Daniel, H., Trovão, J. P. F., Williams, D., & Boulon, L. (2024). Unlocking shore power in St. Lawrence and Great Lakes for cargo ships. Transportation Research Part D: Transport and Environment, 131, Article 104230. https://doi.org/10.1016/j.trd.2024.104230

Transportation Research Part D 131 (2024) 104230

Contents lists available at ScienceDirect

Transportation Research Part D

journal homepage: www.elsevier.com/locate/trd

Unlocking shore power in St. Lawrence and Great Lakes for cargo ships

Hugo Daniel [a,c], João Pedro F. Trovão [a,b,*], David Williams [c], Loïc Boulon [d]

[a] *e-TESC Lab., University of Sherbrooke, Sherbrooke, QC J1K 2R1, Canada*
[b] *Polytechnic Institute of Coimbra, Coimbra Institute of Engineering (IPC-ISEC) and INESC Coimbra, 3030-199, Coimbra, Portugal*
[c] *Fednav Limited, QC H3B 4W5, Canada*
[d] *Hydrogen Research Institute, Université du Québec à Trois-Rivières, QC G9A 5H7, Canada*

ARTICLE INFO

Keywords:
Shore power
Bottom-up method
Shipping emissions
Electrical forecast
Shipping
Bulk carriers
Environmental policies

ABSTRACT

This study investigates for the first time the emissions that a future shore power policy can eliminate in the St. Lawrence and Great Lakes region, providing precise evaluations with an improved bottom-up methodology. The review of cargo ship emission estimation methods showed that latest studies use a methodology that is not suited for evaluating real emissions at berth, but rather general emissions of the ships while at sea. Therefore, an improved method is proposed to determine the emissions specifically at berth with a modified bottom-up analysis that considers further geographical data, operating modes, berth-specific data, the new exclusion-area technique, and new cargo ship types. Also, the results of the proposed method applied in the St. Lawrence and Great Lakes showed that shore power policies can reduce up to an annual maximum of 227,061 t of carbon dioxide equivalent and 25 million dollars annually in external costs to society and governments.

1. Introduction

The world is undergoing a significant shift towards electrification of its industries to reduce greenhouse gas (GHG) emissions and tackle climate change. Electrification offers an effective means of reducing emissions as it eliminates the use of fossil fuels at the source. Although power plants still generate most of the world's electricity using fossil fuels, they are more efficient than smaller combustion engines used in industries for electricity generation. Moreover, the adoption of clean, renewable, and sustainable technologies in the electricity generation sector is increasing rapidly, as demonstrated by the International Energy Agency (IEA, 2022). These technologies are further reducing the carbon footprint of electricity generation facilities.

The maritime industry is one of the sectors that is looking towards electrification to decrease its GHG emissions. Commercial ships require a large amount of electricity to power equipment, lighting, heating, and even propulsion in the case of all-electric ships. This electricity is typically generated by diesel engines using fossil fuels. Although some advancements have allowed renewables to supply a portion of the electrical load, ships still need a fuel source to generate electricity or propulsion power due to their high-power demands. Nonetheless, ships are typically in port for long periods of time, allowing for the opportunity to connect to shore power and shut down the diesel generators. This process, known as shore power or "cold ironing," "onshore power supply," "ship-to-shore supply," or "alternative marine power," offers a crucial first step towards the decarbonization of the maritime industry by converting ships to shore

---

[*] Corresponding author.
E-mail address: Joao.Trovao@USherbrooke.ca (J.P.F. Trovão).

https://doi.org/10.1016/j.trd.2024.104230
Received 7 November 2023; Received in revised form 30 January 2024; Accepted 30 April 2024

power and promoting large-scale electrification.

Certainly, the first step for shore power global adoption is to determine its pros and cons. The study of Daniel *et al.* (Daniel et al., 2022), which identified shore power as the next step toward the decarbonization of shipping assessed this matter. In the next step, governments and organizations are relying on emission estimation studies to determine the emissions of ships at berth and their energy demand which is the topic of this research. Emission evaluation and energy forecast analysis serve as a critical foundation for shore power policy decision-making. Specifically, these studies aim to quantify the reduction of emissions required to legitimize electrification projects. By doing so, the primary objectives are to reduce emissions, improve air quality, minimize social costs, and mitigate air pollution's impact on society. Moreover, the data derived from these investigations allows for informed decisions regarding the prioritization of berths to electrify first, thus optimizing economic resources.

1.1. Object of the work

In the context of reducing emissions with shore power, governments, shipowners, and ports require improved tools to estimate the emissions of ships at berth in shipping regions or networks to better orientate future environmental policies. The electrical grids in the provinces of Quebec and Ontario in Canada are almost carbon-free. However, only a handful of shore power projects have been completed so far in North America according to the United States Environmental Protection Agency (US EPA, 2022) and the review presented in (Daniel et al., 2022). Also, the St. Lawrence and Great Lakes area is characterized by a unique inland shipping network and a massive economy. Indeed, if the regions around the St. Lawrence and Great Lakes were a country, it would represent the third biggest economy in the world behind the US and China (Campbell et al., 2015). Bulk shipping dominates this mighty shipping network since a significant portion of commodities exchanged in the area is in bulk form (TC et al., 2007). The network is also unique because of the Seaway Lock System which enables oceangoing ships to reach major North American cities of the Great Lakes. However, large oceangoing ships are limited to the St. Lawrence area because of the size of the locks. With access to green electricity, dry and liquid cargo ships of the St. Lawrence and Great Lakes have the potential to significantly reduce their GHG emissions and air pollutants. Finally, methods exist to measure emissions, but they are not precise or adapted to emission and energy estimation of ships at berth, and do not integrate all important cargo ship types. For example, cargo ships have different operating mode at berth i.e., "loading and unloading," "at rest," etc. depending on the equipment available on the shore or other factors but these important aspects are not considered in existing methods. Therefore, the objective of this work is to propose an improved method to estimate the emissions of bulk and general cargo ships at berth and demonstrate for the first time that shore power can reduce the emissions in the St. Lawrence and Great Lakes.

The study aims to address the following questions:

1. Is it possible to estimate the emissions of bulk and general cargo ships at berth precisely?
2. What are the environmental, social, and external benefits of shore power in the St. Lawrence and Great Lakes?

The literature review in the subsequent sections will detail the state of the art on shipping emission estimation methods for bulk carriers and general cargo ships.

1.2. Literature review

When trying to estimate the emissions of oceangoing ships, there are two main approaches: bottom-up and top-down. Bottom-up studies analyze factors such as ship movement, engine types, fuel types, engine load, auxiliary load, and more to estimate emissions from individual ships. Subsequently the data is aggregated and processed to estimate large-scale emissions (Toscano and Murena, 2019). The conversion from the energy consumption to emission is done with emission factors. A top-down approach is characterized by an estimation of the emissions based on a direct measurement of the emissions or from a statistical database (R.A.O. Nunes et al., 2017). However, Bojić *et al.* (Bojić et al., 2022) revealed that top-down approaches can only be reliable for large-scale emission inventories of the shipping industry because the bunker sales data is unreliable on the microscale. Also, the top-down approach using the bunker sales data is subject to precision concerns since it must have access to the load of the main engine (ME) to perform a reliable estimation of many air polluters such as particulate matter (PM), elementary carbon, organic carbon, ash, sulphate, nitrogen oxides (NO_x), and carbon monoxide (CO) (Jalkanen et al., 2012). For these reasons, more accurate emission estimations are achieved with a bottom-up approach or mixed top-down and bottom-up approach.

Based on the latest review on shipping emissions (Bojić et al., 2022), the formulas used in the studies can be simplified as presented in (1.1). Indeed, the literature has shown that the studies calculating the emissions from ships with the bottom-up approach are using similar formulas and methods.

$$E_k = EF_k \times P \times T \tag{1.1}$$

where E is the total mass of the emitted atmospheric emission, k is the emission index, EF is the emission factor for a certain atmospheric emission k, P is the power and T is the time.

Generally, the emission formula aggravates the emissions from different equipment such as the main engine, auxiliary engine (AE), and boilers. Also, the power P can be directly supplied by a single value with the use of power tables or derived from (1.2), where it is estimated with P_{MCR} i.e., the total engine or system power at maximum continuous rating (MCR).

$$P = P_{MCR} \times LF \tag{1.2}$$

where LF is the load factor (LF) of the engine.

While ship emission studies are numerous nowadays, only few major studies served as a foundation for the research to shipping emissions. First, the Swedish Environmental Research Institute (IVL) conducted a detailed study in 2004 on fuel emission factors, providing a framework to determine emission factors for various air pollutants (IVL, 2004). Then, the ENTEC environmental consulting firm performed a series of studies, initiated in 2002, aimed to build an emission inventory of shipping in the UK and made significant contributions (ENTEC, 2002). Finally, the Starcrest Consulting Group was commissioned to determine emissions in the Port of Los Angeles (POLA) and the Port of Long Beach (PLOB), contributing to the development of emission inventories in the area.

Recently, the field of emission inventories has seen significant growth and advancement, with numerous studies and large-scale assessments being carried out globally. The International Maritime Organization (IMO) has played a major role by commissioning four major emission inventories, starting in 2000 with a focus on greenhouse gas emissions. These inventories, released in subsequent years, utilize automatic identification system (AIS) data to track ships' movements and activities, making them comprehensive assessments of emissions in the maritime industry.

AIS data can be a very valuable source of information. However, one part of AIS information is not reliable while the other is:

1. Reliable AIS information: The information about the ship location, speed, heading, type, and IMO number are highly precise because they are automatically processed by computer systems.
2. Unreliable AIS information: The navigational status, type of cargo transported, destination, and ship dimensions are updated by humans which often leads to mistakes. Indeed, in (Harati Mokhtari et al., 2008), 30 % of the ships were reporting a wrong navigational status."

The research on emission estimation has primarily targeted cruise and container ships. Tzannatos made a bottom-up study on the emissions from the cruise and passenger vessels calling at the Port of Piraeus. The study use a database from the port authority to determine the time spent by the ships at berth and one from the Lloyd's Register of Ships for the auxiliary engine power (Tzannatos, 2010). Chen *et al.* used AIS data to perform a bottom-up emission estimation study in the container port of Tianjin. They employed a threshold of 1 knot to determine if the ships were at berth and 10 % of the main engine power to determine the power of the ships at berth (Chen et al., 2016).

While many emission estimation studies include dry cargo ships, they have not been deeply analyzed and this literature review intends to fill the research gap with the other ship types. Table 1 presents the main works found in the literature that considers dry cargo ships. For each work, the table presents the type of ship considered, the auxiliary engine power and power determination method, the load factor used when the ship was at berth, the emission factors study sources, and the boiler power demand.

This review focuses on dry bulk carriers and general cargo ships as they share similar characteristics, such as the commodity they transport, their shape, loading and unloading equipment, etc. The emissions are estimated based on the AE and boiler systems as the main engine is shut while the ships are at berth. This review highlights that there are many different pollutants, emission factors, and ways of calculating emission factors, with the calculation of emission factors being a topic of research in itself. Therefore, this review has limited its focus to source references for widely applied emission factors. Previous studies that ignore the auxiliary systems, dry bulk carriers or general cargo ships, and have limited access to source information have been discarded.

In reviewing the 35 studies, shortcomings were observed in the methodologies employed for estimating emissions for bulk carriers. First, the studies do not segregate the bulk carriers into different types which can lead to estimation errors. Indeed, bulk carriers equipped with deck cranes or conveyors have a very different load profile in port than the ones not equipped with one. Concerning the AE power, most of the studies were using a ship-dependent technique. However, 25 % of the studies are considering a fixed AE power ranging from 172 kW to 2085 kW. Primarily, these studies associate the same emissions to a very large carrier and to a small bulk carrier despite the significant size difference between the two and their differing electrical loads. Secondly, no consensus exists among these studies as there is a factor of 10 difference between the smallest and highest values used. Due to this lack of reliability, these methods cannot be used for the purpose of shore power. Most studies focus on the emissions of the main engine, which is satisfactory for the overall emissions of the ship while sailing, but not sufficient in the specific context of shore power. The remaining studies use methods dependent on the ship type and size, but still need improvement in terms of precision.

Then, there are a few methods used to determine the AE power of the ships as presented in the fourth column. The first one is the estimation of the AE power based on a ME to AE ratio. This method was used in 43 % of the cases with ratios of: 0.191, 0.22, 0.23, 0.269, 0.27, 0.3, 0.38, 0.5 for bulk carriers, and 0.191, 0.23, 0.33, 0.82 for general cargo ships. However, only a small number of works performed the estimation of the ratios and most of them refer to other studies. The source studies generally used an external database to estimate the ratio based on the main engine MCR or ship cargo capacity with the AE power with the ratio. This approach has the advantage of using easily accessible data. The second method uses the installed power of a ship based on the information present in a ship database. However, installed power information is often missing. The third method consists of building a table of power demand based on the ship size and type. This method has the advantage of being well detailed and to cover many different types of ships. Notably, the IMO studies decided to use this method to perform their estimations. These power tables have been built based on data from the VBM program of POLA, and ME to AE power ratios provided by ENTEC studies. Finally, a few studies are also combining different methods in a priority list such as the Starcrest method.

The last parameter investigated considering the AE power is the load factor. Different values were found: 12 %, 20 %, 22 %, 40 %, 50 %, 60 %, 70 % and 75 %. It can be observed that no typical loading factor has emerged from the literature. Apart from (Deniz et al.,

Table 1
Review of bulk carrier's emission calculation methods when at berth.

Study	Bulk carrier type	Auxiliary engines			Emission factor sources	Boiler
		Power	Method	Load factor		
(Deniz et al., 2010)	General cargo	*Ship dependent	Power table based on ship size, (ENTEC, 2005)	75 %	(ENTEC, 2005)	NA
(Ng et al., 2013)	Dry bulk carrier	1670 kW	ME to AE ratio of 0.222 derived from the California Air Resource Board (CARB, 2005)	12 %, (SCG, 2008)	(US EPA, 2009), (SCG, 2009)	101 kW
(Yau et al., 2012)	Dry bulk carrier, general cargo	1080 kW, 930 kW	ME to AE ratio of 0.222 and 0.191 from Word Shipping Encyclopedia	22 %, (US EPA, 2009)	(ENTEC, 2002), (Lloyd's Register, 1995), (US EPA, 2006)	0.0125 tFuel/h
(Saraçoğlu et al., 2013)	General cargo	272 kW	Installed power LR database	40 %	(ENTEC, 2005)	NA
(Berechman and Tseng, 2012)	General cargo	*Ship dependent	Percentage of MCR (Tzannatos, 2010), (Villalba and Gemechu, 2011)	22 %, (Joseph et al., 2009), (SCG, 2008)	(ENTEC, 2005), (Dolphin and Melcer, 2008), (ENTEC, 2007)	NA
(McArthur and Osland, 2013)	Solid bulk, general cargo	*Ship dependent	ME to AE ratio from (Trozzi, 2010)	20 %, (Dalsøren et al., 2009)	(Sandmo, 2016)	NA
(Goldsworthy and Goldsworthy, 2015)	Bulk carrier, general cargo	*Ship dependent	ME to AE ratios 0.222 and 0.191 from (US EPA, 2009)	22 %, (US EPA, 2009)	(IVL, 2004), (ENTEC, 2002), (US EPA, 2009), (Cooper, 2005)	109 kW and 106 kW
(Olmer et al., 2017)	Bulk carrier, general cargo	*Ship dependent	Power table from (Smith et al., 2015)	NA	(Smith et al., 2015)	Electrical power table IMO, 2020 (Faber et al., 2020)
(R. A. O. Nunes et al., 2017)	Bulk carrier, general cargo	*Ship dependent	ME to AE ratios 0.3 and 0.23 from European Environmental Agency (EEA, 2016), and (Trozzi, 2010)	40 %, (ENTEC, 2010)	(ENTEC, 2002), (IVL, 2004), (US EPA, 2009)	132 and 137 kW
(Alver et al., 2018)	General cargo	172 kW (avg 2010–2015)	Average installed power of ships that visited the port	75 %	(ENTEC, 2005), (Saraçoğlu et al., 2013)	NA
(ENTEC, 2010)	Bulk carrier, general cargo	*Ship dependent	Installed power. If not present, ME to AE ratios 0.22 and 0.33 from (ENTEC, 2002)	40 %, ENTEC, 2002 (ENTEC, 2002)	(ENTEC, 2002), (ENTEC, 2005), (IVL, 2004), (Cofala et al., 2007), (Endresen et al., 2003)	NA
(Smith et al., 2015)	Bulk carrier, general cargo	*Ship dependent	Power table built with VBP (SCG, 2012), Finnish Meteorological Institute (FMI), (Buhaug et al., 2009), and estimated with ME to AE ratio and installed power when data not available	60 %-70 %, VBP (SCG, 2012), FMI and (Buhaug et al., 2009)	(Bazari and longva, 2011), (ENTEC, 2002), IMO Standard, (IVL, 2004), (US EPA, 2006), (Sarvi et al., 2008)	Electric power table
(Faber et al., 2020)	Bulk carrier, general cargo	*Ship dependent	Same as (Smith et al., 2015), but improved with VBP 2012–2018 ("ClassNK," 2018), and expertise/professional judgment	(Smith et al., 2015)	(Smith et al., 2015), (Jalkanen et al., 2012), (IVL, 2004), MEPC.308(73) 2018 (IMO, 2018), (Halff et al., 2019), US Office of Transportation Air Quality 2020, (Olmer et al., 2017)	*Idem as method
(IVL, 2004)	Bulk carrier, dry bulk carrier	*Ship dependent	Installed power	50 %	Own estimation, (Lloyd's Register, 1995)	NA
(SCG, 2022)	Bulk carrier, general cargo	*Ship dependent	Priority list: 1) Shore power data, 2) VBP data, VBP of a sister ship, estimation from VBP	NA	US EPA, CARB	*Ship dependent
(Jalkanen et al., 2014)	Bulk cargo	1000 kW	Installed power if 1000 kW is bigger than installed power	NA	(Buhaug et al., 2009), (Agrawal et al., 2008), (Petzold et al., 2008), (Lack et al., 2009), (Sarvi et al., 2008), (Cooper, 2003)	*Included in AE
(US EPA, 2006)	Bulk carrier, general cargo	*Ship dependent	ME to AE ratio: 0.222 (bulk), 0.191 (general) based on data from (CARB, 2005)	22 %, (SCG, 2005)	ENTEC, 2002	0.0125 tFuel/h VBP
(US EPA, 2009)	Bulk carrier, general cargo	*Ship dependent	ME to AE ratio: 0.222 (bulk), 0.191 (general) based on data from (CARB, 2005)	22 %, (SCG, 2005)	ENTEC, 2002	NA
(O. US EPA, 2020)	Bulk carrier, general cargo	*Ship dependent	Survey, electrical table from (Smith et al., 2015)	NA	(ENTEC, 2002), (SCG, 2021), (Buhaug et al., 2009), (Smith et al., 2015), (Kristensen, 2012), (IVL, 2004)	*Ship dependent

(*continued on next page*)

Table 1 (*continued*)

Study	**Bulk carrier type**	**Auxiliary engines**			**Emission factor sources**	**Boiler**
		Power	**Method**	**Load factor**		
(CARB, 2006)	Ocean-going vessels	*Ship dependent	Installed power from Starcrest (SCG, 2022)	Starcrest (SCG, 2022)	CARB, EC, ENTEC, IVL	NA
(Dalsøren et al., 2009)	Bulk carriers, general cargo	*Ship dependent	Installed power. If not present, ME to AE ratio ranging from 0.5 to 0.82	20 %, (Cooper, 2003), (ENTEC, 2002), (Flodstroem, 1997)	(Cooper, 2003), (ENTEC, 2002), (EEA, 2002), (Petzold et al., 2008), (Sinha et al., 2003)	NA
(IMAR, 2022)	Bulk carrier	300 kW	Average power based on a survey	NA	(Olmer et al., 2017)	NA
(Gan et al., 2022)	Cargo ships	*Ship dependent	ME to AE ratio: 0.191 Weng *et al.* (Trozzi, 2010)	0.22, US EPA	(Smith et al., 2015)	NA
(Woo and Im, 2021)	Conventional cargo ship, general cargo ship	1681 kW (conventional), 1776 kW (general)	ME to AE ratio: 0.269 (conventional) and 0.191 (general) from US EPA	0.22, (Nicewicz and Tarpanowicz, 2012)	(Smith et al., 2015), US EPA	NA
(Yoo et al., 2022)	Bulk ship, general cargo ship	*Ship dependent	ME to AE ratio: 0.3 (bulk), 0.23 (general) EEA (EEA, 2002),	40 %, (ENTEC, 2010)	Emission control areas, (ENTEC, 2010)	NA
(V et al., 2021)	Bulk carrier, general cargo	*Ship dependent	Installed power from Scheepvaartwest	22 %, (US EPA, 2009)	(ENTEC, 2010)	NA
(Chen et al., 2021)	Bulk/general cargo ships	272 kW	From Starcrest (SCG, 2019)	NA	(SCG, 2019)	125 kW
(Spengler and Tovar, 2022)	Dry bulk carrier, general cargo	*Ship dependent	From IMO 2012 (Buhaug et al., 2009)	NA	EEA, 2016	NA
(Fuentes García et al., 2021)	Bulk carrier	2085 kW	ME to AE ratio: 0.38 from ENTEC, 2010 (ENTEC, 2010)	20 %, (ENTEC, 2010)	(ENTEC, 2010), EEA, US EPA	NA
(Zis and Cullinane, 2020)	Cargo ship	*Ship dependent	Installed power from LR	NA	(Cooper and Gustafsson, 2004), (US EPA, 2009), (Goldsworthy and Goldsworthy, 2015)	*Ship dependent
(Sun et al., 2018)	Bulk cargo ships	*Ship dependent	ME to AE ratio: 0.27 based on LR database	0.4, (Faber et al., 2020)	Own estimation, CCS, BV, LR, (Faber et al., 2020),US EPA	NA
(Gutierrez-Romero et al., 2019)	Grain bulk carrier	*Ship dependent	Direct ship's size to AE formula based on data from the Port Authority of Cartagena	NA	(Dalsøren et al., 2009)	NA
(Adamo et al., 2014)	Steel and iron products carriers	*Ship dependent	Ship size to AE ratio of 0.2 kW/tons based on external data from (Ericsson and Fazlagic, 2008)	0.4, (US EPA, 2009)	MARPOL 73/78, (ENTEC, 2005)	NA
(Stolz et al., 2021)	Bulk carriers	*Ship dependent	ME to AE ratio derived from (IMO, 2020)	NA	(Smith et al., 2014)	*Ship dependent
(ECCC, 2022a)	Merchant bulk	*Ship dependent	Power table from (Smith et al., 2015)	NA	(Smith et al., 2015)	(Smith et al., 2015)

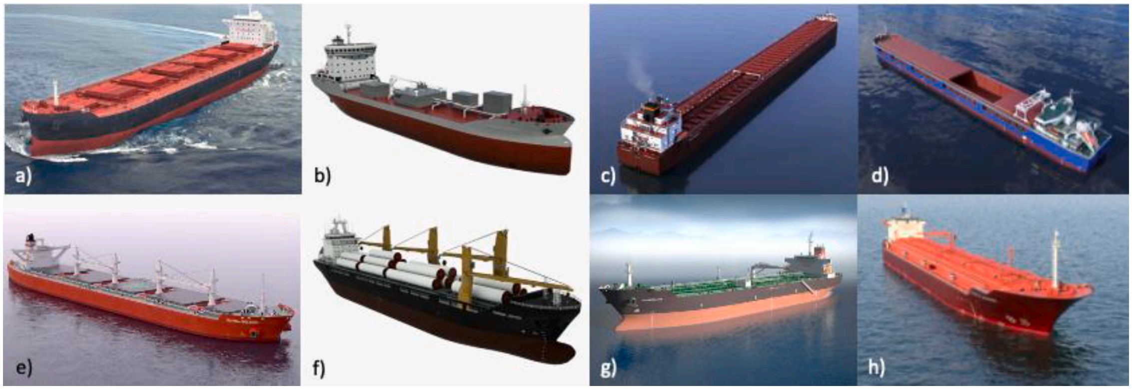

Fig. 1. Ship types a) Gearless bulk carrier, b) Cement carrier, c) Self-unloader, d) Gearless general cargo, e) Geared bulk carrier, f) Geared general cargo, g) Oil tanker, h) Chemical tanker. Pictures from https://www.turbosquid.com.

2010), the studies using a power table did not require a load factor.

Considering the emission factors of the sixth column, the review revealed that despite a very wide range of emission factors, the methods were generally referring to the same studies. The IVL and ENTEC studies were identified as major contributors to the research with all the studies referring or indirectly referring to these studies. Then, some contributions were considered to improve the models.

Finally, 49 % of the studies ignore the emissions coming from the boilers while they can present a good share of the emissions in port. Indeed, in (Chen et al., 2021), the boiler represented about 30 % of the power demand of the ship in port. For the moment, the boilers are generally supplied with fuel in port but when ships will be connected to shore power, the boiler's load could be transferred to the electrical system if the boilers are modified to operate on electricity.

Therefore, it can be concluded from the literature review that the existing method to estimate the emissions of the ships at berth in port can be improved to determine the real emissions that shore power can eliminate. Notably, no work is integrating comprehensive geographical and berth-specific information for bulk carriers and the different types of bulk carriers are not considered while their electrical power demand can vary tremendously. Also, from an electrical provider perspective, the current method lacks the adaptability to provide a reliable electrical demand forecast. This limitation hampers the effective planning of electric demand for ships

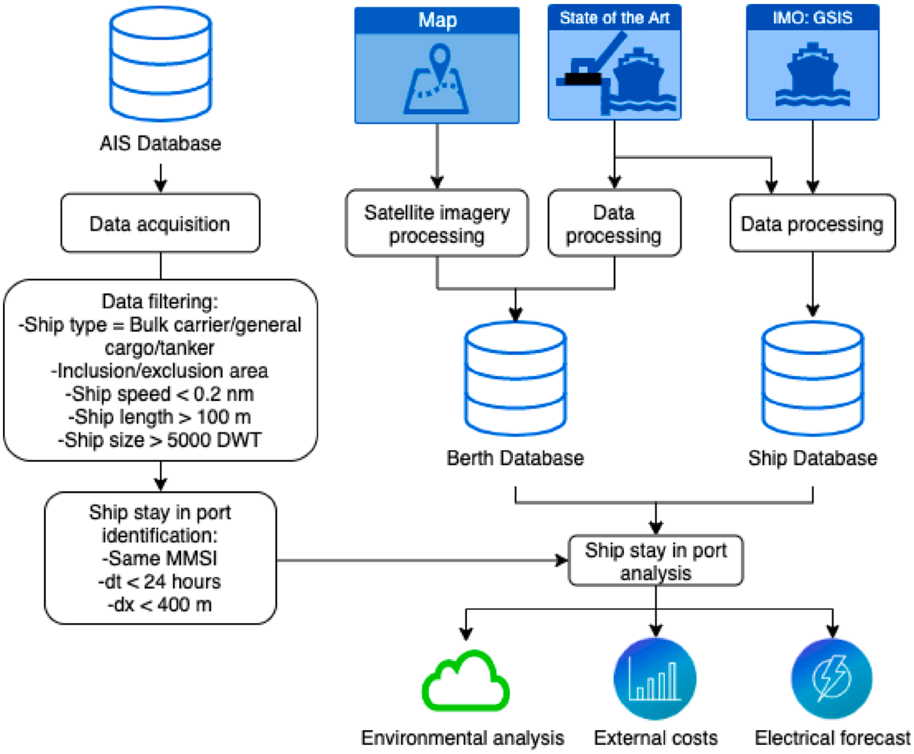

Fig. 2. Flow chart of the automatic identification system acquisition process and processing algorithm.

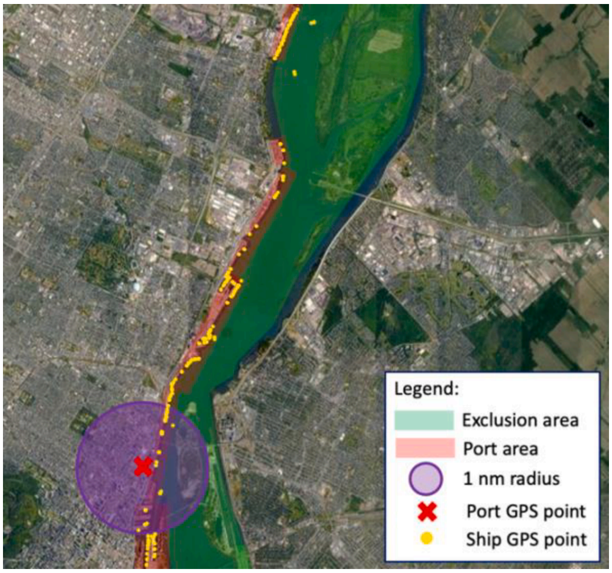

Fig. 3. Exclusion area technique vs. distance-from-point technique.

connected to shore power in the future.

A key factor that also emerged from the review is that the studies always consider the same operating modes for the ships: “cruising at sea,” “manoeuvring in port,” “at anchor,” and “at berth” even if the ships is in “loading” or “unloading” mode. Since the power demand is very different for geared bulk carriers and self-unloaders in loading or unloading mode, these modes should be included in the analysis.

Furthermore, the analysis of the main macroscopic emission inventories, such as IMO (Faber et al., 2020) and ICCT (Olmer et al., 2017), revealed that they are using an ambiguous methodology to determine the operational mode (“maneuvering,” “cruising,” “at berth,” “at anchor”). Indeed, these methodologies use a distance threshold of 1 nm and a speed threshold of 1 knot to determine if the ship is at berth. However, the distance is determined based on a unique port location between the ship and the port. This is a major issue when estimating the real emissions of ships at berth because most ports cover an area that is larger than 1 nm. For large-scale emission inventories, this issue can be neglected as the emissions in port are much smaller than the emissions at sea. In the case of shore power, however, it will result in many erroneous emission estimations. Therefore, a new technique must be introduced to better determine the “at berth” navigational status of the ships. This new technique is proposed in the method section.

1.3. Novelties and goals

The objective of this study is to demonstrate for the first time that an improved bottom-up method can be used to precisely estimate how much shore power can reduce the emissions of dry and liquid cargo ships in the St. Lawrence and Great Lakes region. The analysis incorporates dry bulk cargo ships, liquid bulk cargo ships and general cargo ships since they represent the biggest share of ships in the area.

The base methodology comes from the IMO emission study (Faber et al., 2020). However, as previously discussed, it includes many drawbacks for real estimation of emissions and energy demand in the optic of shore power. Indeed, the base methodology includes erroneous emission estimation of cargo ships at berth, fails to accurately determine the energy and peak power demand for ships in port, and do not integrate different types of bulk carriers. Therefore, this work includes the following novelties:

1. First comprehensive review of emission estimation methods and technics specifically for bulk and general cargo ships at berth.
2. Proposal of an improved methodology to estimate the emissions of the bulk and general cargo ships at berth by integrating further geographical data, berth-specific data, new operating modes, and the exclusion-area technique for the determination of the “at berth” navigational status. The combination of these different factors has never been studied in an emission inventory for ships at berth so far which distinguishes this method from other methods.
3. Consideration of different types of bulk carriers to better represent the electrical power demand at berth such as gearless bulk carriers, geared bulk carriers, self-unloaders, and cement carriers. The integration of these cargo ship types has never been studied yet.
4. First comprehensive evaluation of emissions, external costs and electrical forecast for bulk carriers, general cargo ships and tankers of the St. Lawrence and Great Lakes.

While this work presents a new and improved method for evaluation of the emissions and energy demand for cargo ships of the St.

Lawrence and Great Lakes, the approach can be applied to any region and ship type in the world.

The rest of the document is divided into four sections. Section 2 describes the methods used for emission inventory and external cost calculation. In section 3, the emissions of cargo ships at berth in the St. Lawrence and Great Lakes that could be eliminated with shore power are estimated and discussed. Section 4 presents a validation test of the model and comparison with other sources. Finally, section 5 concludes with the key findings and suggestions for future works.

2. Materials and methods

This section provides the methods used to perform the emission estimation for the bulk carriers and tankers in the St. Lawrence and Great Lakes. First, Fig. 1 presents the considered ship types followed by a description of the general method. While the literature review does not integrate tankers, their modelling is much more advanced than bulk carriers and general cargo ships, and was applied directly. Then, the data filtering process and the exclusion-area technique are explained. Next, the ship stays' in port determination process is detailed followed by the improved bottom-up methodology. Finally, the external cost and fuel cost estimation methods are discussed.

The first step of the improved bottom-up study is to obtain data from the ships stays in port i.e., port calls. This information will be used to estimate the emissions, electrical consumption, fuel consumption or any other metrics. Also, the ship stays' must be linked to other sources of information concerning the ship's characteristics, and berth of call characteristics to enable a full characterization of the ship consumption. The ship stays' have been generated using AIS since it is a reliable source of information that is widely available and standardized.

Commercial ships are using AIS to broadcast their position to other ships as a security measure and extensive literature reviews cover the different AIS databases and techniques (Tu et al., 2018). Also, a pre-processing of the data is required to improve the quality of the analysis as presented in (Zhao et al., 2018). Therefore, AIS historical records are a perfect database to analyze the ship's time spent in port using the bottom-up approach. Indeed, the position accuracy of the different AIS databases is 0.0001° (Tu et al., 2018), which is equivalent to 1.1112 m. However, the databases include billions of AIS messages from thousands of ships. An algorithm is required to handle the large files and the large quantity of data. Fig. 2 presents the flow chart of the AIS acquisition and data processing algorithm.

2.1. Filtering and exclusion-area technique

First, the data is downloaded chunk by chunk and filtered based on the ship type, location, speed, length, size, and navigational status. To eliminate non-oceangoing liquid and dry cargo ships, a filter is applied to the type, size, and length of the ship. Ships smaller than 5000 deadweight tonnage (DWT) and 100 m are not considered following the IMO CII index (The Marine Environment Protection Committee, 2022). Also, tugs and barges are excluded. Then, the speed and the location are used to eliminate AIS points where the ships are not moored at berth. Therefore, a combination of the navigational status, speed over ground (SOG) and location data are used to determine if the ship is at berth.

However, current state-of-the-art AIS methodologies use a technique to determine the operating mode of the ship i.e., "sailing," "maneuvering," "anchorage," and "at berth" that is not reliable for "at berth" specific emission estimations. Generally, aSOG threshold of < 1 knot and a distance threshold of < 1 nm between the ship and the closest port categorizes an AIS point to be in the "at berth" navigational mode. In this article, this technique is referred to as the distance-from-point technique, and is used in the IMO studies (Faber et al., 2020) and ICCT studies (Olmer et al., 2017). While effective for large-scale inventories encompassing sailing emissions, it is unsuitable for berth-specific emissions due to its drawback of erroneously including data points from ships engaged in maneuvers, at anchor, or sailing. Even more problematic is the fact that the St. Lawrence and Great Lakes include many rivers with ships at anchorage and ships at berth being in the 1 nm radius. Furthermore, many ports of the St. Lawrence and Great Lakes cover an area larger than 1 nm. In consequence, all the data points outside of the 1 nm zone are categorized as "anchorage" points. For large-scale emission inventories, this value is small compared to the sailing emissions of the ships and it can be neglected, but not in this case.

The new proposed method was called the exclusion-area technique because it uses a port area instead of distance from a point eliminating the problematic radius distance threshold, and many anchorage and maneuvering points. While being restrictive, the exclusion-area should be designed in a way that excludes ships at anchorage but preserves any AIS point in the port area. Therefore, not all "maneuvering" AIS data points are eliminated. To do so, a SOG threshold is used. This methodology is more suited for estimation of cargo ship emissions at berth because it can perform better segregation of the data while being efficient for large port areas and preserving a low computational effort. For example, the exclusion-area technique performs much better in enclosed areas or rivers where the land is close to the maritime road. Fig. 3 presents the difference between the distance from the point technique and the exclusion-area technique.

In the distance-from-point technique, the program measures the distance from the port location point. For example, the IMO studies use the World Port Index database and only considers the AIS points within 1 nm of the port points. A purple circle represents this area in Fig. 3. However, most of the port area is not covered by this technique and the program assigns the AIS data points to another operational mode than "at berth." The exclusion-area, represented by the shaded green area, eliminates all the AIS data points within this area and considers the rest as "at berth" points if the SOG is less than 0.2 knots. Again, this work uses a more conservative value compared to the more generic SOG threshold of 1 knot to eliminate data points of the ships maneuvering in port.

The supplementary materials contain the source files of the inclusion and exclusion-areas used in the study. Finally, the exclusion-area can be generated manually or by an extension of the coastal lines.

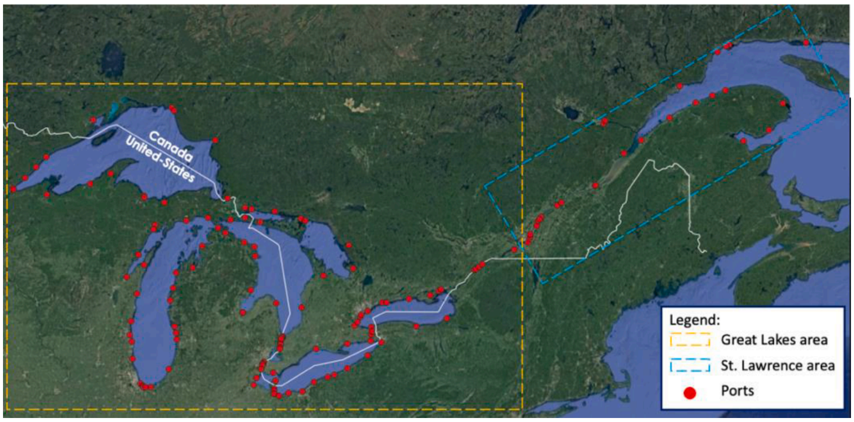

Fig. 4. Studied St. Lawrence and Great Lakes areas and ports.

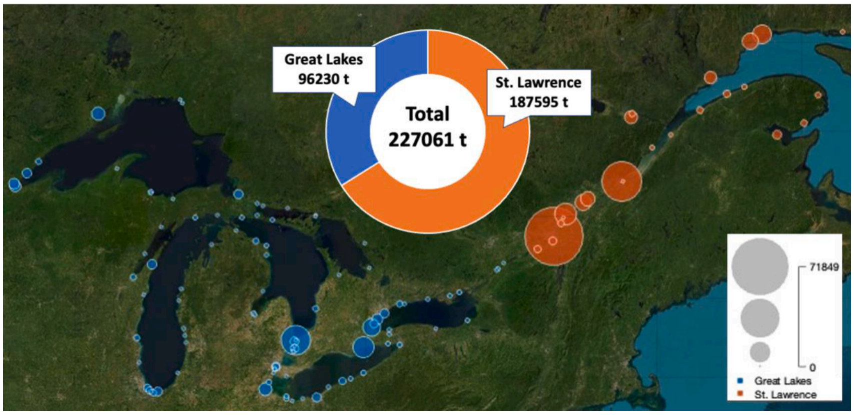

Fig. 5. Carbon dioxide equivalent emissions in the St. Lawrence and Great Lakes for bulk carriers, general cargo ships and tankers.

2.2. *Ship's stays in port creation process and analysis*

The next step toward the analysis of the emissions and external cost calculation is to build the ship stays' matrix. To do so, a program determines when to aggregate groups of filtered AIS data points when they respect three criteria. First, the ship must be the same for all the points. It is possible to use the IMO number of the ship or the maritime mobile service identity number for that concern. The second criterion relies on measuring the distance between the location of the data point to the location of a group of data points. The distance threshold is set to 400 m to cover a radius of 200 m which is a common berth length in the Great Lakes and St. Lawrence. Finally, the last criterion is to segregate the groups of data points based on the time interval between a new data point and the last data point of the ship stay in port. Since dry and liquid bulk cargo ships stay between one and two days in port per port call (UNCTAD, 2023), the threshold time is set to 24 h between the last AIS data of a ship stay and a new data point. The method is based on the IMO study (Faber et al., 2020) method to fill missing AIS data points.

Once the ship stays' have been found by the program, the next step from the flow chart of Fig. 2 is to associate the ship database and berth database with each ship stay. These two databases are built based on external information sources on ships and berths. For the ship database, the IMO GISIS database (IMO, 2023) can generally be used. Hence, more data is integrated into each ship stay such as a port name, a berth number, a terminal type, a berth equipment list, a ship IMO status, an IMO ship type, etc. This data will be used to accurately determine the electrical demand of the ship in port.

The next subsection introduces the improved bottom-up methodology used to estimate the electrical consumption of the ships in port and the related emissions.

2.3. *Upgraded bottom-up methodology*

This work modifies the base methodology used in the IMO studies (Faber et al., 2020) for bottom-up emission inventories to integrate different bulk carrier types, and different operating modes such as "loading," "unloading," and "at rest." It is considered that a ship is in "loading" or "unloading" mode when the ship's gear is used to load and unload the cargo. When the ship is not engaged in

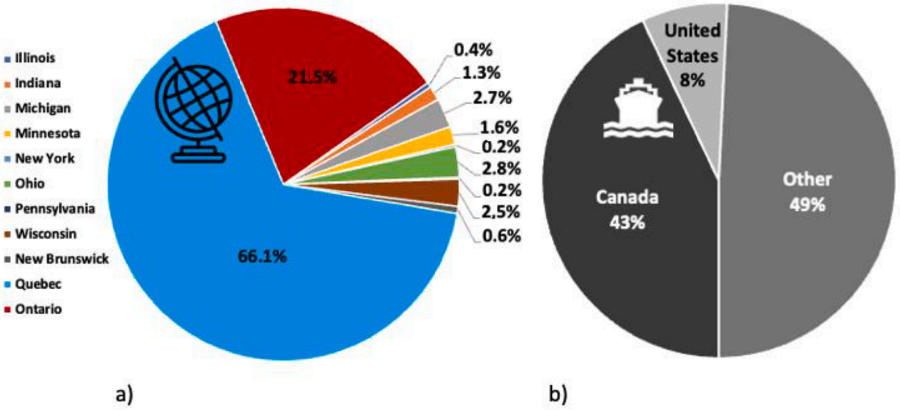

Fig. 6. Repartition of annual carbon dioxide equivalent emissions of ships at berth in the Great Lakes and St. Lawrence: a) Per state and provinces, and b) Per flagship.

loading or unloading operations, it enters the "at rest" mode. During this period, the load on the diesel generator is minimized as only a few activities are carried out on the ship.

To estimate the emissions, the generic formula (1.1) is used, but with an adaptation for the proposed approach as presented in (2.1).

$$E_k = \sum_{st=1}^{nST} AE\_EF_k \times AE\_ST_{elec\,st} + B\_EF_k \times B\_ST_{elec\,st} \tag{2.1}$$

where E_k is the total amount of the k atmospheric emission, st is the ship stay in port, nST is the total number of ships stays in port, AE_EF_k is the emission factor of the atmospheric emission k for the auxiliary engines, AE_STelec_{st} is the total AE energy consumption for the ships stays in port st, B_EF_k is the emission factor for the boilers (B), B_STelec_{st} is the total boiler energy consumption for the ship stay in port st.

Then, the $STelec_{st}$ can be calculated based on the product of the time at berth for a specific ship stay in port T_{st} and the related function of the average power of a ship P_{avg}. The formula is presented in (2.2). The same formula is used for the auxiliary engines and boilers.

$$AE\_ST_{elec_{st}} = T_{st} \times R_{mode} \times P_{avg}(type, size, mode) \tag{2.2}$$

where $type$ is the ship type, $size$ is the ship size in DWT or cubic metre, $mode$ is the operational mode of the ship at berth where $mode \in$ {"At rest," "Loading," "Unloading"}, and R_{mode} is the ratio of operation time.

More specifically R_{mode} is a ratio used to determine the share of time that a specific ship type spends in the loading or unloading modes versus at rest. Loading and unloading operations are not continuous and it is not currently practically feasible to identify when a

Table 2
Estimated bulk carriers, general cargo ships and tanker ships annual emissions in different ports of the St. Lawrence and Great Lakes.

Port	Emissions (t CO_2e)	Port	Emissions (t CO_2e)
Ashtabula	131	Milwaukee	512
Baie-Comeau	2880	Muskegon	64
Becancour	4242	Nanticoke	9209
Burns Harbor	1420	Oshawa	586
Calcite	527	Oswego	179
Chicago	961	Port Alfred	3346
Cleveland	1411	Port-Cartier	5313
Conneaut	229	Quebec	33,303
Detroit	1051	Saginaw River	298
Duluth	2135	Sarnia	18,118
Erie	358	Sept-Îles	7367
Goderich	479	Sorel	9938
Green Bay	479	Superior	2513
Hamilton	6358	Thunder Bay	3412
Havre-Saint-Pierre	165	Toledo	3210
Johnstown	204	Toronto	1422
Lorain	35	Trois-Rivières	5320
Meldrum Bay	166	Two Harbors	1595
Monroe	408	Valleyfield	800
Montreal	71,843	Windsor	1234

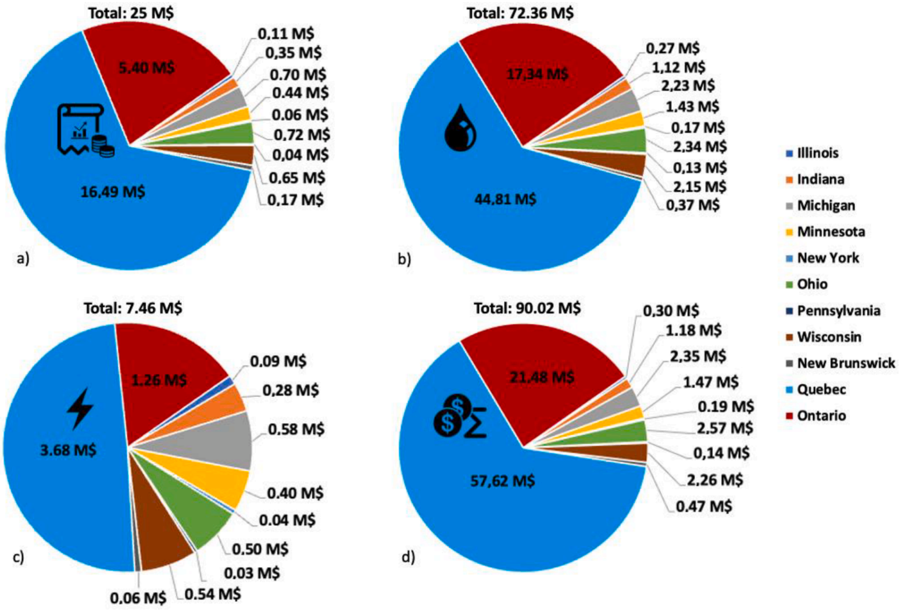

Fig. 7. Social and operational annual costs per area in USD for a) External cost b) Fuel cost c) Shore power electrical cost d) Operational resulting benefits.

ship uses specific loading and unloading gear with the available databases. However, the share of time spent at rest versus loading and unloading is known for the different ship types.

To determine the R_{mode} value, the operating mode must first be determined with the flowchart of Appendix B. The proposed algorithm decides if the ship needs to use its equipment or not and under which conditions based on the ship type, terminal type, and the availability of loading or unloading equipment on the shore. If the mode is "at rest", the R_{mode} is set to 100 %. If a geared bulk carrier is loading or unloading, the evaluations of the typical working hours in the St. Lawrence and Great Lakes enabled to determine that the R_{mode} ratio of the ships in these conditions is about 56 % i.e., 13.5 h of work per day in loading or unloading mode. Geared general cargo ships also use the same value. For the self-unloaders, a similar analysis performed with stakeholders of the industry provided a

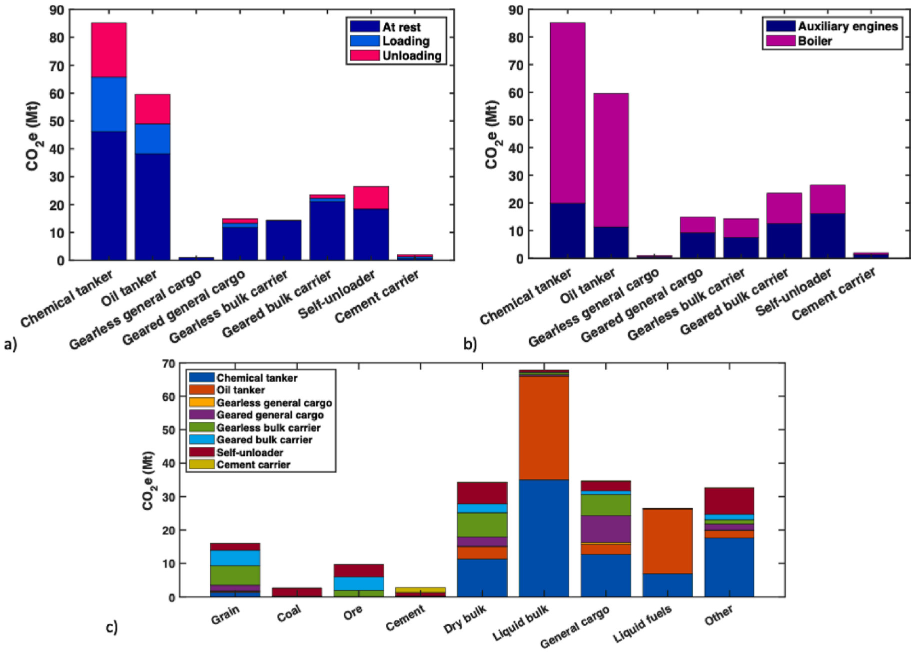

Fig. 8. General ship metrics as a function of the annual carbon dioxide equivalent emissions for a) Operating mode per ship type b) Auxiliary versus boiler emissions per ship type c) Ship types per terminal type.

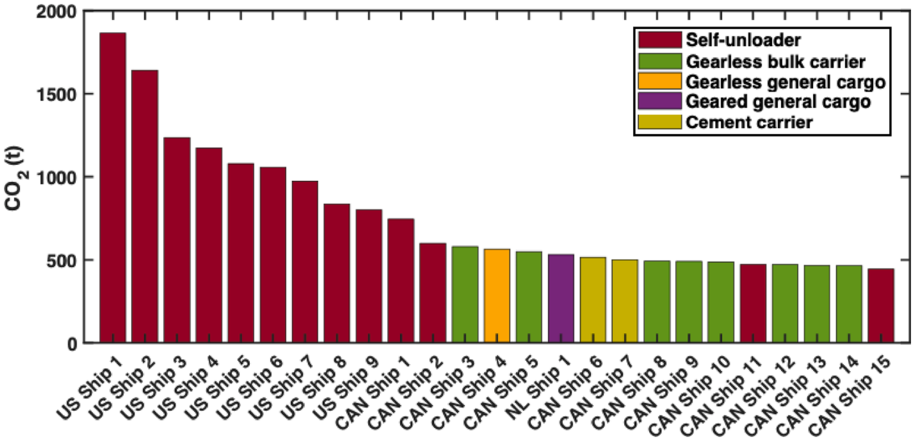

Fig. 9. Top 25 bulk carriers and general cargo ships with the most emissions that shore power can reduce based on the annual carbon dioxide equivalent emissions.

R_{mode} value of 92 % when they are unloading cargo. Indeed, the turnaround time of self-unloaders is very quick because of their high unloading speed. For oil tankers, an analysis of the literature and in-port operations has determined that they are continuously in loading or unloading mode. Indeed, the typical in-port operations of oil tankers encompass tank inspections, loading and unloading, as well as tank cleaning, with the goal of efficiently extracting the oil. Therefore, the loading and unloading equipment are continuously in use (Dawoud, 2021). In this case, the R_{mode} ratio is set to 96 %. For chemical tankers, the ratio is based on (Korkmaz et al., 2023) which includes an analysis of a chemical tanker operational modes. In the analysis, 25 % of the time in port is spent to load and unload cargo. The R_{mode} ratio of cement carriers could not be obtained directly and an analysis of the AIS data considering a typical loading and unloading speed of 1000 t/h (CSL, 2023) enabled to identify a ratio of 33 %. It is noteworthy that, as a consequence of this model, the investigation of winter lay-ups is disregarded, as the stay in ports are treated independently of the season.

The P_{avg} function is a lookup table using the ship type, size, and operating mode to return the average power demand for a specific combination. The method is the same as the one used in the IMO studies (Faber et al., 2020). Appendix B. presents an adapted and modified version of the auxiliary and boiler power output table of the IMO studies. The differences are that 1) it integrates new operational modes: "at rest," "loading," and "unloading," 2) it only considers the power demand at berth, and 3) it introduces four new ship types: gearless bulk carriers, geared bulk carriers, self-unloaders, and cement carriers. Furthermore, Appendix C has information on peak loads which is critical when performing electrical demand forecasts of shore power. The power demand for ships has been produced based on a combination of the IMO Fourth GHG study (Faber et al., 2020) and a survey among different shipowners: Fednav,[1] Survey CSL,[2] Survey Algoma.[3] However, the table includes some assumptions. First, the data is subdivided into categories of ship types and size to provide more granular average of power demand for the different equipment used on the ships i.e., cranes, ballast pumps, air compressor, water pumps, hydraulic pumps, etc. Certain ships might require more or less power than their category average. However, obtaining data on all individual ships in not feasible which is why power tables are used. In general, the bigger a ship is, the bigger the power demand, which explains why the power is increasing with size. Indeed, the ballast pumps, cranes and other electrical loads need to be able to load and unload more cargo, and cope with the bigger crew size.

Finally, the emissions are estimated based on the equation (2.1). The emission factors were taken from the San Pedro Bay Ports Emission Inventory Methodology Report (SCG, 2022) which uses the most up-to-date methods for emission factors determination. Since only the auxiliary system and boilers are considered when the ship is at berth, the methodology was greatly simplified. Additionally, the global warming potential of N_2O and CH_4 were integrated to estimate the equivalent carbon emissions as per the IMO emission inventories. They are based on the global warming potential developed by the Intergovernmental Panel on Climate Change of 265 for N_2O and 28 for CH_4 (IPCC, 2013).

Furthermore, the emission factors from Appendix B were considered to reflect the emissions coming from the electricity generation process. That made it possible to estimate the real emissions that shore power can reduce if ships were connected to the grid tomorrow. However, the total emissions are the best indicator because the GHG emission profile of the shore electrical grid network should be much greener in the coming years thanks to the energy transition.

Finally, the Appendix A. details the reasoning for selecting the emission factor, fuel cost and external costs. The cost of fuel and the external costs are critical for the study. Indeed, the cost of fuel is a crucial factor in determining operational expenses for shipowners and the aim of reducing the social and environmental costs associated with shipping emissions motivates the implementation of shore power projects. The next section discussed the results of the study using the improved method.

---

[1] https://www.fednav.com/en.

[2] https://www.cslships.com/en.

[3] https://www.algonet.com/.

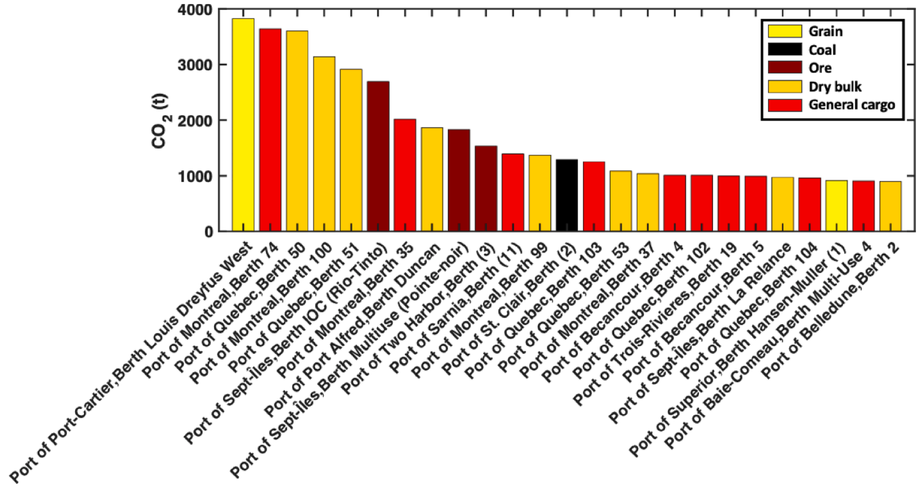

Fig. 10. Top 25 berths with the highest emission reduction potential based on the annual carbon dioxide equivalent emissions of bulk carriers and general cargo ships only.

3. Results and discussion

The Fig. 4 presents the St. Lawrence and Great Lakes sections studied in the analysis and its related ports.

The study has identified more than 70,000 ship stays' at berth, i.e. port calls, between 2018 and 2022 in the St. Lawrence and Great Lakes with the Canadian Coast Guard (Government of Canada, 2019) and United States Coast Guard (MarineCadastre, 2023) AIS database. During this period, 3136 different bulk carriers, general cargo ships and tankers of more than 5000 DWT and 100 m in length visited 814 different berths among 111 ports. The determination of the annual emissions used a five-year average for further accuracy. Also, the details about berth equipment and descriptions are based on the Greenwood's Guide to Great Lakes Shipping 2022 (Great Lakes Seaway Review, 2022). Finally, the berth list and exclusion-area were produced with satellite imagery processing (Google Earth, 2022).

Fig. 5 presents the total emissions of carbon dioxide equivalent between the St. Lawrence area and the Great Lakes area. The emissions are displayed on a satellite map based on the port total carbon dioxide equivalent emission. The size of the circles represents ports where the emissions are greater, and the colour segregates the Great Lakes ports from the St. Lawrence ports. Finally, the pie chart presents the cumulated emissions for the Great Lakes and the St. Lawrence.

The results indicated that most of the emissions are coming from the St. Lawrence area. The difference is explained by the fact that the St. Lawrence is visited by more ships and a greater number of large ocean-going ships which emits more emissions than the smaller ships. Indeed, the Seaway Lock System limits the size and the numbers of ships that can reach the Great Lakes to lakers of about 35,000 DWT. While many small inland ships are sailing in the Great Lakes and into the rivers and canals connected to the Great Lakes, these ships are out of scope for this study. Barges and pusher tugs are also excluded because of their size or because they do not emit an AIS signal. In summary, even if the Great Lakes benefit from a strong maritime network and trade, the highest potential for oceangoing ships emission reduction at berth lies in the St. Lawrence.

Based on the results, shore power for bulk carriers, general cargo ships and tankers can reduce a theoretical maximum of 227,061 t

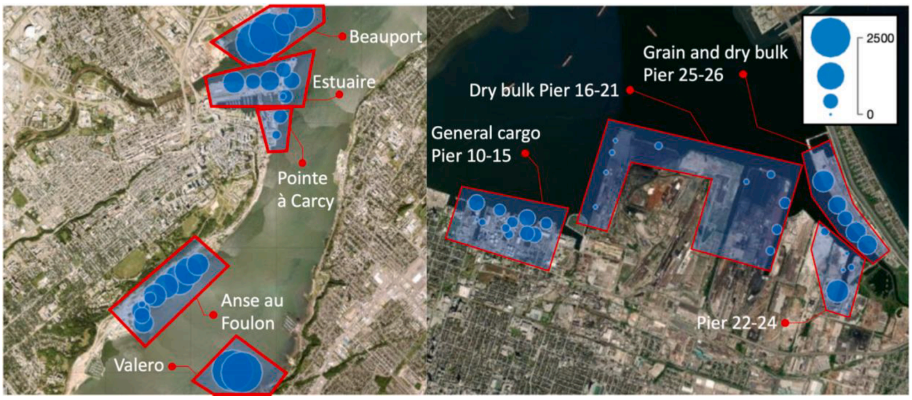

Fig. 11. Annual carbon dioxide equivalent emission per berth in a) Port of Quebec b) Port of Hamilton.

of CO_2e in the St. Lawrence and Great Lakes annually. Taking an average of 3.1 t of CO_2 per year per light car, shore power can take 73,300 cars off the road per year which is the equivalent all the light cars out of the city of Trois-Rivieres (Government of Quebec, 2023).

When considering the current emissions of electricity production i.e., the emissions coming from electricity generated with coal and other fossil fuels, the maximum emissions that shore power can reduce only drops by 6.3 %. However, in states where power plants generate most of the electricity with fossil fuel, the real share of the saved emissions is about 50 %. Nevertheless, global emission reduction targets and policies are focused on achieving 45 % emission reduction by 2030 and zero emissions by 2050 (UN, 2015). Therefore, it can be argued that by the time shore power is fully integrated into the port network, the emissions from electricity production will be negligible. It is already the case with the province of Quebec which has an almost carbon-free electricity generation system thanks to hydropower. Further results about emission considering the electricity generation process are available in the supplementary materials.

The Fig. 6 presents a) the repartition of emissions of carbon dioxide equivalent per state and provinces, and b) the repartition of the emission of carbon dioxide equivalent per flagship country.

With 66.1 % of the emissions at berth, the province of Quebec is the one that has the most to gain with policies regarding shore power for bulk carriers, general cargo ships and tankers. In the second position, the province of Ontario covers 21.5 % of the emissions and benefits of a low-carbon electricity system thanks to nuclear. The rest of the carbon emissions are split between the different US states around the Great Lakes and New Brunswick starting with Ohio for 2.8 %, Michigan for 2.7 %, Wisconsin for 2.5 %, Indiana for 1.3 %, Minnesota for 1.6 %, New Brunswick for 0.6 %, and Illinois for 0.4 %. The full table of emissions of CO_2, N_2O, CH_4, NO_x, SO_x, and $PM_{2.5}$ is detailed in the supplementary materials.

Then, international ships emit the most with 49 % of the emissions and Canadian ships with 43 % of the emissions. The US ships come in last position with 8 % of the emissions. These results indicate that domestic ships from Canada and the United States represent about half of the ship's emissions at berth and international ships the other half.

3.1. Port emissions

Table 2 presents a list of the ports and their emissions of cargo ships at berth. The list is based on the 40 ports modelled in the economic impact study of maritime shipping in the St. Lawrence and Great Lakes (Martin Associates, 2018). Furthermore, the full list of ports and emissions covered in this article is available in the additional content.

Based on the results, only a few ports really stand out based on the quantity of emission they can potentially reduce with shore power. The port of Montreal is the first one with a reduction potential of 71,843 t of CO_2e annually. Then, the Port of Quebec, the Port of Sarnia, the Port of Sorel, the Port of Nanticoke, and the Port of Sept-Îles also benefit from an important potential of emission reduction with shore power with 33,303 t CO_2e, 18,118 t CO_2e, 9938 t CO_2e, 9209 t CO_2e, and 7267 t CO_2e, respectively. Together, these ports represent more than 65 % of the overall emissions of the ships at berth.

3.2. Shore power social and operational costs

The CO_2e emissions are a great indicator of the shore power environmental potential. Nevertheless, the external cost related to pollution and the cost of fuel are also important indicators because they represent an important share of the operational expenditure (OPEX) of using fossil energy to supply the ships at berth with electricity. While the capital expenditure (CAPEX) is another important metric, this topic is out of the scope for this analysis and will be discussed in the future work section. Also, it is possible to subtract the cost of electricity supplied by the local grid of each port from the aggregated cost of fuel consumption and external cost to see the resulting economic benefits of using shore power. Fig. 7 presents the high-level annual cost analysis by state or province.

From this analysis, shore power for the bulk carriers, general cargo ships and tankers in the St. Lawrence and Great Lakes has the potential to save annually a total of US$25 M to the society and governments. Indeed, based on the results, bulk and general cargo ships at berth in the St. Lawrence and Great Lakes emit about 502 t of NOx, 136 SO_x, and 47 t $PM_{2.5}$ are emitted annually. These air pollutant emissions have negative impacts on air quality and the carbon dioxide emission result in more cost to the government due to climate change. Implementing an environment policy targeting shore power could be self-funded if the government invests the US$25 M, rather than paying for costs related to health issues and climate change caused by emissions. Then, the results show that US$72.36 M is paid in fuel by shipowners. If shore power is globally adopted in the St. Lawrence and Great Lakes, it is estimated based on the industrial electricity cost per state from Appendix B that the electrical cost will reach US$7.46 M, annually. Then, the resulting net benefit is obtained by subtracting the cost of electricity to the external cost and fuel cost which gives US$90.02 M annually that shipowners and governments could share.

3.3. Operational analysis of the model and results

Fig. 8 dives more deeply into the operational analysis of the model and results.

In a), the emission per operational mode and ship type is presented. As predicted in the introduction, the self-unloaders spent a considerable part of their time in the unloading mode where they use their boom conveyer to unload cargo. In this mode, their auxiliary power demand is 1300 kW on average which requires a lot of energy. For bulk carriers and general cargo, the share of emissions in loading and unloading mode are less important, but still are important for the model when it comes to the electrical forecast that will be discussed later. Another key aspect presented by this graph is that chemical tankers followed by oil tankers

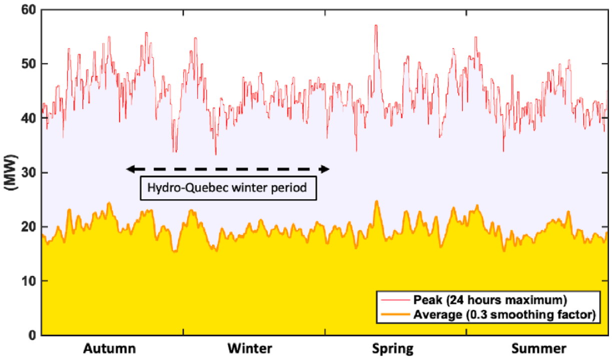

Fig. 12. Daily electrical forecast of power and peak power of shore power in the province of Quebec.

generated most of the emissions. Since tankers visit only a few berths, the amount of emission they can reduce with shore power is very high. Then, the next ship types with the most emission that shore power can reduce are the geared bulk carrier segment followed by self-unloaders, general cargo, gearless bulk carriers, and finally cement carriers.

In Fig. 8 b) the accent is given to the repartition of the emissions between the auxiliary system and the boilers. For bulk carriers, boilers represent less than 50 % of the emissions. However, they represent more than 75 % of the emissions for tankers which is massive. Luckily, low-cost electrification technologies exist for the boilers which will permit transferring the load on the auxiliary system easily.

Finally, the emissions per terminal type and ship type are shown on Fig. 8 c). While the same berth can host multiple types of terminals, the type is based on the berth's most important terminal type. This importance level has been established with the help of the berth database. The important aspect to consider from this graph is to see on the high-level which types of ships share the same berths and terminal types. The bulk terminals such as grain, ore, coal, cement, and dry bulk are mostly visited by gearless bulk carriers, geared bulk carriers and self-unloaders. Self-unloaders are also much present in the "Other" berths. This is because they can efficiently unload cargo in remote areas. Then, bulk carriers and tankers share many berths. While the liquid bulk and liquid fuel berths are nearly exclusively visited tankers, they also visit general cargo, other, and dry bulk berths in large numbers. Therefore, it should be concluded that bulk carriers, general cargo ships and tankers share many of the same berths. Also, the selected shore power system must be interchangeable between all the ship types apart from specialized dry bulk berths such as grain, ore, coal, and cement berths.

Top ships and berths that benefit the most from shore power.

The following Fig. 9 and Fig. 10 presents the top 25 bulk carriers and top 25 bulk berths in the St. Lawrence and Great Lakes with the most emissions that shore power could reduce.

The top 25 bulk carriers indicated that the self-unloaders are the bulk carriers with the emissions that shore power can reduce followed by gearless bulk carriers. However, the key element in this graph is that a policy targeting the conversion to shore power of one ship can reduce the emissions tremendously. If these ships are on liner routes, it will be even more advantageous to convert them to shore power. It is important to note that this analysis does not tell if a ship is more polluting or less efficient than others. Indeed, the emissions from the cruising and maneuvering are missing and many assumptions were made to arrive at this emission amount.

Looking at the top 25 berths, the Port of Port-Cartier grain berth Louis Dreyfus West is the berth that has the best emission reduction potential in terms of emissions reduction. Also, general cargo berths and dry bulk berths are the berths with the most emission that shore power can reduce. This view of the emissions per berth also shows that shore power projects should not only consider the total port or total state/province emissions, but mostly the berth emissions. Indeed, ports with great emission reduction potential, such as the Port of Hamilton, do not show on the graph but berth #2 of the Port of Belledune does. The more a berth is frequented and has a high emission level, the more electricity it will use. a shorter return on investment period for the shore power system.

Finally, Fig. 10 does not include tankers because their high emission rate would have eclipsed the bulk berths of the top 25. Overall, the berths with the most emission that shore power can reduce between tankers, bulk carriers and general cargo are the tanker berths, especially the berths where the ships go to bunker.

Also, the proposed methodology enables to get a precise resolution of the estimated cargo ship emissions at berth. The following analysis show how the emission estimation model proposed in this work can be used by ports to measure their emissions. In Fig. 11, the Port of Quebec and the Port of Hamilton are taken as examples to present at which berths shore power should be installed based on the emission that can be saved. To do so, the satellite maps contain circles representing the emissions that are emitted at each berth, annually. The additional materials include the same analysis for all the major ports.

For the port of Quebec, the biggest share of the emissions comes from the Valero fuel products terminal where many ships are bunkering. The second section with the most emissions at berth is the Beauport section. This combined dry bulk and liquid terminal is very busy and the integration of shore power could reduce an important share of the port emissions. Finally, the general cargo terminal at berths of Anse au Foulon represents the third-best emission reduction section.

For the Port of Hamilton, the grain and dry bulk terminal of piers 25 and 26 represent the section where the most emissions can be reduced. Then, the mixed break bulk, liquid bulk, dry bulk, and general cargo terminals of piers 10 to 15 present the second most interesting option. Finally, shore power could also have a good impact if installed at pier 21 of the dry bulk iron ore terminal.

While this analysis is very insightful to provide information on the berths that can reduce most emissions, it is important to note that the market is the factor leading a berth to be more visited than another one. Also, the technical aspects of shore power are not considered. Therefore, the results from this analysis cannot guarantee that a certain number of emissions will be reduced if shore power is used. The goal instead is to present the global shore power potential as an emission-reduction measure.

3.4. Electrical forecast

This part of the result section presents an electrical forecast example and details its implication. For grid operators and electrical suppliers, electricity production must be predicted. Indeed, the construction of electrical generation plants is a long process. Also, the electrical forecast shows that the approach presented in this work will still be used in the future when all ships will be connected to shore power. Even if there will not be any emissions to estimate, the energy forecast will still need to be determined. Therefore, this analysis presents the forecast of the daily electrical energy required for shore power in function of the time of the year. The maximum peak power demand that can be seen on the network if all ships require their maximum power at the same time is also represented. Fig. 12 details the electrical forecast for the province of Quebec. The electrical forecast for the other states and provinces of this study are presented in the additional materials.

The analysis shows that the busiest periods happen during autumn and spring. Indeed, during autumn, the bulk carriers are rushed to transport as much cargo as they can before the closing of the St. Lawrence Seaway for winter. During this period, the average daily energy demand is about 20 MW and the maximum possible peak power demand could reach up to 55 MW. Then, winter is less intensive as many ships are laid up or out of the St. Lawrence and Great Lakes because of the ice. During this period, the average daily energy demand is about 18 MW and the maximum peak power demand is about 45 MW. The black double side arrow presents the winter period for which Hydro-Quebec, the electrical provider in Quebec, needs to diminish its peak demands due to electrical planning policies. Indeed, the great periods of cold in Quebec induce very high-power demands which cost a lot to the province (Godin, 2019). An important element for shore power in Quebec is that the high energy and peak power do not occur at the same period as the rest of the Quebec electrical network which arises during winter. Also, ships can easily turn on their diesel generators for a few hours during winter peak power demand to reduce the pressure on the network. Finally, the electrical demand re-increases at the beginning of spring for an average of about 19 MW and slowly diminishes until the end of summer.

3.5. Validation and comparison

Various sources enabled to confirm the accuracy of the information presented in this work. While there is no other precise database or method to compare the final emissions with, the information of the ships at berth can be compared with alternative sources. The results are presented in Fig. 13 and Table 3. Fig. 13 compares two different metrics based on port call data provided by: FMT,[4] the Port of Trois-Rivieres, the Port of Hamilton, the Port of Cleveland, and Fednav. The first five boxes of Fig. 13 compare the time spent in port during a ship stay in port of the validation data to the found time spent in port found in this study. The difference is expressed in percentages. The last box compares the number of found ships stays in port of this study to the number of ships stays in port of the validation data. Therefore, the validation addresses the accuracy of the time spent in port and the accuracy of the ability of the proposed algorithm to find all stays in port.

The results from Fig. 13 shows that in general, the algorithm performs well to estimate the total spent in port. Indeed, the average precision was between 93 % and 105 %. However, it is suspected that the validation data contains some erroneous data since extremum values were found well over the first and fourth quartiles. In the case of the Fednav data for example, one ship stay in port from this study was twelve times longer than the validation data. That can be explained by the fact that the validation data was generally processed by humans, which might produce human mistakes on some occasions. On the other side, it is unlikely that the AIS database contains ghost AIS data days after the ship left the port, especially after the rigorous filtering process. In that case, the proposed method could be even more robust to determine the time spent in port than the validation data.

The metric of the total number of found ships stays in port per validation database is different because the possibilities of human mistakes are nearly inexistent. However, missing AIS data could lead to missing ship stays'. The results showed that the proposed algorithm found between 70 % and 97 % of the ship stays' among the different validation databases. This figure is expected to improve with time since AIS coverage is improving over the years. Also, the fact that some ships stays are missing and not the opposite shows that the proposed algorithm cannot overestimate the number of ships stays in a port.

Table 3, on the other hand, uses the ICCT Great Lakes and St. Lawrence emission inventory 2019 (Meng and Comer, 2022) to compare the results.

The comparison of the "at berth" emissions from the 2019 ICCT Great Lakes-St. Lawrence Seaway Ship Emission Inventory (Meng and Comer, 2022) with the 2019 data of this study for bulk carriers, chemical tankers, and oil tankers showed a difference of −15.7 %, 182.6 %, and 377.7 % respectively for CO_2 emissions in the same area and using the same power table. Indeed, the ICCT study only covers the area going from the city of Duluth to the city of Quebec and is not specific to at berth emissions. When compared to the total CO_2e emissions generated with the updated power table, the proposed approach found a difference of − 4.2 %, 182.6 %, and 377.7 %, respectively. While bulk carriers present similar emission rates, the tanker's emissions are much higher than for the ICCT study which

---

[4] https://fmtcargo.com.

suggests that the ICCT study underestimated the emissions of ships at berth. The massive emission difference is most likely due to the use of the exclusion-area technique instead of the distance from technique to determine the navigational status of ships. It also shows that the improved method presented in this work is more suited for emission estimation of ships at berth.

Finally, the IMO does not estimate emissions at berth for ships in the St. Lawrence and Great Lakes, unlike the ICCT study. Nonetheless, a comparison between the exclusion-area technique and the IMO distance-from-point technique was conducted. The exclusion-area technique found 343.3 % more emissions than the IMO distance-from-point technique, emphasizing the inadequacy of the IMO method for at-berth emission estimation. In world-scale IMO emission estimation studies, the incorrect categorization of "at-berth," "maneuvering," or "anchorage" emissions is not a concern, but it poses an issue for port-scale emission estimation.

Overall, the proposed model is valid because the results fall within a very good range compared to other data sources. It also presents better results for the time and emissions at berth compared with other sources and cover more areas.

4. Conclusion

In conclusion, this study aims to estimate the emissions of cargo ships at berth for bulk and general cargo ships that shore power can reduce and to determine for the first time the environmental, social, and external benefits of shore power in the St. Lawrence and Great Lakes. Based on the results of the original review of emission estimation methods specifically for cargo ships at berth,this study proposes for a novel and improved method precisely designed for estimating emissions of ships at berth. For instance, the improved method considers further geographical data, berth-specific data, and the exclusion-area technique. The study also integrates the new operating modes "loading" and "unloading" for bulk carriers, considers different types of bulk carriers to better represent the electrical power demand at berth and provides an enhanced evaluation of the electrical demand forecast for shore power networks.

Also, the IMO, ports, governments, and other organizations can use the proposed improved technique in their emission estimation and energy demand studies of ships at berth. The method can be applied to any ship types or area in the world which is a major advantage.

4.1. Policy implication

According to the analysis, a shore power policy for bulk carriers, general cargo ships and tankers have the potential to reduce annually 227,061 t of CO_2e, 502 t of NO_x, 136 SO_x, and 47 t $PM_{2.5}$ in the St. Lawrence and Great Lakes. Reducing these emissions is the equivalent of taking 73,300 cars off the road per year or about the equivalent of all the light cars of the city of Trois-Rivieres. With 66 % of the emissions at berth in the province of Quebec and 22 % in Ontario, Canada has the most to gain with shore power in the St. Lawrence and Great Lakes. The analysis of the top 25 berths and ships with the most emissions that shore power can reduce highlights the complexity of the deployment of shore power. It also shows that shore power projects should not only consider the total port or total state emissions, but also the individual berths and ships that have the best emission reduction potential. Moreover, the study estimated the additional demand for electricity providers to consider in their future grid planning policies considering shore power. The electrical forecast analysis revealed the peak demand for shore power electricity in the Province of Quebec occurs during Autumn and Spring.

Overall, this study provides a reliable approach for evaluating the total emissions that shore power can reduce and highlights the need for future works to study the shore power network implementation in the St. Lawrence and Great Lakes. The benefits of shore power include a reduction in the annual cost of US$25 M to society and governments, and US$72.36 M to ship owners in fuel, with a predicted electricity cost of US$7.46 M and a net benefit of US$90.02 M, annually. The US$25 M in external costs associated with health issues and climate change caused by emissions could be used to fund a shore power projects instead of being paid retroactively by the governments. However, the limitations of this study include the uncertainty of emissions reduction if shore power is introduced due to various technical and market-related factors. Also, the study only considered the emissions and did not consider the CAPEX and all the OPEX data to fully determine the berths and ships that can reduce the most emissions with shore power.

4.2. Future works

Future research should concentrate on the implementation of the shore power network in the St. Lawrence and Great Lakes region, exploring the most effective shore power systems for each berth and policies to promote shore power adoption. This can be achieved through technical analysis of shore power and multi-criteria decision analysis by addressing the barriers to its implementation such as investment costs or CAPEX, operational costs or OPEX, standardization of shore power systems between berths, and market-related factors.

CRediT authorship contribution statement

Hugo Daniel: Visualization, Validation, Project administration, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **João Pedro F. Trovão:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Funding acquisition, Conceptualization. **David Williams:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Funding acquisition, Conceptualization. **Loïc Boulon:** Writing – review & editing, Visualization, Validation, Supervision.

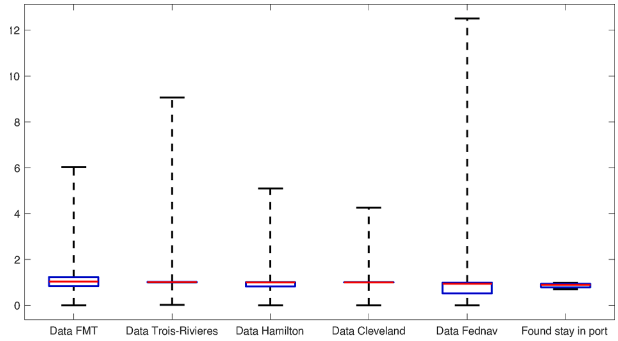

Fig. 13. Validation statistical analysis with port calls data.

Table 3
Comparison table based on ICCT Great Lakes and St. Lawrence emission inventory 2019 (Meng and Comer, 2022).

Dataset	Measured value	Comparison value	Precision
Estimated vs ICCT bulk carrier emissions 2019	43,134 $tCO_2^{*\dagger}$ 49,033 $tCO_2^{\dagger}$	51,176 tCO_2	84.3 % 95.8 %
Estimated vs ICCT chemical tanker emissions, 2019	93,662 $tCO_2^{*\dagger}$ 93,622 $tCO_2^{\dagger}$	33,123 tCO_2	282.6 % 282.6 %
Estimated vs ICCT oil tanker emissions, 2019	61,940 $tCO_2^{*\dagger}$ 61,940 $tCO_2^{\dagger}$	12,965 tCO_2	477.7 % 477.7 %
Exclusion-area vs IMO distance-from-point technique estimated bulk carrier emissions in St. Lawrence area 08/2019	2,942 tCO_2	857 tCO_2	343.3 %

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

This work is supported by the Canada Research Chairs Program (950-230672), by the Mitacs Accelerate Program (IT17570), by the Portuguese Recovery and Resilience Plan (RRP), through project number 56, ATE (*Aliança para a Transição Energética* - 02/C05-i01.02/2022.PC644914747-00000023), and in part by Fednav.

The authors express their gratitude to Environment Canada and Climate Change, the Canadian Coast Guard, Fednav, FMT, CSL, Algoma, the Ports of Quebec, the Port of Hamilton, the Port of Cleveland, and the Port of Three-Rivers for their support in conducting this study. Their contribution was invaluable and greatly appreciated.

Appendix A

The following presents the reasoning used to determine and select the emission factors, the cost of fuel and the external costs.

For the emission of carbon dioxide, the fuel used in this study for the auxiliaries and boilers is marine diesel oil (MDO). Indeed, ships sailing in emissions control areas need to use low Sulphur fuels of 0.1 % m/m to respect the Annex VI of the international Convention for the Prevention of Pollution from Ships. Since all the St. Lawrence and Great Lakes lies in an emissions control area, the diesel generators and boilers generally burn MDO. While some ships have started to use biofuels in the last years to lower their GHG, they still represent a minor portion of the total fleet emissions and the conversation on alternative fuels for the maritime industry is currently inconclusive.

Also, the cost of fuel is a crucial factor in determining operational expenses for shipowners. This study considers an average fuel cost of US$727/t for international vessels, which reflects the average price of MDO at the Port of Montreal between 2018 and 2022. This estimate for international ships is consistent with the average cost of the Port of Rotterdam for the same period which is a reference in the industry for fuel prices. For domestic ships originating from Canada and the United States, it is assumed that they obtain fuel from the Great Lakes area, with the Port of Windsor’s average MDO cost of US$1347/t serving as the reference point. This estimate is based on the average price recorded over the period from 2017 to 2022.

Finally, the aim of reducing the social and environmental costs associated with shipping emissions motivates the implementation of shore power projects. The maritime industry is estimated to be responsible for 13 % of NOx and 12 % of sulphur oxides (SO_x) emissions worldwide (Smith et al., 2014). These emissions not only have a direct impact on the well-being of populations living near ports but also result in crop loss and biodiversity loss. The cost of air pollutants is usually estimated using a cost per unit mass of the pollutant for CO_2, CO, NO_x, SO_x and PM. The various shore power studies use different external costs which are summarized in Table 4.

Table 4
External cost for shore power studies literature review in USD/t of emission.

Study	Area and sector	CO_2	CO	NO_x	SO_x	PM
(Innes and Monios, 2018)	UK, transport	11.52	–	13,020	–	58,670
(Spengler and Tovar, 2022)	Spain, urban	31.09	4.42	–	*Population dependent: 15,350–38,970	*Population dependent: 84,390–214,350
(Progiou et al., 2021)	Greece, shipping	–	–	4,220	12,950	34,640
(Tzannatos, 2010)	Greece, shipping	–	–	22,130	23,260	123,950
(Zis, 2019)	Baltic Sea, transport	119.5		6,243	6,974	18,331

The estimation of external costs associated with air pollution from shipping is challenging due to the wide variability of costs based on geographical location and population density. Therefore, external cost estimates obtained from one study cannot simply be transferred to another, as the conditions differ. To determine the specific external costs for a particular area and activity, researchers often rely on models and software that take these factors into account.

Luckily, Environment and Climate Change Canada (ECCC, 2019) has performed an analysis to determine the external costs. For CO_2, it is accepted that its social cost has a value of CAN$50/t. This figure also accounts for dioxide carbon equivalent (CO_2e) emissions. Moreover, Health Canada (HC, 2022) has performed a very detailed analysis of the external costs of different air pollutants for the area of Southwestern British Columbia and the area comprised in the Windsor–Quebec City corridor. The latter happens to cover an important part of the St. Lawrence and Great Lakes shipping routes. However, there are some issues with the study for using the results in the maritime industry. First, the Health Canada study only considers on-road mobility, off-road mobility, manufacturing, and ore industries. Second, the corridor is limited to the area between Windsor and Quebec. Therefore, all the area from Windsor to Thunder Bay and from Quebec to Sept-Iles is not modelled. Finally, the study only considers the Canadian territory. While it is known that the use of the air pollutants' external cost factors will not be accurate for the maritime industry, the lower bound of each external cost factor can still provide a conservative cost estimate. Indeed, a similar process has been done in other shore power studies as seen in the work of (Innes and Monios, 2018), (Spengler and Tovar, 2022), and (Zis, 2019) from Table 4. Therefore, the air pollutants' external cost factors that could be used for the maritime industry in the St. Lawrence and Great Lakes are CAN$380,000/t of PM2.5, CAN $4900/t of NO_x, and CAN$10,000/t of SO_x.

Appendix B

The following presents supplementary tables and figures related to this article.

Table 5
Characteristics of the electric grid networks in the St. Lawrence and Great Lakes, with N = Nuclear, NG = natural gas, H = hydropower, and C = coal. Based on a conversion rate of CAN$1.25 to US$1 and on: (ECCC, 2022b), (ECCC, 2020), (US EPA, 2020), (EIA, 2021), and (IESO, 2022).

Province or State	Electrical network	Main ports	Main sources	Cost (US $/kWh)	Grid carbon intensity 2020–2022 (g/kWh)			
					CO_2e	NO_x	SO_x	$PM_{2.5}$
Canada								
Ontario	Ontario	Hamilton, Toronto, Thunder Bay, Windsor	N, H	2.25	25	0.0358	0.0018	0.001
New Brunswick	New Brunswick	Belledune	N, H, NG, C	3.58	300	0.2436	0.3607	0
Quebec	Quebec	Montreal, Quebec, Trois-Rivieres	H	2.15	1.9	0.0275	0.0062	0.0006
United States								
Illinois	RFC West	Chicago	NG, C, L	7.30	449	0.2667	0.3002	0.0479
Indiana	RFC West	Burns Harbor, Indiana Harbor	NG, C, L	7.39	449	0.2667	0.3002	0.0479
Michigan	RFC Michigan	Detroit	NG, C, L	7.69	526	0.2803	0.3688	0.0290
Minnesota	MRO West	Duluth	C, N, NG	8.29	448	0.4423	0.4255	0.0298
New York	NPCC Upstate New York	Buffalo	NG, N, H	6.34	106	0.0480	0.0122	0.0074
Ohio	RFC West	Cleveland, Toledo	NG, C, N	6.55	449	0.2667	0.3002	0.0479
Pennsylvania	RFC East	Erie	NG, N, C	6.54	297	0.1319	0.1157	0.0218
Wisconsin	RFC West	Milwaukee	NG, C, L	7.63	449	0.2667	0.3002	0.0479
	MRO West	Superior	C, N, NG		448	0.4423	0.4255	0.0298

Table 6

Average auxiliary engine and boiler power output, by ship type, size and operational mode (cells in shaded gray identify original IMO values), inspired from (Faber et al., 2020).

Size (DWT)	Aux boiler (kW)	Aux engines (kW)						
	IMO value at berth	IMO value at berth	At rest		Loading		Unloading	
			Average	Peak	Average	Peak	Average	Peak
Gearless bulk carrier								
0–9,999	70	110						
10,000–34,999	70	110	110	600	110	600	110	600
35,000–59,999	130	150	300	600	300	600	300	600
60,000–99,999	260	240	300	600	300	600	300	600
100,000–199,999	260	240	300	600	300	600	300	600
200,000+	260	240	300	600	300	600	300	600
Geared bulk carrier								
0–9,999	70	110						
10,000–34,999	70	110	110	600	110	110	110	110
35,000–59,999	130	150	300	600	300	1200	300	1200
60,000+	260	240	300	600	300	1200	300	1200
Self-unloader								
0–9,999	70	110						
10,000–34,999	70	110	110	600	110	600	110	110
35,000–59,999	130	150	300	600	300	600	1300	1600
60,000–99,999	260	240	300	600	300	600	1300	1600
100,000–199,999	260	240	300	600	300	600	1300	1600
200,000+	260	240	300	600	300	600	1300	1600
Cement carrier								
0–9,999	70	110	200	200	200	600	200	400
10,000–34,999	70	110	200	200	200	600	200	400
35,000–59,999	130	150	200	200	200	600	200	400
60,000–99,999	260	240	240	240	240	600	240	400
100,000–199,999	260	240	240	240	240	600	240	400
200,000+	260	240	240	240	240	600	240	400
Chemical tanker								
0–4,999	670	110						
5000–9,999	670	330	330	330	330	1100	330	1100
10,000–19,999	1000	330	330	330	330	1100	330	1100
20,000–39,999	1350	790	790	790	790	1100	790	1100
40,000+	1530	790	790	790	790	1100	790	1100
Gearless general cargo								
0–4,999	0	90						
5000–9,999	110	240						
10,000–19,999	150	720	240	240	240	240	240	240
20,000+	150	720	300	600	300	600	300	600
Geared general cargo								
0–4,999	0	90						
5000–9,999	110	240						
10,000–19,999	150	720	300	720	720	720	720	720
20,000+	150	720	300	720	720	1200	720	1200
Oil tankers								
0–4,999	500	250						
0–9,999	750	375	375	1100	375	1100	375	1100
10,000–19,999	1250	690	690	1100	690	1100	690	1100
20,000–59,999	2700	720	720	1100	720	1100	720	1100
60,000–79,999	3250	620	620	1100	620	1100	620	1100
80,000–119,999	4000	800	800	1100	800	1100	800	1100
120,000–199,999	6500	2500						
200,000+	7000	2500						
Other liquid tankers								
0–999	1000	500						
1000+	1000	500						

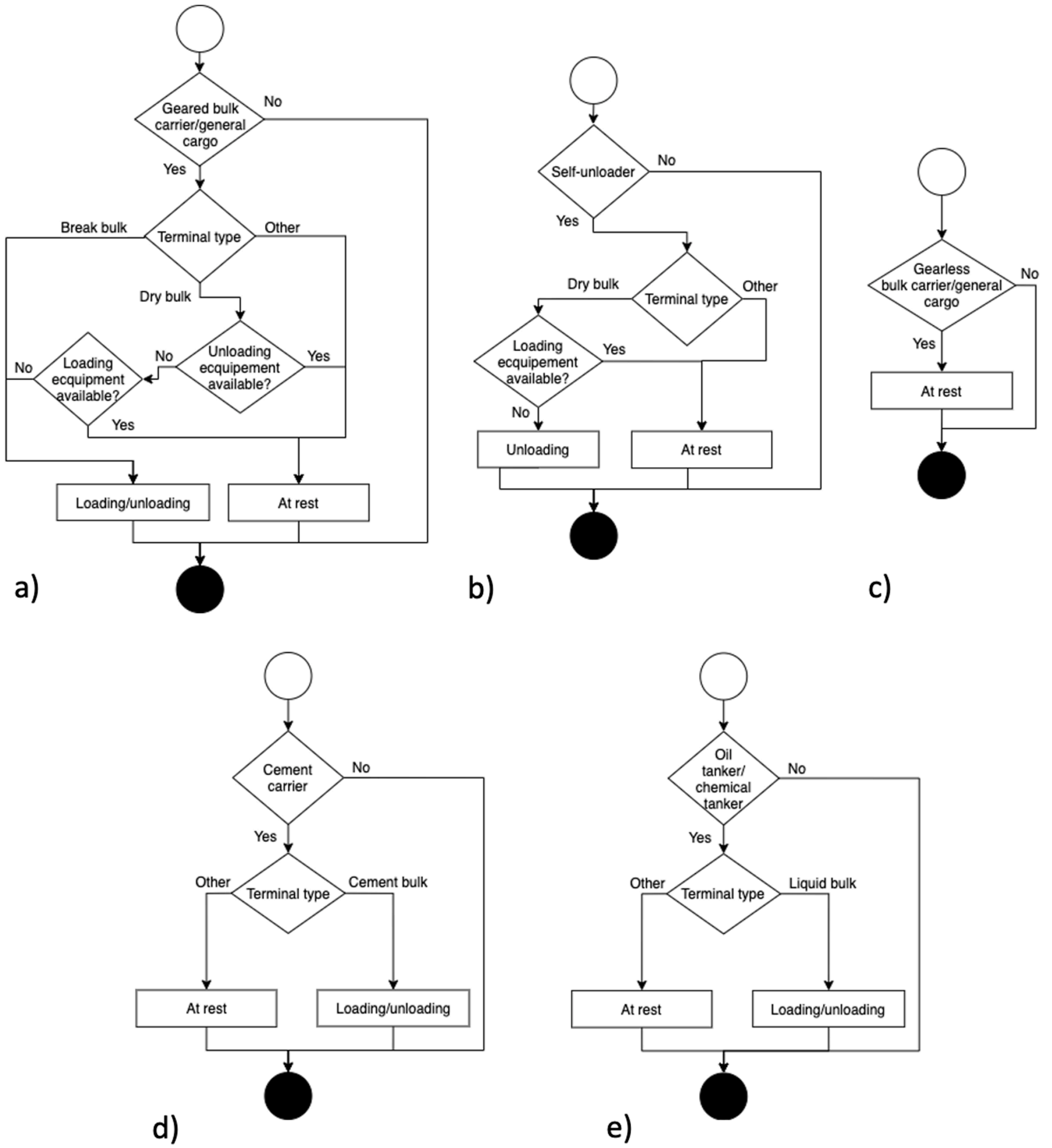

Fig. 14. Flow chart of operating mode at berth determination algorithm in function of geographical information for a) Geared bulk carrier and geared general cargo b) Self-unloader c) Gearless bulk carrier and gearless general cargo d) Cement carrier e) Oil tanker and chemical tanker

Appendix C

The following presents the list of acronyms.

Table 7
List of acronyms.

Acronym	Meaning
AE	Auxiliary engines

(*continued on next page*)

Table 7 (*continued*)

Acronym	Meaning
AIS	Automatic identification system
C	Coal
CAPEX	Capital expenditure
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent
DWT	Dead weight tonnage
US EPA	United States Environmental Protection Agency
GHG	Greenhouse gas
H	Hydropower
ICCT	International Council on Clean Transportation
IMO	International Maritime Organization
MCR	Maximum continuous rating
MDO	Marine diesel oil
ME	Main engine
N	Nuclear
NG	Natural gas
NO_x	Nitrogen oxides
OPEX	Operational expenditure
PM	Particulate matter
SOG	Speed over ground
SO_x	Sulfur oxides
VBP	Vessel boarding program

Appendix D. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.trd.2024.104230.

References

Adamo, F., Andria, G., Cavone, G., De Capua, C., Lanzolla, A.M.L., Morello, R., Spadavecchia, M., 2014. Estimation of ship emissions in the port of Taranto. Measurement 47, 982–988. https://doi.org/10.1016/j.measurement.2013.09.012.

Agrawal, H., Malloy, Q.G.J., Welch, W.A., Wayne Miller, J., Cocker, D.R., 2008. In-use gaseous and particulate matter emissions from a modern ocean going container vessel. Atmos. Environ. 42, 5504–5510. https://doi.org/10.1016/j.atmosenv.2008.02.053.

Alver, F., Saraç, B.A., Alver Şahin, Ü., 2018. Estimating of shipping emissions in the Samsun Port from 2010 to 2015. Atmos. Pollut. Res. 9, 822–828. https://doi.org/10.1016/j.apr.2018.02.003.

Bazari, Z., longva, T., 2011. Assessment of IMO Mandated Energy Efficiency Measures for International Shipping (MEPC 63/INF.2).

Berechman, J., Tseng, P.-H., 2012. Estimating the environmental costs of port related emissions: The case of Kaohsiung. Transp. Res. Part Transp. Environ. 17, 35–38. https://doi.org/10.1016/j.trd.2011.09.009.

Bojić, F., Gudelj, A., Bošnjak, R., 2022. Port-related shipping gas emissions—A systematic review of research. Appl. Sci. 12, 3603. https://doi.org/10.3390/app12073603.

Buhaug, Ø., Corbett, J.J., Endersen, Ø., Eyring, V., Faber, J., Hanayama, S., Lee, D.S., Lee, D., Lindstad, H., Markowska, A.Z., Mjelde, A., Nelissen, D., Nilsen, J., Pålsson, C., Winebrake, J.J., Wu, W., Yoshida, K., 2009. Second IMO GHG Study 2009.

Campbell, M., Cooper, M.J., Friedman, K., Anderson, W.P., 2015. The economy as a driver of change in the Great Lakes–St. Lawrence River basin. J. Gt. Lakes Res., The Great Lakes Futures Project: Using Scenario Analysis to Develop a Sustainable Socio-ecologic Vision for the Great Lakes-St. Lawrence River Basin 41, 69–83. https://doi.org/10.1016/j.jglr.2014.11.016.

CARB, 2005. California Air Resources Board: Oceangoing Ship Survey, Summary of Results.

CARB, 2006. Diesel Particulate Matter Exposure Assessment Study for the Ports of Los Angeles and Long Beach.

Chen, S., Meng, Q., Jia, P., Kuang, H., 2021. An operational-mode-based method for estimating ship emissions in port waters. Transp. Res. Part Transp. Environ. 101, 103080 https://doi.org/10.1016/j.trd.2021.103080.

Chen, D., Zhao, Y., Nelson, P., Li, Y., Wang, X., Zhou, Y., Lang, J., Guo, X., 2016. Estimating ship emissions based on AIS data for port of Tianjin. China. Atmos. Environ. 145, 10–18. https://doi.org/10.1016/j.atmosenv.2016.08.086.

ClassNK [WWW Document], 2018. URL https://www.classnk.de/hp/en/index.html (accessed 12.6.22).

Cofala, J., Amann, M., Heyes, C., Wagner, F., Klimont, Z., Posch, M., Schoepp, W., Tarasson, L., Whall, C., Stavrakaki, A., 2007. Analysis of Policy Measures to Reduce Ship Emissions in the Context of the Revision of the National Emissions Ceilings Directive (Other). Final Report; submitted to Unit ENV/C1, DG Environment European Commission, Belgium [2007].

Cooper, D., 2003. Exhaust emissions from ships at berth. Atmos. Environ. 37, 3817–3830. https://doi.org/10.1016/S1352-2310(03)00446-1.

Cooper, D., 2005. HCB, PCB, PCDD and PCDF emissions from ships. Atmos. Environ. 39, 4901–4912. https://doi.org/10.1016/j.atmosenv.2005.04.037.

Cooper, D., Gustafsson, T., 2004. Methodology for calculating emissions from ships: 2. Emission factors for 2004 reporting.

CSL, 2023. Pneumatic Self-Unloaders | CSL Group [WWW Document]. URL https://www.cslships.com/en/our-operations/self-unloaders/how-it-works/pneumatic-self-unloaders (accessed 2.28.23).

Dalsøren, S.B., Eide, M.S., Endresen, Ø., Mjelde, A., Gravir, G., Isaksen, I.S.A., 2009. Update on emissions and environmental impacts from the international fleet of ships: The contribution from major ship types and ports. Atmos. Chem. Phys. 9, 2171–2194. https://doi.org/10.5194/acp-9-2171-2009.

Daniel, H., Trovão, J.P.F., Williams, D., 2022. Shore power as a first step toward shipping decarbonization and related policy impact on a dry bulk cargo carrier. eTransportation 11, 100150. https://doi.org/10.1016/j.etran.2021.100150.

Dawoud, S.M., 2021. Techno-economic and sensitivity analysis of hybrid electric sources on off-shore oil facilities. Energy 227, 120391. https://doi.org/10.1016/j.energy.2021.120391.

Deniz, C., Kilic, A., Cıvkaroglu, G., 2010. Estimation of shipping emissions in Candarli Gulf. Turkey. Environ. Monit. Assess. 171, 219–228. https://doi.org/10.1007/s10661-009-1273-2.

Dolphin, M.J., Melcer, M., 2008. Estimation of ship dry air emissions. Nav. Eng. J. 120, 27–36. https://doi.org/10.1111/j.1559-3584.2008.00151.x.

ECCC, 2019. PRICING CARBON POLLUTION.

ECCC, 2020. Canada's air pollutant emissions inventory report. : En81-30E-PDF - Government of Canada Publications - Canada.ca.

ECCC, 2022a. Marine Emissions Inventory Tool [WWW Document]. URL https://www.canada.ca/en/environment-climate-change/services/managing-pollution/marine-emissions-inventory-tool.html (accessed 4.19.23).

ECCC, 2022b. Canada's official greenhouse gas inventory [WWW Document]. URL https://www.canada.ca/en/environment-climate-change/services/climate-change/greenhouse-gas-emissions/inventory.html (accessed 12.9.22).

EEA, 2002. Emission Inventory Guidebook - 3rd edition October 2002 UPDATE.

EEA, 2016. EMEP/EEA air pollutant emission inventory guidebook - 2016 — European Environment Agency (Publication).

EIA, 2021. Electric Power Annual 2021 - U.S. Energy Information Administration [WWW Document]. URL https://www.eia.gov/electricity/annual/ (accessed 12.9.22).

Endresen, Ø., Sørgård, E., Sundet, J.K., Dalsøren, S.B., Isaksen, I.S.A., Berglen, T.F., Gravir, G., 2003. Emission from international sea transportation and environmental impact. J. Geophys. Res. Atmos. 108 https://doi.org/10.1029/2002JD002898.

ENTEC, 2002. ENTEC Report: Preliminary assignment of ship emissions to European Countries, final report.

ENTEC, 2005. Quantification of emissions from ships associated with ship movements between ports in the European community (final report).

ENTEC, 2007. Ship Emissions Inventory – Mediterranean Sea, Final Report.

ENTEC, 2010. UK Ship Emissions Inventory. Department for Environment, Food and Rural Affairs (Defra), Nobel House, 17 Smith Square, London SW1P 3JR helpline@defra.gsi.gov.uk.

Ericsson, P., Fazlagic, I., 2008. Shore side power supply, Master of Science Thesis, Chalmers University of technology, Goteborg Sweden.

Faber, J., Hanayama, S., Shuang, Z., Paula, P., Comer, B., Hauerhof, E., Schim van der Loeff, W., Zhang, Y., Hiroyuko, K., Adachi, M., Jean-Marc, B., Connor, G., Gong, Z., Hirata, K., Hummels, D., Kleijn, A., Lee, D.S., Liu, Y., Lucchesi, A., Muraoka, E., Osipova, L., Qian, H., Rutherford, D., Suárez de la Fuente, S., Yuan, H., Velandia Perico, C., Wu, L., Sun, D., Yoo, D.-H., Xing, H., 2020. REDUCTION OF GHG EMISSIONS FROM SHIPS Fourth IMO GHG Study 2020 – Final report.

Flodstroem, E., 1997. Energy and emission factors for ships in operation.

Fuentes García, G., Sosa Echeverría, R., Baldasano Recio, J.M., W. Kahl, J.D., Granados Hernández, E., Alarcón Jímenez, A.L., Antonio Durán, R.E., 2021. Atmospheric Emissions in Ports Due to Maritime Traffic in Mexico. J. Mar. Sci. Eng. 9, 1186. Doi: 10.3390/jmse9111186.

Gan, L., Che, W., Zhou, M., Zhou, C., Zheng, Y., Zhang, L., Rangel-Buitrago, N., Song, L., 2022. Ship exhaust emission estimation and analysis using Automatic Identification System data: The west area of Shenzhen port, China, as a case study. Ocean Coast. Manag. 226, 106245 https://doi.org/10.1016/j.ocecoaman.2022.106245.

Godin, P., 2019. Hydro-Québec 2020 Les défis du siècle de la transition énergétique.

Goldsworthy, L., Goldsworthy, B., 2015. Modelling of ship engine exhaust emissions in ports and extensive coastal waters based on terrestrial AIS data – An Australian case study. Environ. Model. Softw. 63, 45–60. https://doi.org/10.1016/j.envsoft.2014.09.009.

Google Earth, 2022. Google Earth 2022.

Government of Canada, F. and O.C., 2019. Canadian Coast Guard [WWW Document]. URL https://www.garde-cotiere.gc.ca/index-eng.html (accessed 1.30.23).

Government of Quebec, 2023. Véhicules en circulation - Documentation sur les variables - Données Québec [WWW Document]. URL https://www.donneesquebec.ca/recherche/dataset/vehicules-en-circulation/resource/00ea3ac1-da3c-4ece-aa8c-a2e88529447b (accessed 4.6.23).

Great Lakes Seaway Review, 2022. Greenwood's Guide To Great Lakes Shipping.

Gutierrez-Romero, J.E., Esteve-Pérez, J., Zamora, B., 2019. Implementing Onshore Power Supply from renewable energy sources for requirements of ships at berth. Appl. Energy 255, 113883. https://doi.org/10.1016/j.apenergy.2019.113883.

Halff, A., Younes, L., Boersma, T., 2019. The likely implications of the new IMO standards on the shipping industry. Energy Policy 126, 277–286. https://doi.org/10.1016/j.enpol.2018.11.033.

Harati Mokhtari, A., Wall, A., Brooks, P., Wang, J., 2008. Automatic Identification System (AIS): A Human Factors Approach.

HC, 2022. Health benefits per tonne of air pollutant emissions reduction : region-, sector-, and pollutant-specific estimates for two Canadian regions.: H144-111/2022E-PDF - Government of Canada Publications - Canada.ca.

IEA, 2022. Renewables 2021 – Analysis.

IESO, 2022. Hourly Ontario Energy Price (HOEP) [WWW Document]. URL https://www.ieso.ca/en/Power-Data/Price-Overview/Hourly-Ontario-Energy-Price (accessed 1.12.23).

IMAR, 2022. L'électrification des quais au Québec.

IMO, 2018. MEPC.308(73) - 2018 Guidelines on the Method of Calculation of the Attained Energy Efficiency Design Index (EEDI) for New Ships.

IMO, 2020. Fourth Greenhouse Gas Study 2020.

IMO, 2023. IMO | Global Integrated Shipping Information System (GISIS) [WWW Document]. URL https://gisis.imo.org/Members/Default.aspx (accessed 1.30.23).

Innes, A., Monios, J., 2018. Identifying the unique challenges of installing cold ironing at small and medium ports – The case of aberdeen. Transp. Res. Part Transp. Environ. 62, 298–313. https://doi.org/10.1016/j.trd.2018.02.004.

IPCC, 2013. AR5 Climate Change 2013: The Physical Science Basis — IPCC [WWW Document]. URL https://www.ipcc.ch/report/ar5/wg1/ (accessed 1.22.23).

IVL, 2004. Methodology for calculating emissions from ships: 1. Update of emission factors.

Jalkanen, J.-P., Johansson, L., Kukkonen, J., Brink, A., Kalli, J., Stipa, T., 2012. Extension of an assessment model of ship traffic exhaust emissions for particulate matter and carbon monoxide. Atmos. Chem. Phys. 12, 2641–2659. https://doi.org/10.5194/acp-12-2641-2012.

Jalkanen, J.-P., Johansson, L., Kukkonen, J., 2014. A comprehensive inventory of the ship traffic exhaust emissions in the Baltic Sea from 2006 to 2009. Ambio 43, 311–324. https://doi.org/10.1007/s13280-013-0389-3.

Joseph, J., Patil, R.S., Gupta, S.K., 2009. Estimation of air pollutant emission loads from construction and operational activities of a port and harbour in Mumbai, India. Environ. Monit. Assess. 159, 85–98. https://doi.org/10.1007/s10661-008-0614-x.

Korkmaz, S.A., Erginer, K.E., Yuksel, O., Konur, O., Colpan, C.O., 2023. Environmental and economic analyses of fuel cell and battery-based hybrid systems utilized as auxiliary power units on a chemical tanker vessel. Int. J. Hydrog. Energy. Doi: 10.1016/j.ijhydene.2023.01.320.

Kristensen, H., 2012. Energy Demand and Exhaust Gas Emissions of Marine Engines.

Lack, D.A., Corbett, J.J., Onasch, T., Lerner, B., Massoli, P., Quinn, P.K., Bates, T.S., Covert, D.S., Coffman, D., Sierau, B., Herndon, S., Allan, J., Baynard, T., Lovejoy, E., Ravishankara, A.R., Williams, E., 2009. Particulate emissions from commercial shipping: Chemical, physical, and optical properties. J. Geophys. Res. 114, D00F04. https://doi.org/10.1029/2008JD011300.

Lloyd's Register, 1995. Marine Exhaust Emissions Research Programme.

MarineCadastre, 2023. MarineCadastre.gov | Vessel Traffic Data [WWW Document]. URL https://marinecadastre.gov/ais/ (accessed 1.30.23).

Martin Associates, 2018. ECONOMIC IMPACTS OF MARITIME SHIPPING in the GREAT LAKES - ST. LAWRENCE REGION.

McArthur, D.P., Osland, L., 2013. Ships in a city harbour: An economic valuation of atmospheric emissions. Transp. Res. Part Transp. Environ. 21, 47–52. https://doi.org/10.1016/j.trd.2013.02.004.

Meng, Z., Comer, B., 2022. Great Lakes-St. Lawrence Seaway ship emissions inventory, 2019.

Ng, S.K.W., Loh, C., Lin, C., Booth, V., Chan, J.W.M., Yip, A.C.K., Li, Y., Lau, A.K.H., 2013. Policy change driven by an AIS-assisted marine emission inventory in Hong Kong and the Pearl River Delta. Atmos. Environ. 76, 102–112. https://doi.org/10.1016/j.atmosenv.2012.07.070.

Nicewicz, G., Tarpanowicz, D., 2012. Assessment of marine auxiliary engines load factor in ports. Manag. Syst. Prod. Eng. Nr 3 (7), 12–17.

Nunes, R.A.O., Alvim-Ferraz, M.C.M., Martins, F.G., Sousa, S.I.V., 2017. The activity-based methodology to assess ship emissions - A review. Environ. Pollut. 231, 87–103. https://doi.org/10.1016/j.envpol.2017.07.099.

Nunes, R.A.O., Alvim-Ferraz, M.C.M., Martins, F.G., Sousa, S.I.V., 2017. Assessment of shipping emissions on four ports of Portugal. Environ. Pollut. 231, 1370–1379. https://doi.org/10.1016/j.envpol.2017.08.112.

Olmer, N., Comer, B., Roy, B., Mao, X., Rutherford, D., 2017. Greenhouse gas emissions from global shipping, 2013–2015.

Petzold, A., Hasselbach, J., Lauer, P., Baumann, R., Franke, K., Gurk, C., Schlager, H., Weingartner, E., 2008. Experimental studies on particle emissions from cruising ship, their characteristic properties, transformation and atmospheric lifetime in the marine boundary layer. Atmos. Chem. Phys. 8, 2387–2403. https://doi.org/10.5194/acp-8-2387-2008.

Progiou, A.G., Bakeas, E., Evangelidou, E., Kontogiorgi, Ch., Lagkadinou, E., Sebos, I., 2021. Air pollutant emissions from Piraeus port: External costs and air quality levels. Transp. Res. Part Transp. Environ. 91, 102586 https://doi.org/10.1016/j.trd.2020.102586.

Sandmo, T., 2016. The Norwegian Emission Inventory 2016. Documentation of methodologies for estimating emissions of greenhouse gases and long-range transboundary air pollutants (Working paper), 301. Statistisk sentralbyrå.

Saraçoğlu, H., Deniz, C., Kılıç, A., 2013. An investigation on the effects of ship sourced emissions in Izmir Port. Turkey. Sci. World J. 2013, 1–8. https://doi.org/10.1155/2013/218324.

Sarvi, A., Fogelholm, C.-J., Zevenhoven, R., 2008. Emissions from large-scale medium-speed diesel engines: 1. Influence of engine operation mode and turbocharger. Fuel Process. Technol. 89, 510–519. https://doi.org/10.1016/j.fuproc.2007.10.006.

SCG, 2005. THE PORT OF LOS ANGELES BASELINE AIR EMISSIONS INVENTORY - 2001.

SCG, 2008. THE PORT OF LOS ANGELES INVENTORY OF AIR EMISSIONS FOR CALENDAR YEAR 2008 - REVISED [WWW Document]. URL https://www.portoflosangeles.org/environment/air-quality/air-emissions-inventory (accessed 12.2.22).

SCG, 2009. THE PORT OF LOS ANGELES INVENTORY OF AIR EMISSIONS FOR CALENDAR YEAR 2009.

SCG, 2012. THE PORT OF LOS ANGELES INVENTORY OF AIR EMISSIONS FOR CALENDAR YEAR 2012 - Vessel Boarding Program.

SCG, 2019. San Pedro Bay Ports Emissions Inventory Methodology Report - Versio 1.

SCG, 2021. San Pedro Bay Ports Emissions Inventory Methodology Report - Version 2.

SCG, 2022. San Pedro Bay Ports Emissions Inventory Methodology Report - Versio 3a.

Sinha, P., Hobbs, P.V., Yokelson, R.J., Christian, T.J., Kirchstetter, T.W., Bruintjes, R., 2003. Emissions of trace gases and particles from two ships in the southern Atlantic Ocean. Atmos. Environ. 37, 2139–2148. https://doi.org/10.1016/S1352-2310(03)00080-3.

Smith et al., 2014. REDUCTION OF GHG EMISSIONS FROM SHIPS Third IMO GHG Study 2014 – Final Report [WWW Document]. URL (accessed 6.2.20).

Smith, T.W.P., Jalkanen, J.P., Anderson, B.A., Corbett, J.J., Faber, J., Hanayama, S., O'Keeffe, E., Parker, S., Johansson, L., Aldous, L., Raucci, C., Traut, M., Ettinger, S., Nelissen, D., Lee, D.S., Ng, S., Agrawal, A., Winebrake, J.J., Hoen, M., Chesworth, S., Pandey, A., 2015. Third IMO Greenhouse Gas Study 2014. International Maritime Organization.

Spengler, T., Tovar, B., 2022. Environmental valuation of in-port shipping emissions per shipping sector on four Spanish ports. Mar. Pollut. Bull. 178, 113589 https://doi.org/10.1016/j.marpolbul.2022.113589.

Stolz, B., Held, M., Georges, G., Boulouchos, K., 2021. The CO2 reduction potential of shore-side electricity in Europe. Appl. Energy 285, 116425. https://doi.org/10.1016/j.apenergy.2020.116425.

Sun, X., Tian, Z., Malekian, R., Li, Z., 2018. Estimation of vessel emissions inventory in Qingdao Port based on big data analysis. Symmetry 10, 452. https://doi.org/10.3390/sym10100452.

TC, U.S. Army Corps of Engineers, U.S. Department of Transportation, The St. Lawrence Seaway Management Corporation, Saint Lawrence Seaway Development Corporation, Environment Canada, U.S. Fish and Wildlife Service, 2007. Great Lakes-St. Lawrence Seaway Study | Great Lakes St. Lawrence Seaway Development Corporation.

The Marine Environment Protection Committee, I., 2022. MEPC.348(78).

Toscano, D., Murena, F., 2019. Atmospheric ship emissions in ports: A review. Correlation with data of ship traffic. Atmos. Environ. X 4, 100050 https://doi.org/10.1016/j.aeaoa.2019.100050.

Trozzi, C., 2010. Emission estimate methodology for maritime navigation 12.

Tu, E., Zhang, G., Rachmawati, L., Rajabally, E., Huang, G.-B., 2018. Exploiting AIS data for intelligent maritime navigation: A comprehensive survey from data to methodology. IEEE Trans. Intell. Transp. Syst. 19, 1559–1582. https://doi.org/10.1109/TITS.2017.2724551.

Tzannatos, E., 2010. Ship emissions and their externalities for the port of Piraeus – Greece. Atmos. Environ. 44, 400–407. https://doi.org/10.1016/j.atmosenv.2009.10.024.

UN, 2015. The Paris Agreement.

UNCTAD, 2023. Port call and performance statistics: time spent in ports, vessel age and size, annual.

US EPA, 2006. Current Methodologies and Best Practices in Preparing Port Emission Inventories. (No. PB2006112993). ICF Consulting, Fairfax, VA.; Environmental Protection Agency, Washington, DC. Office of Policy.

US EPA, 2009. Current Methodologies in Preparing Mobile Source Port-Related Emission Inventories Final Report April 2009 [WWW Document]. URL https://www.epa.gov/moves/current-methodologies-preparing-mobile-source-port-related-emission-inventories-final-report (accessed 12.2.22).

US EPA, 2020. eGrid - CO2 total output emission rate (lb/MWh) 2020 [WWW Document]. URL https://www.epa.gov/egrid/data-explorer (accessed 12.9.22).

US EPA, O., 2020. Port Emissions Inventory Guidance [WWW Document]. URL https://www.epa.gov/state-and-local-transportation/port-emissions-inventory-guidance (accessed 12.2.22).

US EPA, O., 2022. Shore Power Technology Assessment at U.S. Ports [WWW Document]. US EPA. URL https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P1016C86.pdf.

V, K., Z, P., J, Č., 2021. Estimating Shipping Emissions – A Case Study for Cargo Port of Zadar, Croatia. TransNav Int. J. Mar. Navig. Saf. Od Sea Transp. 15.

Villalba, G., Gemechu, E.D., 2011. Estimating GHG emissions of marine ports—The case of Barcelona. Energy Policy 39, 1363–1368. https://doi.org/10.1016/j.enpol.2010.12.008.

Woo, D., Im, N., 2021. Spatial analysis of the ship gas emission inventory in the Port of Busan using bottom-up approach based on AIS data. J. Mar. Sci. Eng. 9, 1457. https://doi.org/10.3390/jmse9121457.

Yau, P.S., Lee, S.C., Corbett, J.J., Wang, C., Cheng, Y., Ho, K.F., 2012. Estimation of exhaust emission from ocean-going vessels in Hong Kong. Sci. Total Environ. 431, 299–306. https://doi.org/10.1016/j.scitotenv.2012.03.092.

Yoo, Y., Moon, B., Kim, T.-G., 2022. Estimation of pollutant emissions and environmental costs caused by ships at Port: A case study of Busan Port. J. Mar. Sci. Eng. 10, 648. https://doi.org/10.3390/jmse10050648.

Zhao, L., Shi, G., Yang, J., 2018. Ship trajectories pre-processing based on AIS data. J. Navig. 71, 1210–1230. https://doi.org/10.1017/S0373463318000188.

Zis, T., 2019. Prospects of cold ironing as an emissions reduction option. Transp. Res. Part Policy Pract. 119, 82–95. https://doi.org/10.1016/j.tra.2018.11.003.

Zis, T., Cullinane, K., 2020. The desulphurisation of shipping: Past, present and the future under a global cap. Transp. Res. Part Transp. Environ. 82, 102316 https://doi.org/10.1016/j.trd.2020.102316.