multiplied with average emission factors for NO_X for different fuel types. The effects from ships complying (or not complying) with Tier III standards will hence not be visible in the statistics. One recommendation is therefore that it should be examined if the official method could include such information in the estimations. 4) The official statistics of emissions from international maritime transport, 'international bunkers', are still based on the previous official method and do not include information based on AIS data. Ships tend to bunker more fuels in Sweden some years and bunker more fuels outside of Sweden in other years, which mainly depends on the price of fuels in Sweden relative to the price of fuels at the ships' next destination. Hence, since ship movements are not accounted for, the emissions can fluctuate between years even if the number of vessels and the travelled distances would be the same.

9. Conclusions

The main purposes of this report have been to provide an overview of the current situation of maritime transport in Sweden and to provide BAU scenarios for the future development of emissions from maritime transport. Due to uncertainties related to the official statistics, this was done by using an alternative method for estimating emissions which is based on AIS data in 2015. The report has also focused on examining how the estimated emissions from maritime transport contribute to the achievement of the Swedish environmental quality objectives.

For domestic maritime transport, the results suggest that the emissions of CO_2, SO_2, PM_{10} and NO_X in 2015 are at least twice as high as emissions in official statistics based on the previous official estimation method. Compared with the emissions estimated by the new official method, the estimated emissions in this report are about the same for SO_2 and PM_{10}, but slightly lower for CO_2 and slightly higher for NO_X. For international and transit traffic, the estimated emissions of CO_2, SO_2, PM_{10} and NO_X in 2015 are substantially higher than the emissions from domestic maritime transport, both according to the official statistics and the estimation method used in this report.

Based on the estimated BAU scenarios until 2045, the targets related to the Swedish environmental quality objective of *Reduced climate impact* are indicated not to be achieved by continuing with business as usual. In the most optimistic scenario, emissions of CO_2 from domestic maritime transport are expected to decrease by 19% by 2030 and by 45% by 2045. When including the additional methane emissions associated with the use of LNG, the total GHG emissions would instead decrease by 15% by 2030 and 39% by 2045. Hence, comparing these estimated reductions to the Swedish GHG targets of reducing emissions by 70% by 2030 (compared to 2010 levels) and achieving zero net emissions by 2045, it is indicated that these targets will be far from being reached.

Regarding the Swedish environmental quality objectives of *Clean air, Natural acidification only* and *Zero eutrophication*, the estimated emissions of SO_2, PM_{10} and NO_X are at least twice as high as previous estimations in official statistics. Hence, achieving the objectives can be expected to be even further away. Moreover, the findings in this report suggest that international and transit traffic contribute considerably higher levels of emissions than domestic traffic. International maritime transport is also found to contribute a substantial share of the total domestic emissions of SO_2, PM_{10} and NO_X. As the estimations cover a geographical area surrounding Sweden, these emissions can be expected to affect the Swedish environmental quality objectives through the transport of emissions by winds. This finding demonstrates that it is important to consider emissions from international and transit traffic when examining Swedish environmental quality objectives. Hence making international cooperation and agreements important avenues for reducing emissions.

To reach the targets set within the Swedish environmental quality objectives, more and/or stronger policy instruments and measures should be considered. The findings in this report suggest that a fuel switch towards alternative fuel types has the highest effect on the reduction of emissions, but reducing transport demand and improving energy efficiency are also indicated to have important effects. LNG is often highlighted as an alternative fuel that can contribute to the achievement of environmental objectives. Even though the use of LNG contributes to the reduction of air pollutants, the findings in this report indicate that total GHG emissions can be expected to increase when also considering the associated methane emissions. Since ships have an average lifetime of about 25 years, the ships that are ordered and invested in today (in 2020) will likely still be in the ship fleet when the Swedish target of zero net GHG emissions in 2045 should be reached. As the 2045-target includes emissions from a lifecycle perspective, it is important to consider all emissions along the process of extraction, transport, bunkering and combustion of LNG. In future research, it could therefore be relevant to further examine the use of LNG from a lifecycle perspective and to include emission factors that take the lifecycle perspective into account in official statistics.

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Appendix with sensitivity analyses

The appendix provides sensitivity analyses of the estimated emissions in this report, using an alternative forecast of future transport demand and alternative emission factors.

Future transport demand

In the BAU scenarios estimated in this report, the future transport demand is based on the most recent forecast by the Swedish Transport Administration (2018a). As described in section 6, there are one high and one low forecast in which the domestic annual average growth rate of maritime freight transport over the period 2012-2040 is estimated to be 1.9% and 0.9% in the high and low scenarios, respectively. The corresponding average annual growth rates for international freight transport are 2.2% and 0.9% in the high and low scenarios, respectively. However, as there are other forecasts of the future growth of maritime transport, this section provides a sensitivity analysis with a reducing transport demand over time.

Global maritime trade increased by 2.7% in 2018, which can be compared with the previously higher growth of 4.1% in 2017 and the historical average of 3.0% annual average growth over the period 1970-2017 (UNCTAD, 2019). The slowdown can mainly be explained by trade tensions and country-specific developments, such as recessions in some countries and the decision by the United Kingdom to leave the EU. UNCTAD (2019) estimates that international maritime trade will increase, on average, by 3.4% annually over the period 2019-2024. The forecast is based on the income elasticity of maritime trade over the period 2006-2018 and the GDP forecast of the International Monetary Fund for the period 2019-2024. There are, however, several uncertainties related to the future expected development of maritime transport. For example, trade patterns may change due to trade tensions, especially between China and the United States, and the transition towards low-sulphur fuels and low-carbon shipping and uncertain developments in different market segments may also influence the future growth of maritime transport.

The estimated growth rate by UNCTAD (2019) is hence higher than what is assumed in this report. The difference can likely be explained by the fact that the forecast by UNCTAD (2019) includes global maritime transport, whereas the forecast by the Swedish Transport Administration (2018a) only covers the Swedish domestic (and partly international) maritime transport. To use the higher forecasted growth rate of the global maritime transport in BAU scenarios related to maritime transport in Sweden would, therefore, be misleading. However, the trend of a reduction of maritime transport over time can be included in a sensitivity analysis.

The trend of a reducing growth rate is also identified in a forecast by DNV GL (2019). The forecast covers global maritime transport, measured in tonne-miles, and estimates an annual average growth rate of 2.3% for the period 2018-2030 (see Table 17). After 2030, seaborne trade is forecasted to stabilise at an annual average growth rate of 0.3% until 2050. As the table shows, the predicted growth rate differs between different types of seaborne trade.

Table 17. Historic and predicted average annual percentage growth in tonne-mileage of seaborne trade.

Type of trade	**Average annual percentage growth**		
	2010–2018	**2018–2030**	**2030–2050**
Crude oil	2.3%	1.5%	-2.1%
Oil products	2.4%	2.9%	0.0%
Natural gas	6.1%	7.2%	3.2%
Bulk	4.3%	1.7%	-0.1%
Container	2.4%	3.6%	1.5%
Other cargo	2.4%	2.2%	0.6%
Average	**3.7%**	**2.3%**	**0.3%**

Source: Copied from DNV GL (2019).

A fifth scenario is included as sensitivity analysis for the four BAU scenarios estimated in this report, which is based on the forecasted reduction of annual growth rate over time from Table 17. The following assumptions are made in the sensitivity analysis (for a detailed description of the assumptions, see section 7):

- High energy efficiency improvement based on IMO (2015) forecasts, which is the same assumption as in scenario (2), (3) and (4).
- No fuel switch based on the Swedish Energy Agency (2019) forecast, which is the same assumption as in scenario (1), (2) and (3).
- Passenger transport demand based on the historical trend of passenger-kilometres, which is the same assumption as in scenario (1) and (2).
- Emission factors based on Carlsson et al. (2019), which is the same as in all four scenarios.

Since the fifth scenario is a sensitivity analysis, only CO_2 emissions are estimated for illustrative reasons. Emissions of SO_2, PM_{10} and NO_X are hence not estimated in the sensitivity analysis. Figure 48 illustrates the estimated domestic CO_2 emissions in the sensitivity analysis of a reducing growth rate, represented by the black dashed line, along with the four BAU scenarios estimated in section 7.2. Using the forecast of first increasing, then decreasing growth rates over time, in combination with the assumptions of high energy efficiency improvements and no fuel switch, it is found that CO_2 emissions are reduced more than scenario (1) and (2). However, the BAU scenarios (3) and (4) are found to reduce emissions even more.

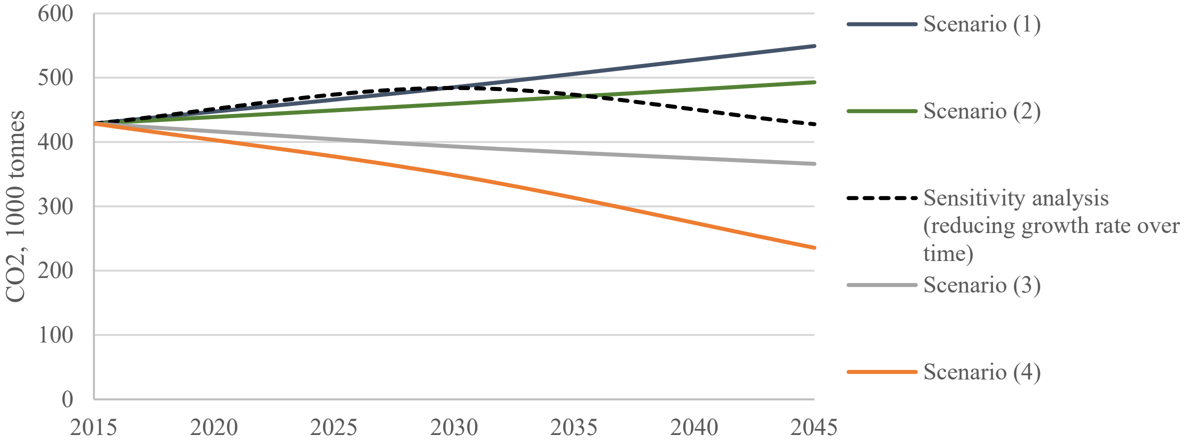

Figure 48. Estimated domestic CO_2 emissions until 2030 and 2045 for the four BAU scenarios and a sensitivity analysis with reducing growth over time. (using the TTP perspective, excluding methane emissions from LNG in scenario 4). Source: own calculations based on DNV GL (2019) and information and data described in section 7.1.

Figure 49 illustrates the estimated international CO_2 emissions in the sensitivity analysis of a reducing growth rate, represented by the black dashed line, along with the four BAU scenarios estimated in section 7.3. Using the forecast of first increasing, then decreasing growth rates over time, in combination with the assumptions of high energy efficiency improvements and no fuel switch, it is found that CO_2 emissions are reduced more than scenario (1), (2) and (3) until 2045. However, the BAU scenario (4) is found to reduce emissions more.

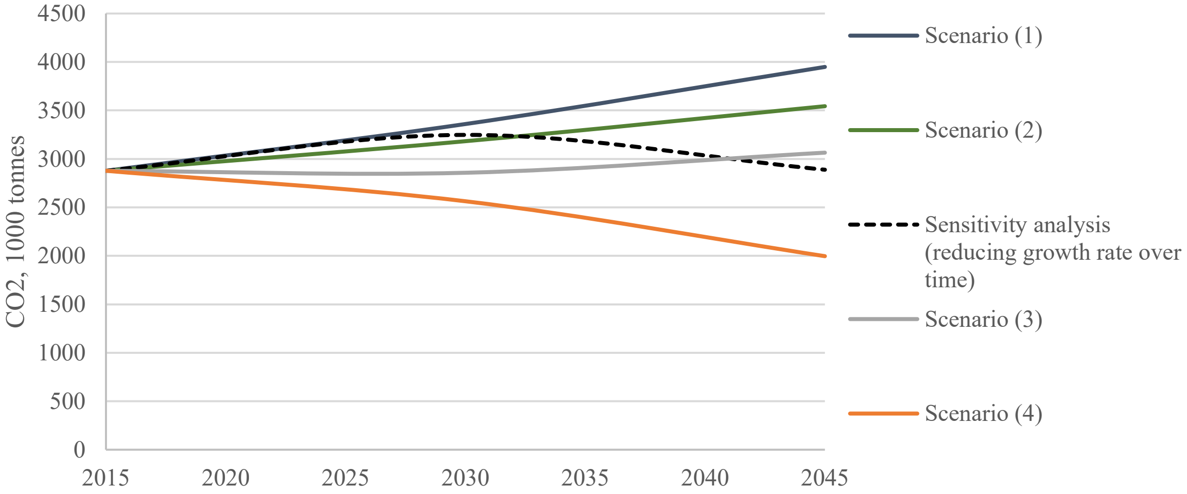

Figure 49. Estimated international CO_2 emissions until 2030 and 2045 for the four BAU scenarios and a sensitivity analysis with reducing growth over time. (using the TTP perspective, excluding methane emissions from LNG). Source: own calculations based on DNV GL (2019) and information and data described in section 7.1.

Emission factors

As mentioned in section 3, the description of which emission factors have been applied in the official method for the estimation of emissions could be improved. The Swedish informative inventory report (IIR) provides information about the methodology, data sources, uncertainties and quality assurance of the estimated air emissions in the Swedish official statistics (Swedish EPA, 2019d). The report is updated every year. The most recent report was published in 2019 and includes information related to the estimated emissions over the period 1990-2017. The updated version of the report, describing the estimated emissions over the period 1990-2018, is expected to be published in April 2020. Hence, when this report was finalised (March 2020), the Swedish IIR for the updated methodology was not yet published.

The information provided in the Swedish IIR (Swedish EPA, 2019d) regarding emission factors for domestic and international maritime transport include the following: Spreadsheets are published on Swedish EPA's website and contain implied emission factors for mobile combustion. The Swedish Maritime Administration provided the emissions factors for NO_X and SO_2 for the period 2005-2015. As from 2016, this is the responsibility of the Swedish Transport Agency, in accordance with the Swedish climate legislation. The reported emissions of particulate matter include the condensable fraction of particles. Emissions by national navigation in the period 1990-2004 are estimated using emission factors from Cooper and Gustafsson (2004).

There are a number of aspects that would benefit from being improved. First, in the spreadsheets published on Swedish EPA's website, there are no emission factors for LNG. Furthermore, the available data on fuel types in the official statistics do not include any usage of LNG or LBG, despite the fact that there are currently (February 2020) ships in domestic traffic using LNG for propulsion (Svensson, 2019). Furthermore, there are no explanations in the IIR as to what has been assumed in the estimations regarding these aspects. Second, there is no published information about how the emission factors of SO_2, PM_{10} or NO_X have been estimated or what aspects they include. The inclusion of such information in the next publication of the Swedish IIR would improve the understanding of how emissions are estimated.

Sensitivity analyses for the estimated emissions of CO_2, SO_2, PM_{10} and NO_X for domestic maritime transport in 2015, using different sources of emission factors, are presented in Table 18. The emission factors used in the base-case are based on Carlsson et al. (2019) which, for several reasons, is the most suitable choice of emission factors for this study. First, Carlsson et al. (2019) present updated emission factors taking current and future policies, such as SECA and NECA, into consideration. As this report also estimates future emissions, such estimates of future emission factors are useful. Second, the emission factors for NO_X are disaggregated by ship size, which is an advantage since different ship sizes have different emission profiles. Third, emission factors are provided for all fuel types used in this report. Fourth, the emission factors are expressed in g/kg fuel which is an advantage since the data on fuel consumption based on AIS data is expressed in tonnes, hence resulting in fewer required conversions.

For the sensitivity analyses, three sources of emission factors are used. Swedish EPA (2020) provides a spreadsheet with information about the emission factors used in the official statistics. However, as mentioned, the sources and methods for how the emission factors are developed are not described. Hence, information about whether SECA and NECA are taken into consideration is not available. Furthermore, only three fuel types are included (diesel, eo1, eo2-6) in Swedish EPA (2020) and the emission factors for NO_X are not disaggregated by engine capacity. Cooper & Gustafsson (2004) provide the previous emission factors used for the estimation of emissions, but only include two fuel types (residual oil and marine distillates) and NO_X emission factors are not disaggregated by engine capacity. EEA (2019) provides emission factors for maritime transport in Europe and only include two fuel types (MDO/MGO and bunker fuel oil) and NO_X emission factors are not disaggregated by engine capacity.

Hence, there are a number of differences in these estimations compared to the estimations in the base-case (from section 5). First, none of the three alternative sources provides emission factors for LNG. Second, the emission factors are expressed in kg/m^3 in Swedish EPA (2020) and, hence, the emission estimation requires a conversion from tonnes of fuel to m^3 of fuel[24]. Third, the NO_X emission factors are expressed as an aggregated value and, therefore, do not take ship size into account.

The estimated CO_2 emissions from domestic traffic in the sensitivity analyses are about the same as in the base-case. The estimated emissions of SO_2, PM_{10} and NO_X are, however, more varying. The SO_2 emissions are substantially higher when using emission factors based on Cooper & Gustafsson (2004) and EEA (2019), which potentially can be explained by those studies not taking into account the effects of SECA; Cooper & Gustafsson (2004) is a relatively old study which, therefore, does not consider the effects of SECA and EEA (2019) uses average emission factors for all maritime transport in Europe, including ship journeys made outside of the SECA.

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[24] To estimate emissions based on emission factors from Swedish EPA (2020) a conversion factor based on BP (2019) is used to convert the fuel consumption from tonnes to m^3. The conversion factor for crude oil is assumed for MGO, MDO and ULSFO. The conversion factor for residual fuel oil is used for HSFO. The emission factor for eo1 is used for the fuel types of MGO, MDO and ULSFO. The emission factor for eo2-6 is used for the fuel type of HSFO.

Table 18. Sensitivity analysis for estimated emissions of CO_2, SO_2, PM_{10} and NO_X for domestic maritime transport in 2015, using different sources of emission factors.

	Base case	**Sensitivity analyses**		
	Carlsson et al. (2019)	Swedish EPA (2020) [a]	Cooper & Gustafsson (2004) [b]	EEA (2019) [c]
CO_2, 1000 tonnes	429	425	430	
SO_2, tonnes	270	223	1142	2704
PM_{10}, tonnes	290	110	155	445
NO_X, tonnes	9593	6119	12 373	10 655

[a] The NO_X emission factors are not disaggregated by engine capacity. The emission factors for the year 2015 are used. Emission factors for LNG are not available, hence emissions from LNG are excluded in this estimation.

[b] Cooper & Gustafsson (2004) do not include methane emissions from LNG, since there are no emissions factors available in that report and the NO_X emission factors are not disaggregated by engine capacity.

[c] EEA (2019) does not include emission factors for CO_2 and the NO_X emission factors are not disaggregated by engine capacity.

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