Data study into onshore power demand highlights strategic implications for shore power rollout and emission reduction in ports

Green Deal Validation – NO_x shore power

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Summary

AFIR and Fuel EU Maritime legislation require increased use of onshore power supply (OPS) in European ports to meet the sustainability goals of maritime transport. OPS is considered an effective way to reduce greenhouse gas (GHG) and pollutant emissions, such as NO_x, in port areas. A challenge for ports is the appropriate dimensioning of OPS infrastructure. The available infrastructure should be sufficient to facilitate the vessels that are obligated to use it, but since energy contract tariffs are based on the maximum available power, over-dimensioning the power supply infrastructure results in an increase in CAPEX and OPEX for both shipowners and port authorities. However, data on energy use of maritime vessels at berth is scarce, and only publicly available as averages over ship segments during an entire port stay. This validation report presents a comprehensive analysis of operational profiles in different ship segments, offering critical information on the power demand of these vessels. Data was acquired through direct collaboration with ship owners, operators, and port authorities, enabling the collection of high-resolution operational profiles and onboard equipment usage patterns. The analysis reveals significant variability in power demand based on operational behaviour. By aligning OPS capacity with actual demand patterns, ports can optimise investments and installed power. Significant differences were found between the collected operational profile and both the figures reported by the International Maritime Organization (IMO) and the emission factors used in the Emission Inventory and Monitoring system for the Shipping Sector (EMS). These findings underscore the need for enhanced monitoring and reporting protocols, particularly for fuel consumption rates and emissions at berth, and support the development of targeted mitigation strategies to reduce environmental impact in port areas.

Contents

1 Introduction

1.1 General

1.1.1 Green Deal

Firm objectives have been set by the International Maritime Organization (IMO) for shipping and yet the Dutch Green Deal goes one step further. The IMO agreements mean that the transport performance by seagoing vessels must improve to such an extent that CO_2-emissions per tonne-kilometre will be reduced by an average of 40-60% by 2030. The Green Deal aims for an absolute reduction of 70-100% in 2050 compared to 2008, regardless of market growth.

These ambitious goals call for solutions that can be applied today, because ships that are put into service today will most likely still be operational in 2050. The potential of available sustainable maritime solutions is great and is constantly expanding, but none of the available solutions is suitable for all ship types and in all operational conditions. The decision to opt for a sustainable solution also depends on the business case in which the ship must be able to operate. Currently, there is a lack of objective information on the match between sustainable solutions and type of business case.

In addition to direct CO_2-emissions, the emissions of greenhouse gases CH_4 and N_2O and air-polluting emissions such as NO_x, NH_3, SO_x and particulate matter are of great importance. The emissions of NO_x, SO_x and particulate matter from shipping are relatively high and are decreasing slowly due to insufficiently effective emission legislation and slow fleet renewal.

The diversity of available sustainable maritime solutions makes it difficult to determine which solution is most suitable for application as this depends on many factors. For example, each solution differs in the required space on board, the layout of the ship and integration with other systems, as well as for the costs and earning capacity of the ship itself. There is a large array of available sustainable solutions for various ship types, for various operational conditions and lengths of shipping routes. It is therefore important that the effects of these solutions are made transparent in an independent manner and that through validation reliable information is collected so that these solutions can be weighed against each other (ref. NL Green Deal art.12 paragraph 3: “Knowledge institutions will work with the industry to provide independent insight into and validate the effects of the sustainable maritime solutions so that comparison of these solutions is possible and it is easier for shipowners and financiers to compare.”).

The results of the performed validations provide reliable information for all parties in the maritime chain, making it easier to choose sustainable solutions.

1.1.2 Validation Process

Transparency towards all parties in the maritime chain (from ship owners, ship operators and other logistics operators, shippers, financiers, suppliers, shipyards, to government) is important in the implementation of these validations. The sector itself is investigating which sustainable maritime solutions have the greatest potential to accelerate the energy transition. The technologies with the greatest potential are then validated at independent knowledge institutions.

We call this form a cluster study; the sector is represented in this by KVNR and NMT, the knowledge institutions involved are MARIN and TNO, possibly supplemented by an external party if this is necessary for the implementation of a concrete validation case. Transparency is achieved by making the results public through reports that present an overview of how the various sustainable maritime solutions, grouped by theme, perform in terms of social impact, technical impact and economic impact.

1.1.3 Green Deal validation

The Green Deal validation program of the Ministry of Infrastructure and Water Management offers the opportunity to independently review reduction measures. The marine sector, represented by KVNR and NMT, plays an important role in putting forward the key solutions for GHG reductions which can be implemented or scaled up in the near future. KVNR and NMT consult the sector (technology providers and ship owners) to identify the most important techniques to validate. Thereafter, the contacts are handed over to the knowledge institute that is most knowledgeable, which can also be both, making it a joint validation project.

The validation needs to include the following aspects:

- **Economic aspects**; this will be briefly highlighted in section 1.2.
- **Operational aspects**; this will be briefly highlighted in section 1.2.
- **Regulatory framework and technical standards**; international maritime regulations and standards that promote the adoption of shore power systems.
- **Applicability to the maritime fleet**; related to the six reference ships identified in the Green Deal (See Table 1.1).
- **Environmental impact**; impact on reduction of GHG and pollutant emissions. This is the core of the validation: the provider claims an emission reduction technique, which is validated by an independent study.
- **Scalability and future proofness**; with respect to the scalability of the technology over multiple regions and its potential usage in the future.

	Lengte m	Breedte m	Geinstal. vermogen kW	Waterver-plaatsing m³	DWT ton	Auto-nomie dagen	Operationele conditie	Snelheid kts	Tijdsdeel %	Vermogen kW	Huidig geïnstalleerd systeem Huidige brandstof
General Cargo											**4-stroke ICE-direct, medium speed**
	112	18.2	4290	12800	9216	30	transit	13	55	3861	**MGO**
							manoeuvreren	5	10	557.7	
							in haven	0	35	0	
Sleep boot											**Z-drive ICE-direct, high speed**
	32	12	5000	1140	285	15	transit	12.5	25	4275	**Diesel**
							slepen	4	25	4275	
							wachten/haven	0-2	50	500	
Offshore supply											**4-stroke ICE-electric, high speed**
	82	17.5	6000	5800	2900	5	transit	14.5	45	5130	**MGO**
							manoeuvreren	2	25	600	
							in haven	0	35	0	
Crew tender catamaran											**4-stroke ICE-direct, high speed**
	25	9	2100	90	20	3	transit	23.5	40	1850	**Diesel**
							manoeuvreren + on-/off loading	5	10	210	
							in haven	0	50	0	
Baggerschip											**4-stroke ICE-direct, medium speed**
	125.00	28.00	12000	29750	21000	14	Transit	16	22	7814	**MGO**
							baggeren	2	31	8730	
							Varen,dumpen door pomp	1	12	5567	
							varen, dumpen door deuren	1	14	6126	
							lossen aan kade	0	12	9948	
							in haven	0	10	0	
Superjacht											**4-stroke ICE-electric-hybrid, high speed**
	100	17.2	13000	4600	460	14	top snelheid	22	5	12300	**Diesel**
							cruise snelheid	18	10	6450	
							endurance snelheid	12	20	2550	
							manoeuvreren	4	10	1250	
							voor anker	0	20	600	
							in haven	0	35	0	

Table 1.1: Green Deal Validation reference vessels and their mission profiles. For dredgers and yachts, the hotel-load is accounted for. For the transport vessels, the hotel-load is low and not included in these high-level mission profiles [1].

1.2 Technology specific introduction

1.2.1 Onshore Power Supply

Onshore Power Supply (OPS) is considered an effective way to reduce greenhouse gas and pollutant emissions in port areas. By supplying vessels with electric power from shore, generator sets do not have to be used to power the on-board systems during the port visit. Maritime shipping has a strong impact on local pollutant emissions, particularly in port areas. This primarily concerns emissions from ships that are manoeuvring or stationary in port areas. For example, in the Port of Rotterdam, the emissions of stationary and manoeuvring seagoing vessels account for more than 78% of the total transport related emissions in the port area [2]. NO_x emission reductions can be achieved through after-treatment technologies, the use of alternative energy carriers, and the implementation of OPS [3]. The implementation of OPS is the focus of this research. In the following, we briefly explore the economic and operational dimensions of Onshore Power Supply (OPS), before outlining the key challenges that hinder efficient rollout of OPS connections. These challenges form the foundation of the validation study presented in this work.

Economic aspects

The implementation of shore power involves both capital (CAPEX) and operational (OPEX) expenditures on the ship and shore sides. Onshore, key components include the power source, frequency converters, transformers, and distribution networks, all culminating in the shore connection interface. Ship-side installations feature switchboard interfaces, transformers, receptacles, and control systems. CAPEX on the ship side is primarily driven by the shore power connection panel, main switchboard interface, and step-down transformer. Onshore CAPEX is influenced by infrastructure costs, including grid connection and equipment, as outlined in market studies [4]. OPEX includes electricity pricing, maintenance, and potential discounts, while savings are realised through reduced fuel consumption and generator maintenance.

Variable costs are affected by energy losses (e.g., 5% from frequency conversion), utilisation rates, and energy provider margins.

Operational aspects
Effective OPS implementation requires coordinated procedures between port operators and ship crews to ensure safe and synchronised power transfer. Connection types—blackout, parallel, or automated—vary in duration from 10 to 45 minutes depending on system complexity. Key operational considerations include electrical compatibility, standardised connectors, interlocking systems, and grounding protocols. Synchronisation between shore and ship power systems is essential to avoid blackouts. Procedures must align with IMO and IEC/IEEE 80005-1 standards, supported by trained personnel and emergency protocols tailored to ship and port infrastructure [5].

Challenge
In the Netherlands, a 2024 government inventory shows a growing number of shore power installations in both sea and inland ports, but also highlights the challenge of accurately estimating ships' power demand over time [6]. Currently, there is a lack of accurate knowledge on the fuel- or power demand of vessels in ports. In ports only averages are reported for different vessel types, cargo capacities, or weight sizes [7]. For instance, under the EU MRV (Monitoring, Reporting, Verification) Regulation , operators are required to report, among other metrics, their total fuel consumption at berth. However, these reports only provide absolute fuel (in tonnes) and do not include fuel consumption rates, making it challenging to directly translate the data into power demand. For the roll-out of OPS, it is important to have a validated bandwidth of this power demand in order to prevent over- or under-dimensioning for OPS infrastructure. Over-dimensioning infrastructure can lead to significantly increased costs, which rise disproportionately with higher installed peak power, and puts unnecessary strain on the electricity grid. Under-dimensioning risks operational inefficiencies and potentially slows down adoption of the technology and compliance with FuelEU Maritime [8] and AFIR [9] obligations. Accurate forecasts of power demand are important to ensure that berthing vessels can effectively utilise OPS.

Independent validation of shore power's effectiveness is crucial, especially as providers claim substantial emission reductions. With thousands of ships visiting Dutch ports annually, even conservative estimates suggest that widespread adoption of shore power could lead to significant reductions in CO_2- and NO_x-emissions. Currently, average power data at berth is reported by International Maritime Organization (IMO) [10]. We as TNO also published fuel rate factors for vessels at berth [11]. These factors are currently used in the Emission Inventory and Monitoring for the Shipping Sector (EMS). These factors are provided in Appendix B. Within this study, we validate the reported figures that provide a general indication of onshore power demand, by providing additional data insights on operations over time and computing fuel rate factors based on acquired data. This validation can refine models of energy consumption per ship segment and further highlight the environmental benefits of shore power.

This work focusses on getting insights in the power demand of multiple sea-going vessels and investigates the differences and spread of power demand over time for different ship segments. This report shines light on the central research question: What are the temporal characteristics of energy and power demand of berthed sea-going vessels? To address this, the study examines how vessel type, size and operation affects the time-resolved power demand during port visits. More specifically, the analysis explores several interrelated factors that influence demand variability and operational behaviour during port stays. Furthermore, the impact of power distributions on CO_2- and NO_x-emissions is discussed, providing insights into the environmental implications of OPS infrastructure planning.

2 Regulatory framework and technology standards

2.1 Regulatory framework

The deployment and adoption of OPS systems in maritime transport is increasingly shaped by a regulatory landscape at the European Union (EU) and international levels. These regulations aim to reduce greenhouse gas (GHG) and pollutant emissions from ships and to accelerate the decarbonisation of the maritime sector. This section briefly highlights the most relevant regulations in place for OPS deployment.

2.1.1 European regulations

EU Monitoring, Reporting and Verification (MRV) Regulation
The EU MRV Regulation mandates that ships over 5000 gross tonnage (GT) operating to, from, or within EU ports have to monitor and report their CO_2-emissions. This data collection forms the backbone of evidence-based policymaking for maritime decarbonisation and supports the development of further regulatory instruments.

Fit-for-55 package
The Fit-for-55 legislative package significantly strengthens the EU's climate ambitions for maritime transport, introducing several key regulations that directly impact OPS infrastructure and usage:

- The **FuelEU Maritime regulation** requires a gradual reduction in the intensity of GHG (measured in g CO_2/kWh) of the energy used onboard ships. It also mandates the use of OPS for container and passenger ships with a size above 5,000 GT at EU ports by 2030. Additionally, it obligates TEN-T network ports to provide the necessary shore power infrastructure to support this transition [8].
- Revision of the **EU Emissions Trading System (EU ETS)** extends the ETS to include shipping, thereby subjecting maritime emissions to carbon pricing and incentivising cleaner energy use, including OPS [12].
- The **Renewable Energy Directive (RED)** sets a target of 14.5% reduction in fuel GHG intensity by 2030 and requires that 29% of transport energy be derived from renewable sources, further encouraging the use of clean electricity for shore power [13].
- The **Alternative Fuels Infrastructure Regulation (AFIR)** mandates the installation of shore power infrastructure at TEN-T network ports that exceed certain annual port-call thresholds for container, Ro-Ro passenger, and passenger ships over 5,000 GT [9].

2.1.2 International Maritime Organization (IMO) Regulations

At the global level, the IMO has introduced stricter air pollution controls: NO_x Emission Control Areas (NECA) have been in effect in the North Sea and Baltic Sea since 2021.

Ships with keel laying after January 1, 2021, must comply with Tier III NO_x standards, which are approximately 70% stricter compared to Tier II [7, 10]. However, real-world compliance challenges persist due to emissions from auxiliary engines and low engine load operations in ports.

2.1.3 Impact on OPS technology

The regulatory push from both the supply side (port infrastructure requirements under AFIR) and the demand side (mandatory OPS usage under FuelEU Maritime) is a major driver for OPS technology development and deployment within the European Union. Together, these regulations ensure that:

1. Container ships, cruise ships and other passenger ships (above 5,000 GT) must be equipped with suitable connections for using OPS while at berth.
2. TEN-T network ports must have relevant infrastructure and connections in place to deliver OPS to these ships by 2030.

This dual obligation creates a synchronised incentive structure, fostering investment in OPS systems and ensuring their effective utilisation across the EU maritime network.

2.2 Connection standards

This section briefly highlights the relevant technical connection standards currently in place for OPS connections, relevant for port and ship operations [14].

Shore Power standards

- IEC/IEEE 80005-1: Utility connections in port: HVSC systems – General requirements High Voltage shore side electricity (up to 20 MVA per vessel).
- IEC/IEEE 80005-2: Utility connections in port: HVSC systems – Data communication for monitoring and control.
- IEC/IEEE 80005-3: Utility connections in port: HVSC systems – General Requirements Low Voltage shore side (typically less than 1 MVA).
- IEC 62613-2: Plugs, socket-outlets and ship couplers for high-voltage shore connection systems (HVSC-Systems) – Part 2: Dimensional compatibility and interchangeability requirements for accessories to be used by various types of ships.
- IEC 60309-5: Plugs, socket-outlets and couplers for industrial purposes - Part 5: Dimensional compatibility and interchangeability requirements for plugs, socket-outlets, ship connectors and ship inlets for low-voltage shore connection systems (LVSC).

Ship Standards

- IEC 60092-101: Electrical installations in ships - Part 101: Definitions and general requirements.
- IEC 60092-503: Electrical installations in ships - Part 503: Special features - AC supply systems with voltages in the range of above 1 kV up to and including 36 kV.
- IEC 61363-1: Electrical installations of ships and mobile and fixed offshore units - Part 1: Procedures for calculating short-circuit currents in three-phase AC.

3 Applicability to the maritime fleet

To assess the applicability of OPS across the maritime fleet, we conducted a detailed study linking vessel-specific power demand profiles to average power profile IMO numbers and ship types. These insights enable a granular understanding of OPS applicability beyond the traditionally targeted container and passenger vessels through current regulations. In this section, we highlight the current power demand knowledge on Dutch fleet categories, describe our methodology, and showcase our results on power demand profiles over time for different ship segments.

3.1 Methodology

Data was acquired through direct collaboration with ship owners and operators, enabling the collection of operational profiles and onboard usage patterns. To assess the onshore power demand of maritime vessels in detail, a comprehensive dataset was requested from ship operators encompassing both general ship characteristics and detailed power-related metrics. The requested general ship data includes:

General ship data

- IMO number
- Ship type
- Gross tonnage [GT]
- Cargo capacity
- Operational or cargo characteristics
- Annual overview of port visits with corresponding durations

Additionally, both the active power and reefer power demand was requested at high temporal resolution (preferable 5 minute intervals), in combination with GPS coordinates and logged operational activities. Specific subsystems such as hotel load, heating/cooling, number of reefers at arrival and departure were also included to enable granular analysis of energy demand profiles.

Operational time-dependent data

- Active power demand [kW]
- Datetime [UCT]
- GPS coordinates
- Logged operational activities

Furthermore, auxiliary generator specifications were requested to understand the onboard power generation. This includes generator type, regulatory NO_x-classification (IMO Tier), maximum power rating, brand/model, fuel type, and operational hours. This data is used to estimate emissions from onboard generation, which could potentially be avoided by using OPS.

Generator specifications

- Generator(s) used at the shore
- IMO Tier or build year of the generator(s)
- Maximum Continues Power Rating [kW], MCR
- Nominal rotational speed [RPM]
- Fuel type
- Specific Fuel-Oil Consumption (SFOC) in gram fuel per kilowatt-hour

Not all requested data was available from every collaborating party at the desired level of detail. As digitalisation is still a work in progress for many owners and operators, accessing the requested information is often challenging, and in many cases, the data is not yet monitored systematically. Aside from MRV, which requires reporting the total fuel consumed, there is no standardised practice in the maritime sector for collecting more detailed power demand data. Consequently, the availability of data varies significantly between operators and vessels.

This data request was sent out to a large number of ship owners and operators in accross selected ship segments. The selection covers ships regulated under AFIR (specifically container vessels, cruise ships, and ferries) as well as vessels included in the Green Deal reference vessels (general cargo and offshore). Tankers were also considered because they could become relevant if the AFIR scope is expanded in the future.

3.2 Results

We showcase the acquired data on onshore power demand across the investigated vessel types, ship owners, and operators. First, we describe how the power data are visualized and compared with the average power data reported by the International Maritime Organization (IMO) and with those used in the Emission Inventory and Monitoring for the Shipping sector (EMS), as published by TNO [10, 11]. Afterwards, we will go through all investigated ship types and sizes, starting with the Green Deal Reference Ships [1].

3.2.1 Data visualisation

This section explains how temporal power demand profiles are visualised to capture the statistical spread in power demand over time for the different investigated sea-going vessels. Figure 3.1 shows a time series of the vessel's power demand during a representative port stay. This highlights fluctuations in auxiliary power over time, offering insight into typical operational patterns, peak demands, and periods of low activity. Such temporal resolution is crucial for understanding and quantifying the dynamic load profiles and identifying operational phases such as the use of cranes, loading, unloading and refrigeration of cargo.

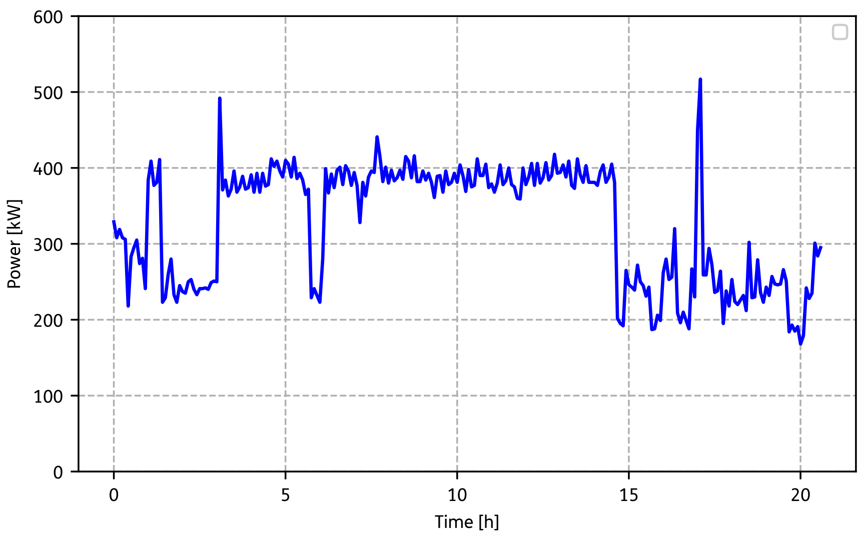


Figure 3.1: Example of a time series power demand profile for the investigated sea-going vessels.

Figure 3.2 presents a histogram of the time series profile in Figure 3.1, revealing the frequency distribution across the observed range. This helps identify the most common operating power levels and the spread of demand, which is essential for sizing energy systems and evaluating efficiency.

Comparing data with IMO and EMS figures

In order to compare the power demand profiles to average power values reported by IMO (Appendix A) and EMS (Appendix B), we visualize the power profiles in a probability density function (PDF) in Figure 3.3. This provides a smoothed view of the histogram distribution and enables the comparisson of multiple vessels in a single graph. The probability density functions are compared with the reported IMO values for similar ship sizes (blue dotted vertical line) and with EMS calculated average power demand values (black dotted vertical lines). In the example of Figure 3.3, the power demand of only one vessel is shown.

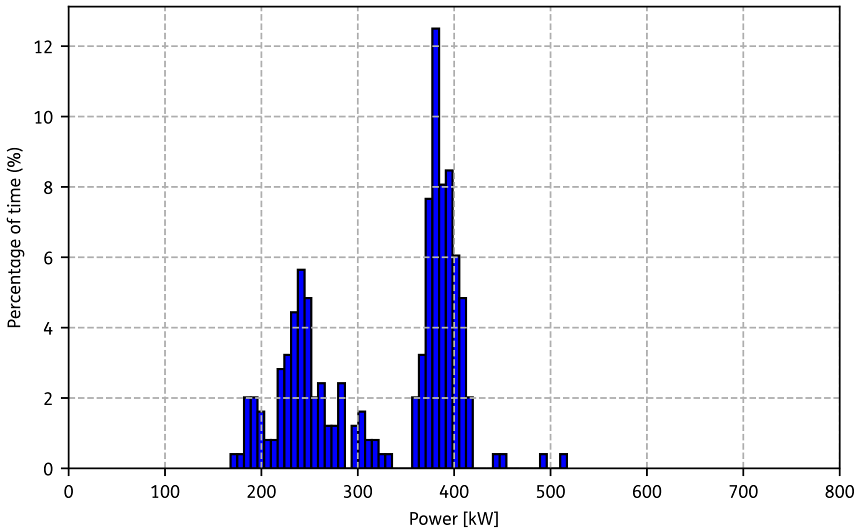


Figure 3.2: Example of a histogram distribution of the time series power demand profiles.

However, in most figures in this chapter, the figure contains vessels with different gross tonnages. As the EMS average power values are based on the gross tonnage of a vessel, we have calculated the value for the vessel with the lowest GT in that graph (lower bound) and the vessel with the highest GT in that graph (upper bound).

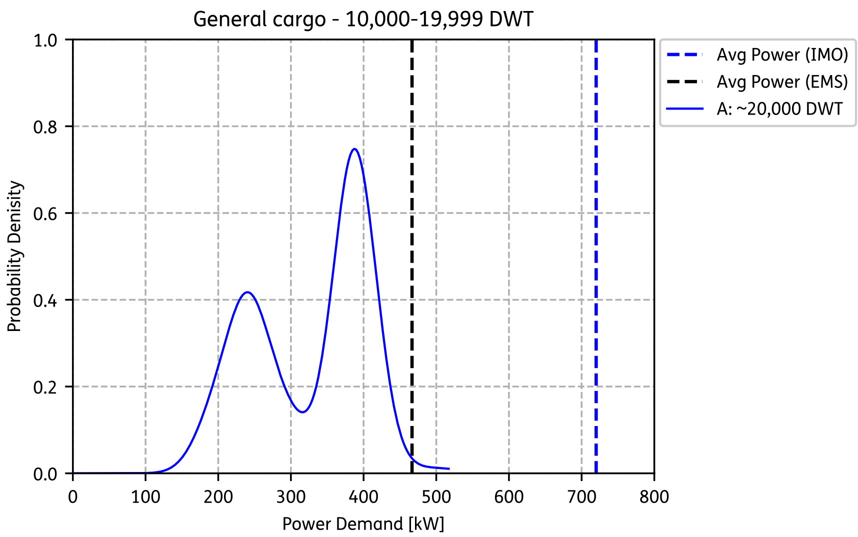


Figure 3.3: Example of a probability distribution of the time series power demand profiles.

The results section presents a detailed analysis of power demand profiles across the various ship types investigated in this study. Each ship type is introduced individually, beginning with a brief description of its operational characteristics. Where additional data is available, profiles are further examined to identify the underlying sources of power demand, such as reefer trailer usage, onboard systems, and operational schedules. This approach allows for a nuanced understanding of energy consumption patterns and supports the identification of key factors influencing onshore power demand. For some ship types, average power consumption for different port visits throughout the year are added to compare with the power distribution plots.

3.2.2 Vessel types regulated under AFIR

3.2.2.1 Container

This section presents an analysis of power demand during port stays for container vessels. A container vessel is a cargo ship specifically designed to transport standardised shipping containers, typically in 20-foot (TEU) units. They vary widely in size, from small feeder ships to ultra-large container vessels exceeding 20,000 TEU capacity. A key feature of modern container vessels is their ability to carry reefer containers—temperature-controlled units used for transporting perishable goods such as food, pharmaceuticals, and chemicals. These containers require continuous electrical power during transit and while berthed, contributing significantly to the vessel's auxiliary power demand. The number of reefer plugs available onboard directly influences the ship's energy consumption profile, especially during port stays. For the investigated container ships in this study, we first compare the average power demand at berth between different TEU container capacity categories, and then portray operational power profiles of the largest capacity categories to focus on the influence of refrigerated container (reefer) loads.

Figure 3.4 shows the variation in average power demand per port visit for container vessels of different TEU-based size classes, based on port calls to a single port by one ship owner between 2024 and 2025. The average power demand of the smallest size class (<4,000 TEU) is significantly lower than the other two size classes. The distributions indicate that vessels in higher weight classes generally exhibit greater average onshore power demand. The substantial variance observed suggests a need for further investigation into the underlying causes.

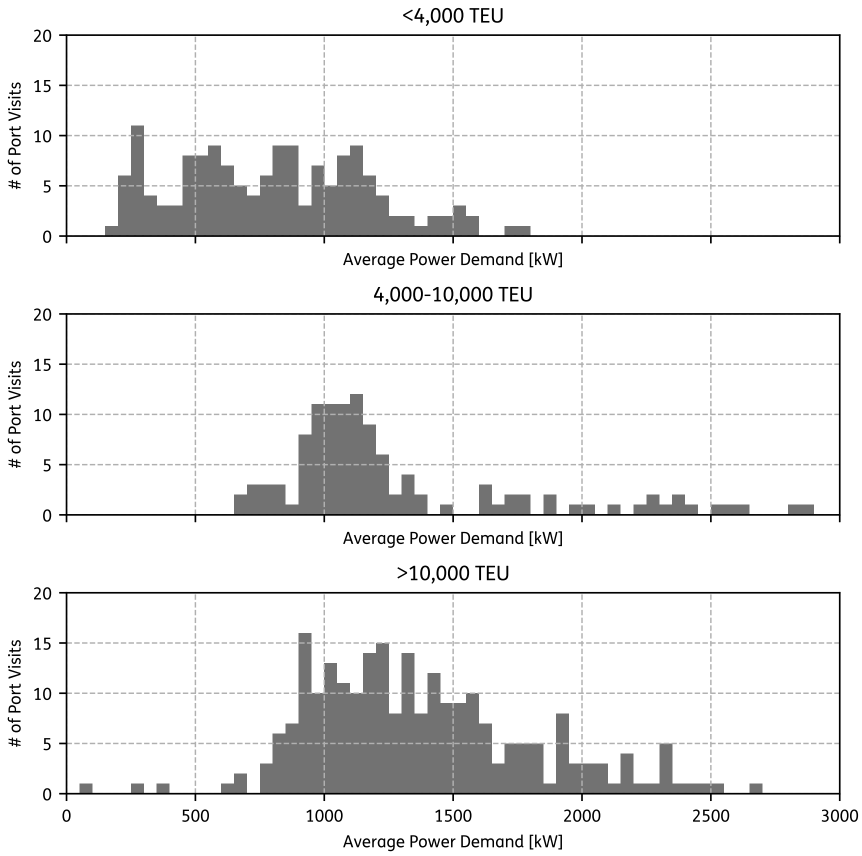


Figure 3.4: Distribution of the average power demand per visit in a specific port between 2024 and 2025 for container vessels of different size classes, based on their TEU capacity.

For three vessels, more detailed data were available, allowing a closer look at power demand on individual ships. The analysis focuses on three container ships of similar size (around 20,000 TEU). Figure 3.5 presents the total active power and total reefer power profiles during the port visits of three comparable container ships in TEU capacity. Container ship A reported 576 reefers at departure, while the number at arrival was not documented. In contrast, Container ship B reported 189 reefers upon arrival and 91 at departure. Container ship C reported similar reefers upon arrival and departure, 154 and 113, respectively. Despite their similarity in ship type and TEU capacity, the temporal evolution of onshore power demand during the port visits differs markedly between the three vessels.

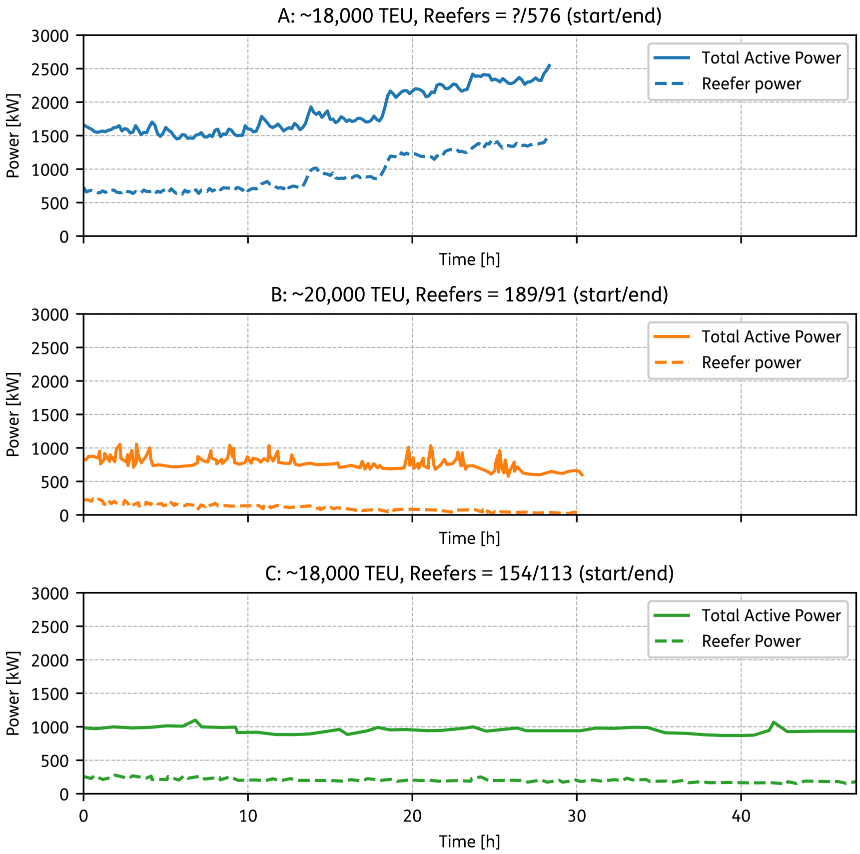
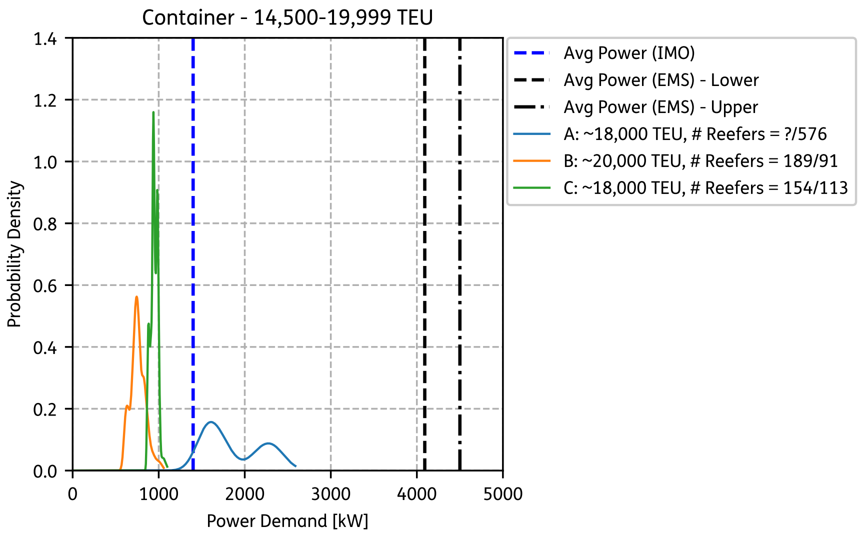


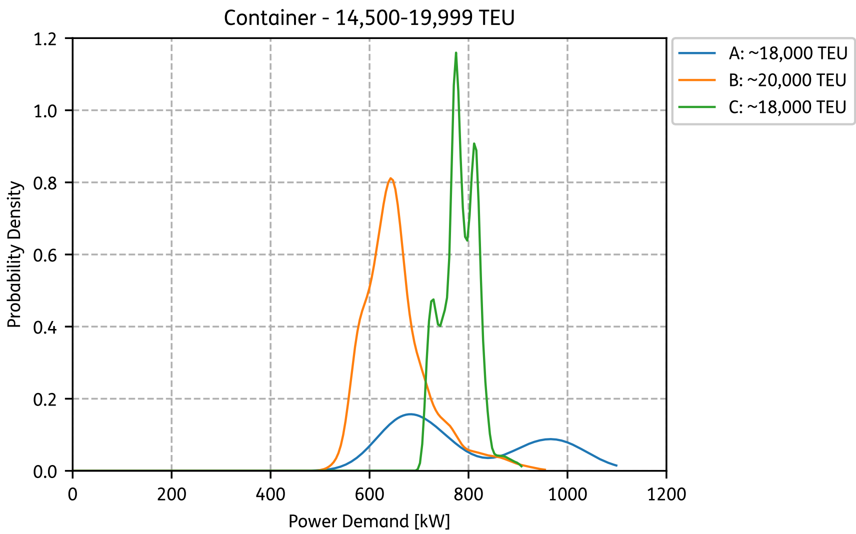
Figure 3.5: Total active power and total reefer power time series during specific port visits for three large container vessels (18,000-20,000 TEU).

The total active power of Figure 3.5 for container ships A, B and C have been converted into power distributions in Figure 3.6a. This way the different operating points of the three vessels can be more easily compared. The differences in these distribution underscores the variation in power demand. The distributions are compared with the average power value for container ships with a similar TEU capacity (14,500–19,999 TEU), as reported by the IMO (Appendix A) and currentlyl used in EMS (Appendix B). Power distributions between these specific ships, and compared to the reported average power, differ drastically.

In Figure 3.6b, the total reefer power of the three container ships has been subtracted from the total active power. This adjustment reveals a much narrower spread in total active power across these ships, indicating that the reefer load is a primary driver of variability in onshore power demand. The reduced variation after removing reefer contributions emphasises the importance of accounting for refrigerated cargo when assessing onshore power needs.



(a) Total active power including reefer power.



(b) Total active power excluding reefer power.

Figure 3.6: Distribution of power demand at berth for a single port visit of container ships A, B, and C.

3.2.2.2 Cruise

A cruise ship is a vessel built to carry passengers on multi-day voyages, typically along coastal or international routes. Cruise ships generally exhibit high power demand during port stays, primarily due to substantial hotel loads, including heating, ventilation, air conditioning (HVAC), lighting, and cabin systems that remain fully operational while docked. Because their power requirements are well-characterised and relatively stable, cruise ships are among the most compatible vessel types for OPS connections.

Figure 3.7 shows the power probability distributions for the port visits of three different cruise ships of the same ship owner. The power demand distributions are relatively narrow, reflecting consistent energy usage patterns. The minor differences in the power demand profiles between the individual ships (4,200 kW for cruise ship B, 4,300 kW for cruise ship A) can be attributed to variations in passenger capacity and ambient temperature at the ports of call, both of which influence the intensity of hotel load requirements. Cruise ship C shows higher power demand, which can can be attributed to its size compared to cruise ship A and cruise ship B. Notably, the ships analysed in this section consistently demonstrate lower average power demand than the IMO and EMS reference values. For the EMS average power, the "Lower" line corresponds to the value calculated for the vessel with the smallest gross tonnage in this figure, while the "Upper" line corresponds to the value for the vessel with the largest gross tonnage.

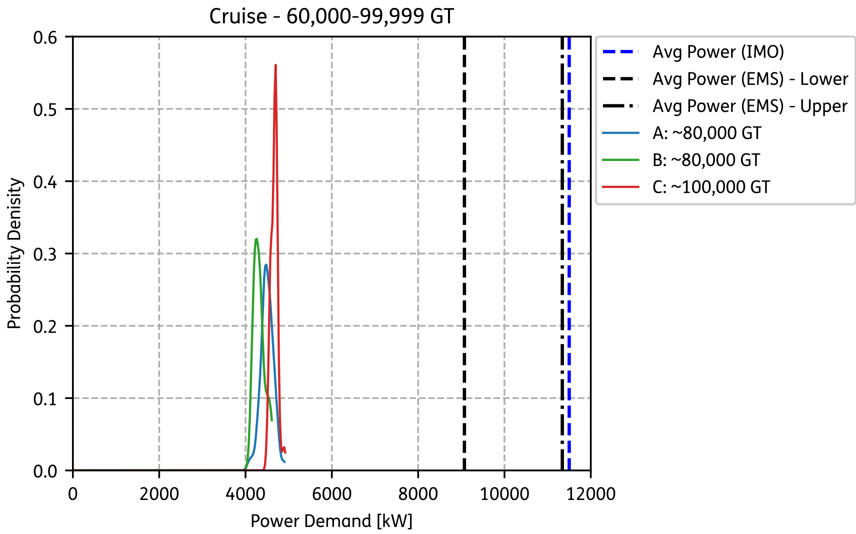


Figure 3.7: Distribution of power demand at berth for 3 different cruise ships.

3.2.2.3 Ro-Pax Ferry

Ferries vary significantly in design, passenger capacity, and cargo configuration, which makes them distinct from one another and difficult to treat as a single vessel type. Within this section, we investigate the power profiles of Ro-Pax Ferries only. A Ro-Pax Ferry is designed to carry both wheeled cargo (such as freight trucks and trailers) and passengers, often including amenities like cabins, lounges, and dining areas. These ships are commonly used on short to medium-distance routes, especially in regions with strong intermodal transport links.

Figure 3.8 shows the supplied shore power profiles of 6 port visits for 1 Ro-Pax Ferry with a weight of 65,000 GT, where a sharp peak at 2,500 kW can be seen. The dashed blue vertical line shows the average power demand of a Ro-Pax Ferry of 20,000+ GT, according to IMO. The dashed black vertical line represents the calculated average power demand of a Ro-Pax Ferry of similar weight range as vessel A, based on the emission factors currently used in EMS.

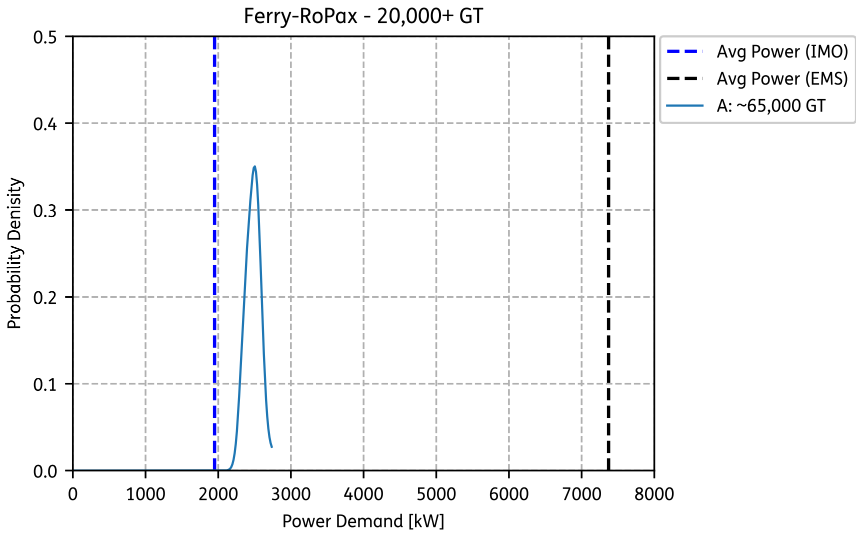


Figure 3.8: Distribution of power demand at berth for 1 specific Ro-Pax Ferry.

Figure 3.9 illustrates the average shore power supplied during each port visit in 2022 for Ro-Pax Ferry ship A, as shown in Figure 3.8, and its sister vessel, ship B. Although the vessels are sister ships with the same specifications, observed differences in power demand (around 300 kW on average) remain only partially explained. A possible factor is variation in operational schedules, particularly the timing of departures. For instance, evening sailings may carry a different number of reefer trailers or passengers onboard that will require a different hotel load based on evening hotel load. These operational nuances suggest that even minor differences in voyage profiles can lead to measurable variations in power demand. The individual histogram distributions for both ship A and B show a broader spread compared to the power profiles observed during a limited number of port visits for ship A. One possible explanation is seasonal variation, which may lead to increased auxiliary power demand during certain periods. This effect could be driven by temperature-related systems or operational adjustments. However, seasonal influences were not investigated further within the scope of this study. Future work could explore this aspect to improve its effect.

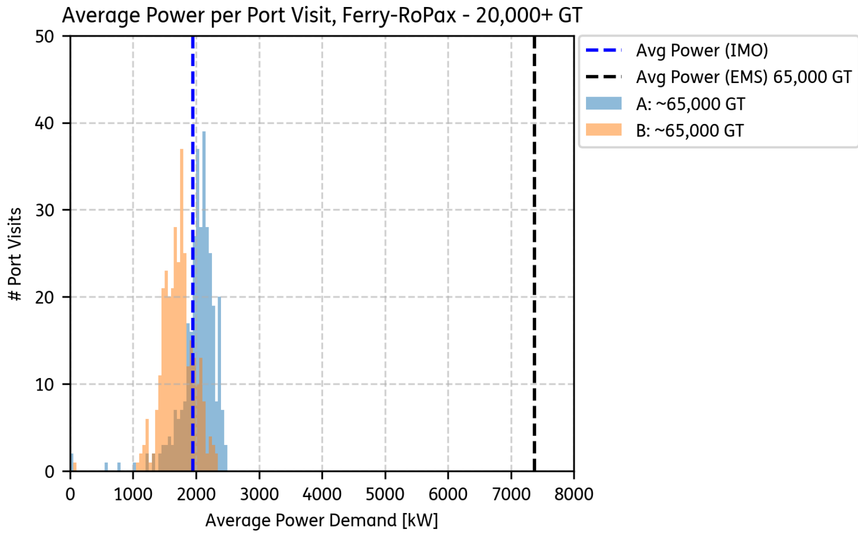


Figure 3.9: Histogram of average onshore power demand over all port visits in 2022 for 2 identical Ro-Pax ferries.

3.2.3 Green Deal Validation reference vessels

This section contains the power demand at berth for two of Green Deal Validation reference vessels shown in Table 1.1: General cargo and offshore vessels.

3.2.3.1 General cargo

We present an analysis of power demand during port stays for sea-going general cargo vessels. A general cargo vessel carries diverse cargo types such as machinery, vehicles, steel products, bagged goods, and sometimes even containers. These ships often feature multiple cargo holds and are equipped with onboard cranes or derricks to facilitate loading and unloading in ports that may lack infrastructure. Based on the cargo and operational planning, power demand at berth may vary over a port visit. The requested power profiles are portrayed for 2 different Dutch general cargo shipowners, with vessels in different general cargo sizes.

Figure 3.10 shows the onshore power distributions for general cargo vessels for the first general cargo shipowner, in the ship size range between 5,000 and 9,999 deadweight tonnage (dwt). This is the difference between the ship's displacement when fully loaded and when empty. The investigated ships have similar weight sizes and all profiles peak in probability around 35 kW to 40 kW. Instances of elevated power demand, occasionally exceeding 100 kW, are also briefly observed. These peaks are typically associated with short-duration activities such as crane or hatch operations, which can significantly increase overall energy consumption during port stays. The ships investigated within this weight category exhibit a significantly lower power demand compared to the reported IMO and EMS average power demand figures within similar ship sizes.

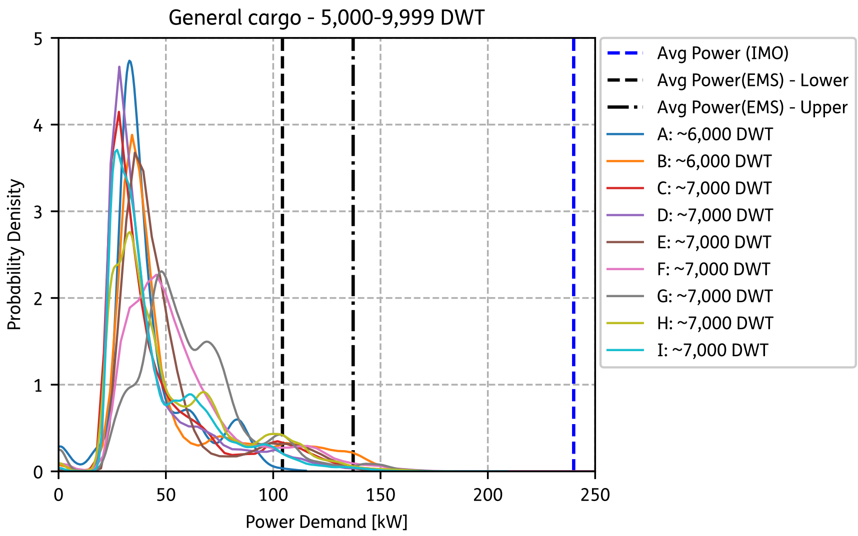


Figure 3.10: Distribution of power demand at berth for 4 different general cargo ships, between 5,000 and 9,999 dwt.

Figure 3.11 shows the power distributions for general cargo vessels for another general cargo shipowner, in the ship size range between 10,000 and 19,999 dwt. The power distribution among the general cargo vessels investigated shows considerable variation, despite their similar weight classifications. For example, general cargo ship A exhibits a power range between 200 and 400 kW, while ship D ranges from 180 to 600 kW, and Ship B shows an even broader variation between 200 and 800 kW. These differences suggest that operational factors—such as onboard equipment usage, cargo handling activities, and voyage-specific conditions—play a significant role in shaping power demand profiles, next to ship size or weight. The ships investigated within this weight category exhibit a significantly lower average power demand compared to the IMO average power (blue dotted line). The average power estimated from EMS data (represented by black dotted lines) appears to better reflect the actual power distributions across different ships.

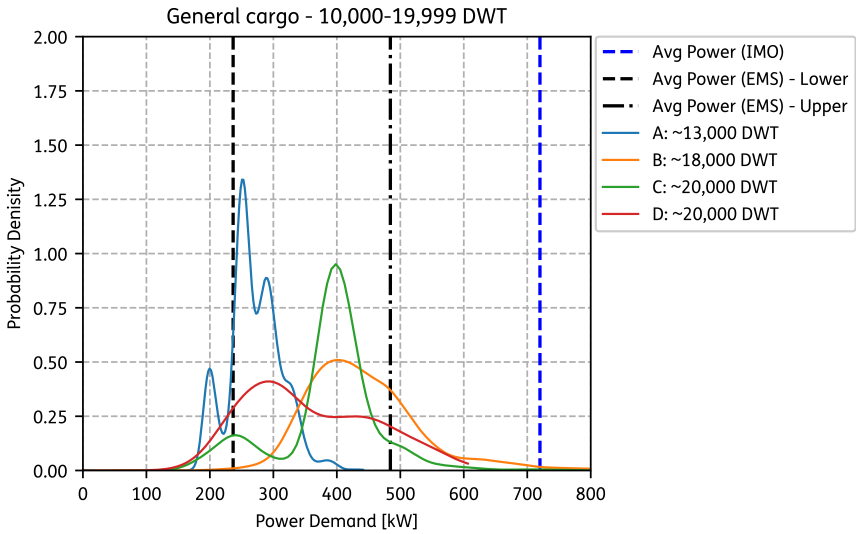


Figure 3.11: Distribution of power demand at berth for 4 different general cargo ships, between 10,000 and 19,999 dwt.

3.2.3.2 Offshore

An offshore ship is a specialised vessel designed to support operations in offshore environments such as oil and gas exploration, wind farm construction, and subsea infrastructure. These ships are built to operate in deep waters and harsh conditions, often far from shore. They are equipped with advanced systems like dynamic positioning, heavy lifting gear, and accommodation facilities for crew and technicians. Offshore ships play a critical role in transporting equipment, maintaining offshore installations, and enabling complex marine operations.

Figure 3.12 presents two port visits from different offshore vessels, each with distinct weight classes. These offshore vessels deviate strongly from the Green Deal Validation reference Vessels in Table 1.1. Since the IMO does not define specific weight ranges for offshore vessels, the average power reported applies to all offshore ships above 0 GT, including very small units. Vessel A exhibits a wide power distribution ranging from below 3,000 kW to over 8,000 kW, indicating highly variable operational demands. In contrast, vessel B shows a narrower distribution between 4,000 kW and 6,000 kW, with a clear peak around 5,000 kW. These differences highlight the diversity in power requirements among offshore vessels and suggest that average values may not adequately represent individual operational profiles. More data will be needed to further explain the differences in the power demand of these offshore ships.

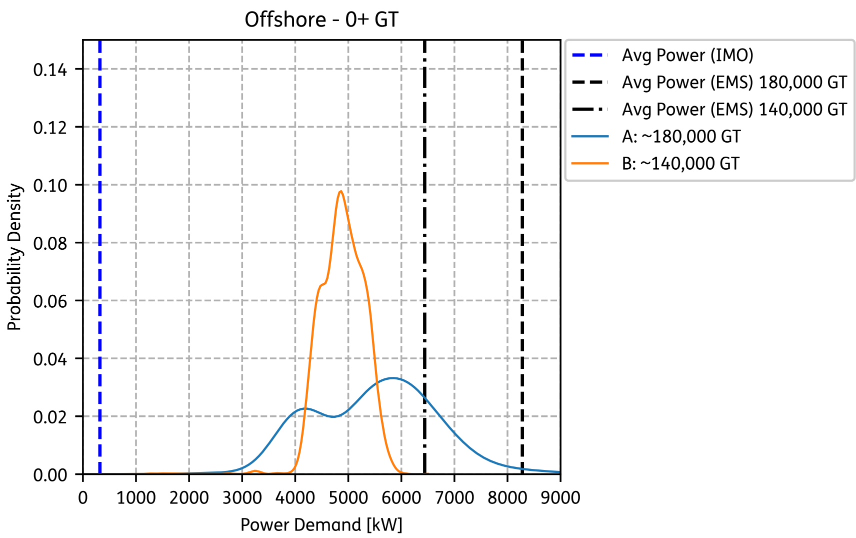


Figure 3.12: Distribution of power demand at berth for 2 port visits for 2 different offshore vessels.

3.2.4 Tankers

3.2.4.1 Chemical tanker

A chemical tanker is a specialized cargo ship designed to transport liquid chemicals in bulk, often including hazardous substances. It features multiple segregated tanks made of stainless steel or coated materials to prevent contamination and corrosion. These vessels follow strict international safety standards to ensure safe handling, storage, and transport of chemical cargoes.

The power demand at berth is influenced by a combination of operational and environmental factors, including:

- Type of operation (loading or unloading)
- Cargo handling using onboard equipment
- Nitrogen purging (N_2)
- Pumps to adjust vessel stability

Figure 3.13 shows the power distributions for 2 different port visits for one specific chemical tanker in the weight range of 20,000 to 59,999 dwt. The light blue distribution represents a port visit where chemicals are loaded, where power demand varies between 350 and 1000 kW, showing distinctive peaks at 500 kW and 700 kW. The orange distribution represents a port visit where unloading happens, where power demand varies between 300 and 1300 kW. The main reason for the difference in power distribution and higher peaks at unloading, would be that during loading the cargo pumps are not in use. These are hydraulic cargo pumps and driven by electrical motor aggregates. The explicitly underlying causes of both the variation and power peaks, and the spread of power demand within both port visits remain uncertain and require further investigation.

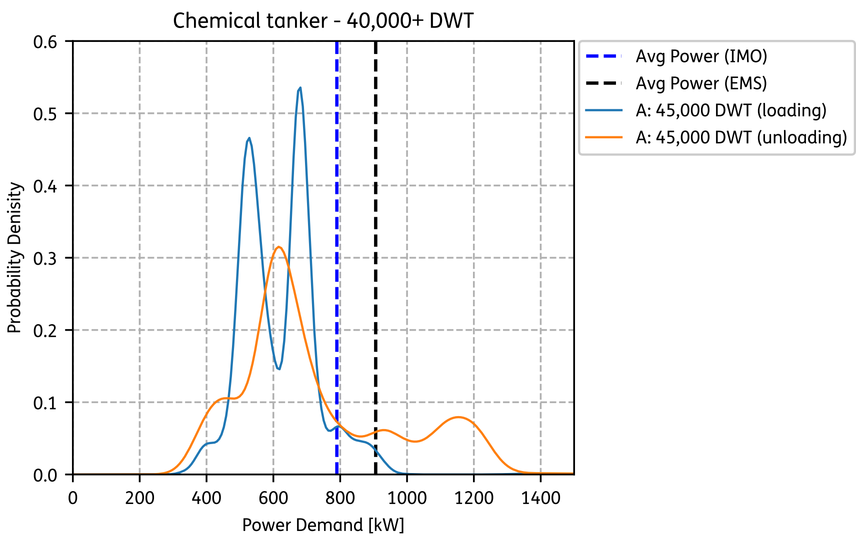


Figure 3.13: Distribution of power demand at berth for 1 chemical tanker, for 2 different port stays.

The average power demand of multiple port visits for loading (14 port visits) and unloading (11 port visits) for the same chemical tanker are highlighted in Figure 3.14. On average, loading power demand is lower compared to unloading power demand, further higligting the difference in power demand due to use of cargo pumps during unloading operations. The dataset is limited to only several port visits. More extensive data over multiple ships and port visits can further explain the difference between both loading and unloading operations.

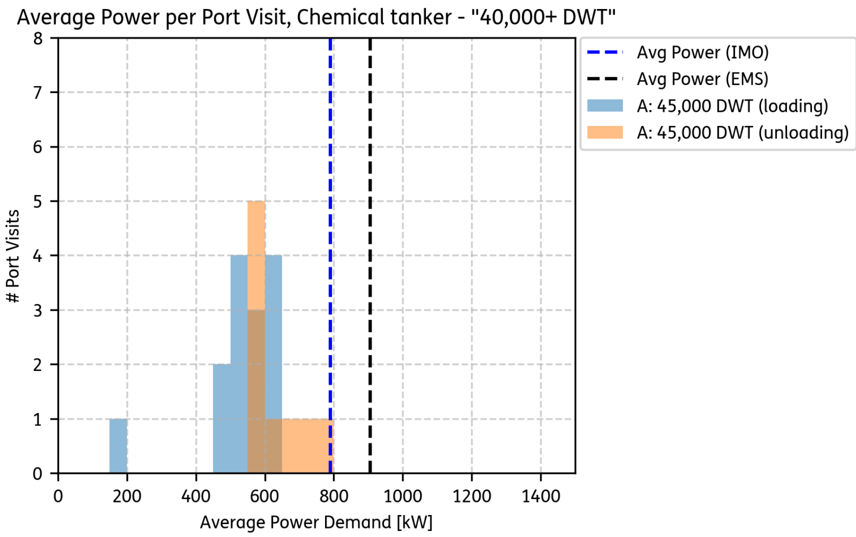


Figure 3.14: Histogram of average power demand at berth for 1 chemical tanker, for both unloading and loading operations during a total of 25 port stays.

3.2.4.2 Liquefied gas tanker

A liquefied gas carrier is a specialised cargo vessel designed to transport gases that have been cooled and compressed into liquid form, such as liquefied natural gas (LNG) or liquefied petroleum gas (LPG). These ships are equipped with insulated and often cryogenic tanks to maintain extremely low temperatures required for storage. The tanks can be spherical, membrane-type, or cylindrical pressure vessels, depending on the design. Due to the hazardous nature of the cargo, these vessels also feature advanced safety and monitoring systems. Their design ensures safe, efficient transport of volatile gases over long distances.

Auxiliary power demand is influenced by a combination of operational and environmental factors, including:

- Product type and quantity
- Type of operation (loading or discharging)
- Loading and discharging temperatures and pressures
- Terminal limitations on temperature or pressure, which may require additional heating or cooling from the vessel

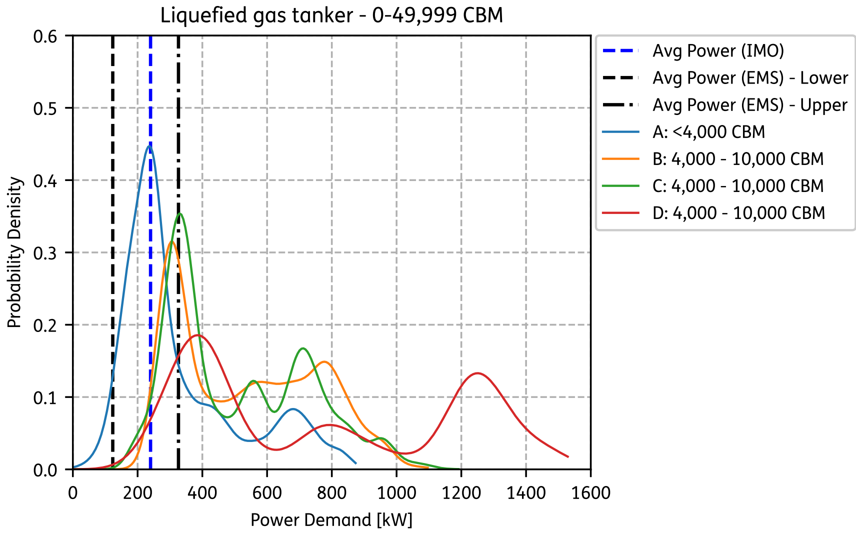
Due to the interplay of these variables, actual power requirements can vary significantly and are difficult to predict precisely. However, among these factors, cargo type (specifically its boiling point) plays a critical role in determining peak power demand. Gases with a low boiling point (below approx. −80 °C) require cascade cooling systems for reliquefication. These systems involve additional equipment and thus higher power consumption by design. On the other side of the spectrum, gases with boiling point around 0 °C require little to no cooling, especially in cold areas. As a result, different cargoes can require different power because of their physical properties. Categorising power demand ranges based on vessel size and gas boiling point is useful, as this provides a practical framework for estimating (peak) power requirements. Cargo handling power demand by vessel type and boiling point is summarised for different oil tanker vessel sizes (in cubic meters) in Table 3.1.

Table 3.1: Cargo handling power demand by vessel size and boiling point.

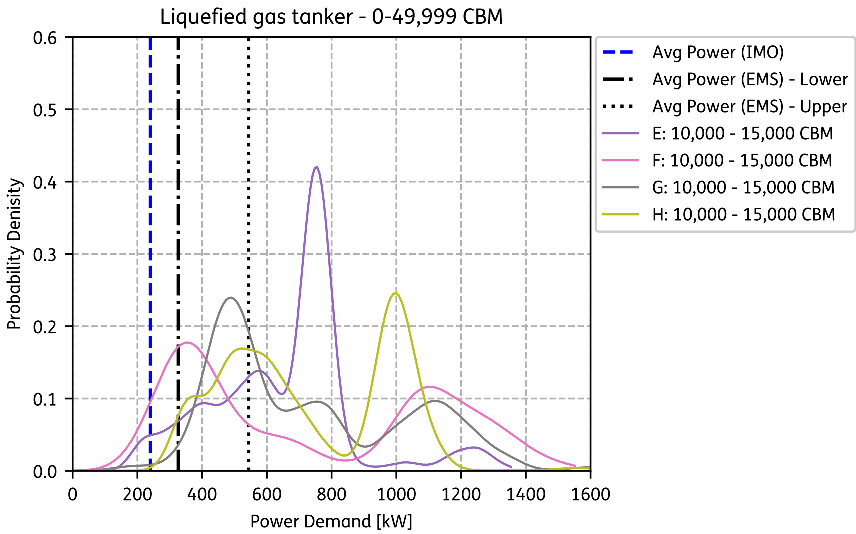
	Boiling point					
Cargo Operations	Below -80°C		-50 to -10°C		Around 0°C	
Vessel Size	Loading	Discharging	Loading	Discharging	Loading	Discharging
<4,000 CBM	–	–	300–500 kW	300–400 kW	300–400 kW	300–400 kW
4–10,000 CBM	1,000–1,400 kW	500–700 kW	600–1,000 kW	400–800 kW	400–600 kW	400–600 kW
10–15,000 CBM	1,100–1,700 kW	500–800 kW	700–1,100 kW	500–900 kW	400–700 kW	400–700 kW

Figure 3.15 presents the aggregated power profile distribution of all port visits for the selected vessels, covering approximately mid-2024 to mid-2025. It also compares the investigated ships in this size category to the average IMO power values between 0-49,999 cubic meter (CBM). In the 4,000–10,000 CBM size range (Figure 3.15a, power profiles typically range from 100 kW to 1,100–1,600 kW, depending on operational activities—refer to the operational load table above for context.

In the 10,000–15,000 CBM category (Figure 3.15b), power demand shows greater variability, with most vessels operating between 100 kW and over 1,500 kW. For example, Ship F, which exclusively transports ethylene (boiling point below -80°C), exhibits loading power between 1,100–1,700 kW and discharging power between 500–800 kW, according to the boiling points for this vessel size in Table 3.1. These peaks can also be seen in Figure 3.15b at 700 kW an 1,100 kW, with a base load of 350 kW. Most other vessels in this category carry mixed cargoes, making it difficult to attribute power demand to carrying specific liquids.



(a) Distribution of power demand for liquefied gas tankers (0-10,000 CBM).



(b) Distribution of power demand for liquefied gas tankers (10,000-15,000 CBM).

Figure 3.15: Distribution of power demand at berth for multiple port visits over 1 year for different liquefied gas tankers.

3.2.5 Other vessel categories

3.2.5.1 Ro-Ro

A Ro-Ro ship is equipped with one or more loading ramps that allow vehicles to roll directly on and off the vessel, enabling fast and efficient loading and unloading. Unlike Ro-Pax vessels, a Ro-Ro vessel is primarily designed for vehicle and cargo transport. As a result, Ro-Ro ferries generally have lower overall onshore power demand than Ro-Pax vessels, since they do not carry the additional load associated with passenger cabins and amenities.

Figure 3.16 shows the supplied shore power distribution of multiple port visits for 1 Ro-Ro ship with a weight of 10,000 DWT. A broad peak at 600-800 kW can be seen. This broader peak could be attributed to cargo handling equipment and pumping systems: Ro-Ro often operate ramps, lifts, and internal conveyors to load and unload vehicles and cargo and to maintain vessel stability.

The dashed blue vertical line represents the IMO-reported average power consumption for a 10,000 DWT Ro-Ro vessel, which is significantly higher than the values observed in the collected data. In contrast, the dashed black vertical line indicates the EMS-based average power for this vessel class, which aligns well with the measured data.

It should be noted that data availability for this ship segment is limited. Additional data and further investigation are required to determine whether the collected values are representative and to explore potential causes for deviations from the IMO average, such as seasonal effects or operational profiles.

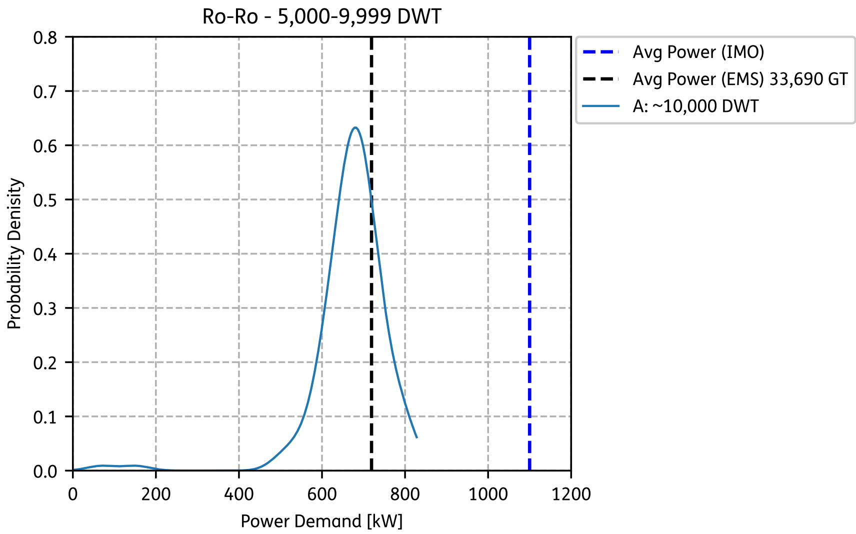


Figure 3.16: Distribution of power demand at berth for one Ro-Ro vessel.

4 Environmental impact

4.1 General

Onshore Power Supply (OPS) is widely recognised as an effective measure to reduce greenhouse gas (GHG) and pollutant emissions in port areas. By supplying vessels with electricity from the shore, onboard diesel generators can be switched off during port stays, significantly lowering fuel consumption and emissions of CO_2, NO_x, particulate matter, and other harmful substances. This is particularly relevant in Dutch ports, where NO_x-emissions from stationary and manoeuvring vessels represent a substantial share of total transport-related emissions. For example, in the Port of Rotterdam, stationary and manoeuvring seagoing vessels account for more than 78 percent of total transport emissions in the port area [2].

Given these figures, OPS has substantial potential to reduce environmental impact across multiple sea-going vessel segments, including the ones investigated outside of FuelEU Maritime and AFIR regulations. This section showcases the environmenal impact of OPS, given the investigated ships and power demand profiles in Chapter 3. Comparison of fuel rate factors in EMS with factors based on current data study

4.2 Comparison of fuel rate factors in EMS with factors based on current data study

In the Dutch emission inventory, the fuel rate factors reported by TNO [11] are currently used to estimate emissions. These fuel rate factors are shown in Tables B.1 and B.2 of Appendix B. Based on the data acquired during this work, we can compute fuel rate factors of our own and compare them to the numbers used in EMS. This comparison is shown in Table 4.1. Note that these fuel rate factors only denote the fuel rate for power generation, using the allocation percentages from Table B.2. Appendix D elaborates on how these numbers are computed.

Table 4.1: Comparisson between fuel rate factors of ships at berth for power generation only (kg/1000 GT·hour) currently used in EMS and fuel rate factors found using the collected data in this study.

Ship type	Fuel rate factors for power generation currently used in EMS [11] (kg/1000 GT·hour)	Fuel rate factors for power generation Indicative values based on current data study (kg/1000 GT·hour)
Bulk carrier	2.16	*no data*
Container ship	4.20	0.89
General Cargo	5.49	4.72
Passenger $\leq$ 30,000 GT	6.23	*no data*
Passenger $>$ 30,000 GT	22.68	10.13 (Cruise), 5.95 (Ferry)
RoRo Cargo	4.27	3.98
Oil Tanker	3.86	*no data*
Other Tanker	7.25	5.25 (Chemical), 12.00 (Liquefied Gas)
Reefer	17.64	*no data*
Other	9.2	*no data*
Tug/Supply	15.6	*no data*

These fuel-rate factors are derived from a linear fit of fuel rate versus gross tonnage. This fit is used to compare the data collected in the present study with the factors currently applied in EMS. However, it should be noted that a linear relationship with gross tonnage may not be the most accurate way to represent vessel fuel rates. More data is needed to establish accurate factors or relations to find fuel rates.

Table 4.1 confirms the findings from Chapter 3: EMS factors align well with the acquired data for General Cargo, Ro-Ro, and Chemical Tankers, but less so for container and large passenger vessels. For these latter types, additional data are needed to validate the fuel rate factors used in the Dutch emission inventory and improve emission estimates.

4.3 Generator load-dependant emission calculations

In the absence of detailed operational data, emissions are typically estimated using high-level metrics such as the fuel rate factors discussed in Section 4.2. With the operational power profiles now collected from ship owners, more detailed emission calculations become possible. The methodology is presented in Section 4.3.1, and results for an example case are shown in Section 4.3.2.

4.3.1 Methodology

4.3.1.1 Fuel consumption rate

To estimate emissions from operational power profiles, the deployment of onboard generators must first be determined. Using the measured power profiles together with generator specifications, emissions can then be approximated.

Since fuel consumption strongly depends on the generator's operating point, the load fraction -defined as the ratio between the actual load and the Maximum Continuous Rating (MCR)- is first derived. The relationship between Specific Fuel Oil Consumption (SFOC) and load fraction is adopted from the IMO GHG Study [10], as shown in Equation 4.1. Typically, SFOC is highest at low loads, reaches a minimum around 75% MCR, and gradually increases again at higher loads. Figure 4.1 illustrates a representative SFOC curve for a generator with a baseline value of $\text{SFOC}_{\text{base}} = 190$ g/kWh.

$$\text{SFOC} = \text{SFOC}_{\text{base}} \times (0.455 \cdot \text{load fraction}^2 - 0.710 \cdot \text{load fraction} + 1.280) \tag{4.1}$$

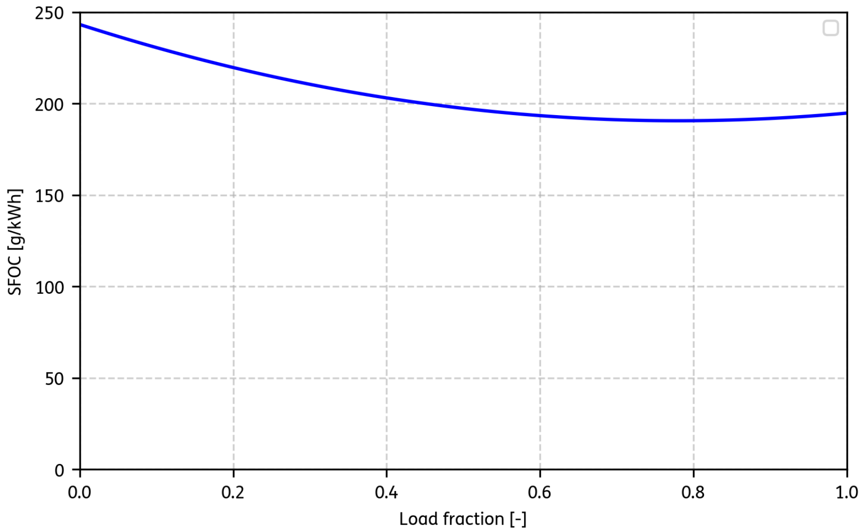


Figure 4.1: Example of Specific Fuel-Oil Consumption (SFOC) versus the load fraction of a generator with $SFOC_{base}$ = 190 gram fuel per kWh.

Although this relationship was originally developed for main engines, the same behaviour also applies to auxiliary generators: higher fuel consumption at both low and very high loads. Therefore, an algorithm was implemented to estimate the load fractions of the available generators by minimising the total fuel consumption (kg/h) for a given power demand. This method offers a reasonable approximation of how power generation is managed on board.

$$\text{Fuel rate (kg/h)} = \text{SFOC} \times \text{MCR} \times \text{load fraction} \tag{4.2}$$

4.3.1.2 Emissions

Once the fuel consumption rate is known, the corresponding CO_2-emissions can be directly calculated using the Well-to-Wake emission factor.

$$CO_2 \text{ [g/h]} = EF_{WTW} \times \text{Fuel rate (kg/h)} \tag{4.3}$$

Here, EF_{WTW} for CO_2 is assumed to be 3173 g/kg MGO [11].

For other substances, such as NO_x, the emissions can be calculated as follows:

$$NO_x \text{ [g/h]} = EF_{base} \times \text{CEF} \times \text{Fuel rate (kg/h)} \tag{4.4}$$

In this expression, EF_{base} denotes the base NO_x emission factor, while CEF is a correction factor that depends on both the generator load fraction and the applicable build year or IMO Tier of the generator. This is explained in more detail in Appendix C.

4.3.2 Results

In this section, the method described above is applied to an example case to illustrate the principle. The example case considers a vessel with two auxiliary generators of the same type. Both generators have the following specifications:

- IMO Tier: II
- Maximum Continues Power Rating [kW], MCR: 360 kW
- Nominal rotational speed [RPM]: 1500 RPM
- Fuel type: MGO
- Specific Fuel-Oil Consumption in gram fuel per kilowatt-hour, $SFOC_{base}$: 190 g/kWh

Using these specifications, an estimate of the deployment of the generators can be made. This is shown in Figure 4.2.

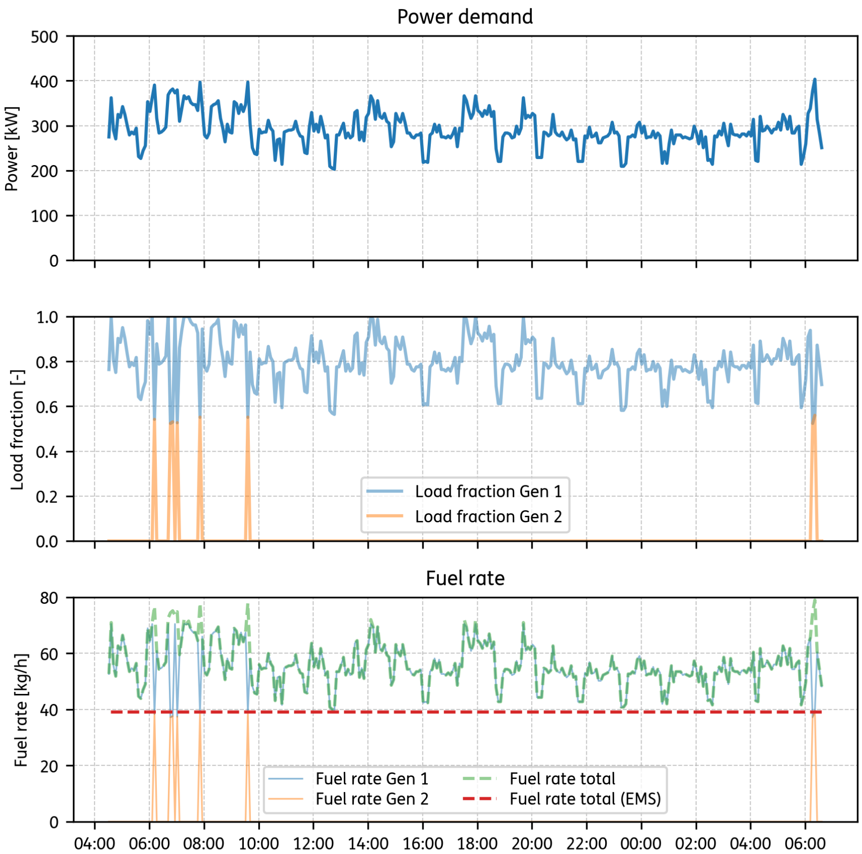


Figure 4.2: Total power demand, generator deployment strategy, and resulting fuel consumption rate during a 26-hour port stay for a vessel operating two auxiliary generators.

The total power demand during the port stay is shown in the upper plot, while the estimated generator load fractions are shown in the second plot. For a large portion of the port stay, the total power demand is below the MCR of a single generator. Consequently, only one generator is required to be in operation. When the total power demand exceeds 360 kW, the second generator is deployed—visible in the plot as the orange line stepping upward.

In this example, the load fraction remains relatively high (above 0.7) for most of the time because the power demand is close to the maximum capacity of a single generator. As demonstrated in Figure 4.1, this corresponds to the fuel-efficient operating regime of the generator.

However, it should be noted that when the power demand approaches the maximum capacity of a generator, operators often choose to activate the second generator as a precaution to avoid blackout events, particularly when the load is dynamic, as is the case in this example. In such a case, instead of one generator operating at a load fraction of 1.0, two generators may operate at a load fraction of about 0.5. This reduces the overall fuel efficiency of the vessel.

Based on the load fraction and SFOC curve, the fuel consumption rate of both generators is calculated and shown in the third plot. The green line represents the combined fuel rate of the two generators. For comparison, the red dashed line shows the fuel consumption rate estimated using the fuel rate factors currently used in EMS [11], see Appendix B. For the port stay considered in this example, the EMS-based fuel consumption prediction is lower than the estimate derived by using the generator specifications.

Figure 4.3 shows how the relation between fuel rate and CO_2- and NO_x-emissions (in kg/h) respectively. As was shown in Equation 4.3, the relation between fuel rate and CO_2-emissions is linear. The NO_x-emissions depend on the load fraction of the operating generator.

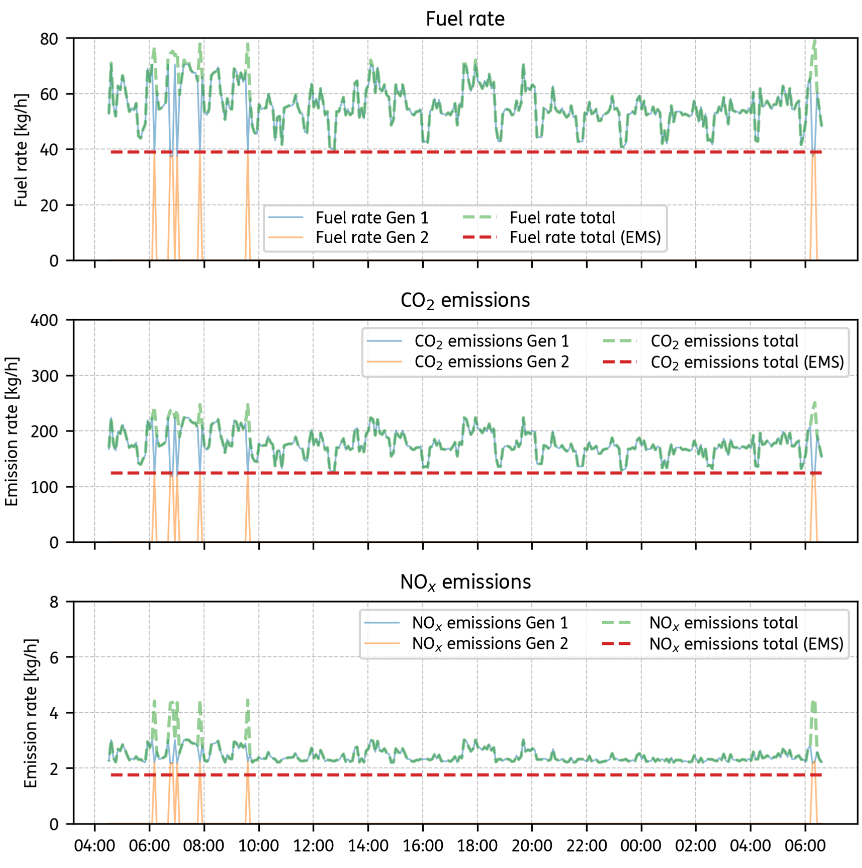


Figure 4.3: Fuel rate, CO_2-emissions and NO_x-emissions during a 26-hour port stay for a vessel operating two auxiliary generators.

As can be seen in the lower subplot, the NO_x emission rate as computed by the load independent EMS factor (red dashed line) is relatively well in line with the total NO_x emission rate calculated by using the load fraction (green solid line) for the cases where the load fraction is high. On the occasions where the load fractions drop to about 0.5, the emissions increase significantly. It is expected that on many occasions the load fractions of generators is low, and these high emissions rates occur frequently. A more extensive data and modelling study is required to investigate this further.

5 Scalability and future proofness

OPS is already a well-established solution for container ships and passenger vessels, particularly within the European Union, where regulatory obligations are driving widespread adoption. For these vessel types, the infrastructure and operational frameworks are maturing rapidly, ensuring a high degree of scalability and long-term viability. Regulatory momentum, such as the FuelEU Maritime regulation, mandates OPS usage for container ships over 5,000 GT and passenger vessels at EU ports by 2030, further accelerating deployment. Despite this progress, OPS infrastructure remains limited relative to the energy demand of berthed vessels, especially reported in countries like Italy, Spain, and France, highlighting significant growth potential [15]. Standardisation through IEC/ISO/IEEE 80005 is improving interoperability across ports and vessels, while newer ships are increasingly equipped with OPS interfaces, easing integration. Funding mechanisms like the Alternative Fuels Infrastructure Facility (AFIF) and the Multiannual Financial Framework (MFF) further support deployment. OPS aligns with long-term sustainability goals under the EU's Fit for 55 and Green Deal, offering operational benefits such as reduced fuel costs, engine wear, and noise pollution. Technological flexibility allows integration with smart grids, energy storage, and renewable sources, enhancing adaptability to future energy systems.

The outlook of OPS deployment for other ship types remains less certain. While there is growing interest, the absence of clear regulatory mandates and the diversity in operational profiles pose challenges to broader implementation. Challenges also include grid capacity constraints, retrofit costs for older vessels, and evolving power demands due to the rise of hybrid and electric ships. As electrification progresses, OPS may also serve as a charging solution for onboard batteries. Although hybrid and fully electric sea-going vessels are not the focus of this study, their emergence underscores a broader shift toward electrification, which aligns well with the OPS ecosystem and may further support its scalability in the long term.

6 Conclusion

This report highlights substantial variability in the onshore power demand between different segments of sea-going vessels. For some shipowners, like container ships, ferry operators, and oil tankers, we have investigated the average power demand per port visit, which varies over similar size classes and multiple port visits over the year for identical vessels. Additionally, by looking at the power demand over time for specific ships, we have investigated that the onshore power demand is primarily driven by specific operational modes. Variability in operations leads to distinct power demand patterns-not only across different ship segments but also among vessels of the same type.

Furthermore, by combining empirical insights on power demand variability with vessel-specific generator specifications, this study enables a more detailed analysis of fuel consumption rates and CO_2- and NO_x-emissions compared to reported averages by IMO and those currently used in EMS, and therefore can validate the environmental impact of OPS. Chapters 3 and 4 show clear deviations between the collected operational profiles and both the IMO framework and the values currently used in EMS. This comparison underscores the importance of detailed operational data in accurately modelling fuel consumption and emissions. While power data collection remains essential for meaningful analysis, the data acquisition for this study was limited due to the absence of standardised measurement systems. Apart from the EU MRV Regulation, which only requires reporting total fuel consumption, there is currently no industry-wide standard for monitoring power demand over time. This makes data collection and detailed emissions modelling cumbersome, as information must be gathered separately from each individual operator.

Our analysis indicates that variations in operational modes - like hotel load, cranes and hatches, loading/unloading and refrigerated units on board - are the main driver behind the observed fluctuations in onshore power demand. As such, it represents one of the primary challenges in developing an effective OPS deployment strategy. These findings underscore the importance of moving beyond generalised assumptions when planning for shore power infrastructure. Variability in power demand demonstrates that vessels of similar type and cargo capacity can exhibit markedly different energy profiles during port stays. This has direct implications for the design and sizing of OPS systems, which must be flexible and responsive to actual operational conditions rather than based solely on vessel classification or gross tonnage.

Three key benefits emerge from further investigation into detailed power demand across ship types. First, aligning OPS capacity with actual demand patterns enables ports to optimise infrastructure investments, ensuring cost-effective and targeted deployment. Second, access to day-ahead information on operational capacity needed at arrival allows shipowners and port authorities to better anticipate electricity demand, facilitating more accurate and efficient participation in day-ahead electricity markets. Third, improved quantification of CO_2- and NO_x-emission reductions strengthens the environmental case for OPS, supporting policy and regulatory initiatives aimed at decarbonising port operations. Although compliance with EU shore power regulations appears feasible for container and passenger vessels, the extension of these regulations to other vessel categories remains uncertain and warrants further investigation. Additionally, the growing relevance of hybrid and fully electric vessels presents new research avenues beyond the scope of this study.

References

[1] MARIN. *Vervolgstappen validatatie methodieken t.b.v. transitie naar emissieloze scheepvaart*. 2020.

[2] P. Xchange. *EmissionInsider: Pave the way to a zero-emissions port*. Accessed: 2025-09-29. 2022.

[3] P. of Rotterdam. *Strategie Walstroom Rotterdamse Haven*. 2020.

[4] C. Delft. *The role of shore power in the future maritime fuel mix*. 2022.

[5] E. M. S. Agency. *Shore-Side Electricity: Guidance to Port Authorities and Administrations. Part 2: Planning, Operations and Safety*. 2022.

[6] R. H. DHV. *Walstroom Inventarisatie 2024*. 30 april 2024. 2024.

[7] I. M. O. (IMO). *Fourth IMO GHG Study 2020*. 2020.

[8] E. Commission. *Decarbonising Maritime Transport: FuelEU Maritime*. 2025.

[9] E. Commission. *Alternative fuels infrastructure, and repealing Directive 2014/94/EU (AFIR)*. 2025.

[10] I. M. O. (IMO). *Fourth IMO GHG Study 2020: Full Report and Annexes*. Accessed: 2025-09-16. IMO, 2020.

[11] H. D. v. d. G. J.H.J. Hulskotte. *Fuel consumption and associated emissions from seagoing ships at berth derived from an on-board survey*. Accessed: 2025-09-16. TNO, 2010.

[12] E. Commission. *EU Emissions Trading System (EU ETS)*. Accessed: 2025-10-15. 2025.

[13] E. Parliament and C. of the European Union. *Regulation (EU) 2023/1805 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC*. Regulation. Sept. 13, 2023.

[14] S. Ships. *Technical Specs & Standards*. Accessed: 2025-10-15. 2025.

[15] I. C. on Clean Transportation. *Shore power needs and CO_2 emissions reductions of ships in European Union ports: Meeting the ambitions of the FuelEU Maritime and AFIR*. 2023.

Signature

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Appendix A
Auxiliary Engine Power Output by IMO

Table A.1: Auxiliary Engine Power Output (kW) by Ship Type, Size, and Operational Mode [10].

Ship Type	Size	Unit	At berth (kW)	Anchored (kW)	Manoeuvring (kW)	Sea (kW)
Bulk carrier	0–9,999	dwt	110	180	500	190
	10,000–34,999	dwt	110	180	500	190
	35,000–59,999	dwt	150	250	680	260
	60,000–99,999	dwt	240	400	1,100	410
	100,000–199,999	dwt	240	400	1,100	410
	200,000+	dwt	240	400	1,100	410
Chemical tanker	0–4,999	dwt	130	130	490	560
	5,000–9,999	dwt	330	490	560	580
	10,000–19,999	dwt	490	560	580	580
	20,000–39,999	dwt	790	550	900	660
	40,000+	dwt	790	550	900	660
Container	0–999	TEU	370	450	790	410
	1,000–1,999	TEU	820	1,200	1,750	900
	2,000–2,999	TEU	610	910	1,900	920
	3,000–4,999	TEU	1,100	1,350	2,500	1,400
	5,000–7,999	TEU	1,150	1,600	2,800	1,450
	8,000–11,999	TEU	1,150	1,600	2,900	1,800
	12,000–14,999	TEU	1,300	1,800	3,250	2,050
	14,500–19,999	TEU	1,400	1,950	3,600	2,300
	20,000+	TEU	1,400	1,950	3,600	2,300
General cargo	0–4,999	dwt	240	130	490	180
	5,000–9,999	dwt	240	130	490	180
	10,000–19,999	dwt	720	370	1,450	520
	20,000+	dwt	720	370	1,450	520
Liquefied gas tanker	0–49,999	cbm	240	240	360	240
	50,000–99,999	cbm	1,700	1,700	2,200	1,700
	100,000–199,999	cbm	2,500	2,000	2,300	2,650
	200,000+	cbm	6,750	7,200	7,200	7,200
Oil tanker	0–4,999	dwt	250	250	375	250
	5,000–9,999	dwt	375	375	375	375
	10,000–19,999	dwt	690	520	850	490
	20,000–59,999	dwt	720	520	600	360
	60,000–79,999	dwt	620	490	770	560
	80,000–119,999	dwt	880	640	910	690
	120,000–199,999	dwt	2,500	770	1,300	900
	200,000+	dwt	2,500	770	1,300	900
Other liquids tankers	0–9,999	dwt	500	500	750	500
	10,000+		500	500	750	500
Ferry-pax only	0–299	gt	190	190	190	190
	300–999	gt	190	190	190	190
	1000–1999	gt	190	190	190	190
	2000+	gt	520	520	520	520
Cruise	0–4,999	gt	450	450	450	450
	2,000–9,999	gt	450	450	580	450
	10,000–59,999	gt	3,500	3,500	3,500	3,500
	60,000–99,999	gt	11,500	11,500	14,900	11,500
	100,000–149,999	gt	11,500	11,500	14,900	11,500
	150,000+	gt	11,500	11,500	14,900	11,500
Ferry-RoPax	0–1,999	gt	105	105	105	105
	2,000–4,999	gt	330	330	330	330
	5,000–9,999	gt	670	670	670	670
	10,000–19,999	gt	1,100	1,100	1,100	1,100
	20,000+	gt	1,950	1,950	1,950	1,950
Refrigerated bulk	2,000–5,999	dwt	1,100	1,200	1,150	1,200
	6,000–9,999	dwt	1,650	1,600	1,650	1,650
	10,000+	dwt	2,850	3,100	3,000	3,100
Ro-Ro	0–4,999	dwt	750	430	1,300	430
	5,000–9,999	dwt	1,100	680	2,200	680
	10,000–14,999	dwt	1,200	950	2,700	950
Vehicle	0–9,999	dwt	800	500	1,100	500
	10,000–19,999	dwt	850	550	1,400	510
	20,000+	dwt	850	550	1,400	510

Appendix B

Auxiliary Engine Power Output in Emission Inventory and Monitoring for the Shipping Sector (EMS)

TNO [11] reported factors to estimate the fuel consumption rate of ships at berth. These factors are currently used in EMS to calculate emissions of vessels at berth. In Table B.1, the auxiliary fuel consumption of a vessel at berth is expressed as a function of its gross tonnage (GT). For example, a 10,000 GT bulk carrier has a fuel consumption of:

Table B.1: Fuel rate of ships at berth (kg/1000 GT·hour)

Ship type	Fuel rate (kg/1000 GT·hour)
Bulk carrier	2.4
Container ship	6.0
General Cargo	6.1
Passenger $\leq$ 30000 GT	8.9
Passenger $>$ 30000 GT	32.4
RoRo Cargo	6.1
Oil Tanker	19.3
Other Tanker	14.5
Reefer	19.6
Other	9.2
Tug/Supply	15.6

$$\text{Fuel rate} = 2.4 \times \left(\frac{10{,}000}{1{,}000}\right) = 24 \text{ kg/h} \tag{B.1}$$

Table B.2 provides the fraction of this fuel that is allocated to electrical power generation, while the remainder is assumed to power the auxiliary boiler systems.

Applying this fraction for the bulk carrier example:

$$\text{Fuel rate for power} = 24 \text{ kg/h} \times 0.9 = 21.6 \text{ kg/h} \tag{B.2}$$

To convert this into generated electrical power (kW), a value for Specific Fuel-Oil Consumption (SFOC) must be assumed. For simplicity a fixed value of 200 g/kWh is adopted. The conversion for the 10,000 GT bulk carrier becomes:

Table B.2: Allocation of fuels usage in engine types and apparatus per ship type at berth (%)

Ship type	Power (MS)	Boiler
Bulk carrier	90	10
Container ship	70	30
General Cargo	90	10
Passenger	70	30
RoRo Cargo	70	30
Oil Tanker	20	80
Other Tanker	50	50
Reefer	90	10
Other	100	0
Tug/Supply	100	0

$$P = \frac{21.6\ \text{kg/h}}{200\ \text{g/kWh}/1000} = 108\ \text{kW} \tag{B.3}$$

This allows the estimated auxiliary power demand to be compared directly with onboard power profiles gathered from the data request.

Appendix C

Emission factors for auxiliary engines

The emission factors presented in this appendix are used to estimate air pollutant emissions from auxiliary and main engines operating on board seagoing vessels. Table C.1 provides emission factors for medium and high-speed marine engines operating at berth. The values are expressed in grams of emitted pollutant per kilogram of fuel consumed (g/kg fuel) and are differentiated based on the year of engine construction and fuel type. These emission factors are referred to as EF_{base}, as they are not dependant on the generator load.

Table C.1: Emission factors of medium/high speed engines (MS) at berth, (g/kg fuel). [11]

Year of build	NO_x	PM-MDO	VOC	CO
Fuel	all	MGO/ULMF	all	all
1900 – 1973	53	1.4	2.7	3.25
1974 – 1979	65	1.5	2.8	3.50
1980 – 1984	73	1.6	2.9	3.75
1985 – 1989	82	1.8	3.1	3.25
1990 – 1994	74	1.3	2.6	2.75
1995 – 1999	59	0.8	2.2	2.75
2000 – 2010	50	0.8	1.6	2.75
2011 – 2022	43	0.8	1.6	2.75
TIER III	12.81	0.91	0.3	1.50

Table C.2 presents correction emission factors (CEF) that account for changes in pollutant formation depending on the engine load. These correction factors are expressed as a function of the engine operating power relative to its Maximum Continuous Rating (MCR)
The emission factor (EF) in grams per kg of fuel can be calculated using the following expression:

$$EF\ [g/kg] = EF_{base} \times CEF. \qquad (C.1)$$

Table C.2: Correction emission factors (CEF) at different power levels % of MCR. [11]

Power % of MCR	CO_2, SO_2		NOx			PM-HFO/PM-MDO	VOC, CH_4	CO
	SP	MS	Tier 0 or I	Tier II	Tier III			
10	1.2	1.21	1.34	1.74	6	1.63	4.46	5.22
15	1.15	1.18	1.17	1.52	3	1.32	2.74	3.51
20	1.1	1.15	1.1	1.36	1.75	1.19	2.02	2.66
25	1.07	1.13	1.06	1.3	1.45	1.12	1.65	2.14
30	1.06	1.11	1.04	1.32	1.45	1.08	1.42	1.8
35	1.05	1.09	1.03	1.34	1.45	1.05	1.27	1.56
40	1.045	1.07	1.02	1.34	1.45	1.03	1.16	1.38
45	1.035	1.05	1.01	1.32	1.45	1.01	1.09	1.23
50	1.03	1.04	1.00	1.3	1.45	1.01	1.03	1.12
55	1.025	1.03	1.00	1.27	1.45	1.00	1.00	1.06
60	1.015	1.02	0.99	1.23	1.4	1.00	0.98	1.00
65	1.01	1.01	0.99	1.13	1.25	0.99	0.95	0.94
70	1.00	1.01	0.98	1.01	1	0.99	0.92	0.88
75	1.00	1.00	0.98	0.95	0.85	0.98	0.89	0.82
80	1.01	1.00	0.97	0.95	0.85	0.98	0.87	0.76
85	1.02	1.00	0.97	0.95	0.85	0.97	0.84	0.7
90	1.03	1.01	0.97	0.95	0.85	0.97	0.85	0.7
95	1.04	1.02	0.97	0.95	0.85	0.97	0.86	0.7
100	1.05	1.02	0.97	0.95	0.85	0.97	0.87	0.7

Appendix D

Comparison of fuel rate factors in EMS with factors based on current data study

In this Appendix, the results from the data collection discussed in Chapter 3 are processed into fuel rate factors in order to compare them to the fuel rate factors in the Emission Inventory and Monitoring for the Shipping Sector (EMS) [11]. These fuel rate factors are shown in Tables B.1 and B.2 of Appendix B. Table B.1 presents the total fuel consumption rate at berth, expressed in kg/1000 GT·hour. Table B.2 shows how this fuel consumption is allocated between power generation and boilers.

The data collected in the current study only cover power generation. Therefore, the fuel rate factors from Table B.1, which represent total fuel consumption at berth, must be adjusted to reflect only the share used for power generation. This adjustment enables a direct comparison with the findings of this current study. It is made by multiplying the total fuel rate factors by the allocation percentage for power generation from Table B.2. The resulting values are shown in the second column of Table D.1.

This power demand data collected in this study can be converted into a fuel rate by assuming a specific fuel oil consumption (SFOC). For simplicity, an SFOC value of 200 g/kWh is assumed, consistent with the assumption made in Appendix B.

To obtain the fuel rate factors, fuel rates are first calculated for all vessels in the dataset by vessel type. These fuel rates are then plotted against the gross tonnage (GT) of the corresponding vessels, as shown in Figures D.1 to D.6. After computing the average fuel rate per GT for each vessel type, a linear fit of the following form is applied:

$$\text{Fuel rate (kg/h)} = \text{Fuel rate factor} \times \frac{\text{GT}}{1000}. \tag{D.1}$$

This linear fit is used to compare the data collected in the current study to the ones currently used in EMS. It should be noted, however, that a linear dependency on GT is not necessarily the most accurate method for characterizing vessel fuel rates.

In Figures D.1 to D.6 we can see that data availability differs a lot per ship type. Particularly for ferries and Ro-Ro vessels, little data was available. Table D.1 confirms what was already presented in Chapter 3: the factors currently used in EMS perform relatively well for General Cargo, Ro-Ro and Chemical Tankers based on the acquired data in this study, but less so for container vessels and large passenger vessels. The plot for liquefied gas tankers is not shown in order to respect confidentiality agreements.

Table D.1: Comparisson between fuel rate factors of ships at berth for power generation only (kg/1000 GT·hour) currently used in EMS and fuel rate factors found using the collected data in this study.

Ship type	Fuel rate factors for power generation currently used in EMS [11] (kg/1000 GT·hour)	Fuel rate factors for power generation Indicative values based on current data study (kg/1000 GT·hour)
Bulk carrier	2.16	*no data*
Container ship	4.20	0.89
General Cargo	5.49	4.72
Passenger ≤ 30,000 GT	6.23	*no data*
Passenger > 30,000 GT	22.68	10.13 (Cruise), 5.95 (Ferry)
RoRo Cargo	4.27	3.98
Oil Tanker	3.86	*no data*
Other Tanker	7.25	5.25 (Chemical), 12.00 (Liquefied Gas)
Reefer	17.64	*no data*
Other	9.2	*no data*
Tug/Supply	15.6	*no data*

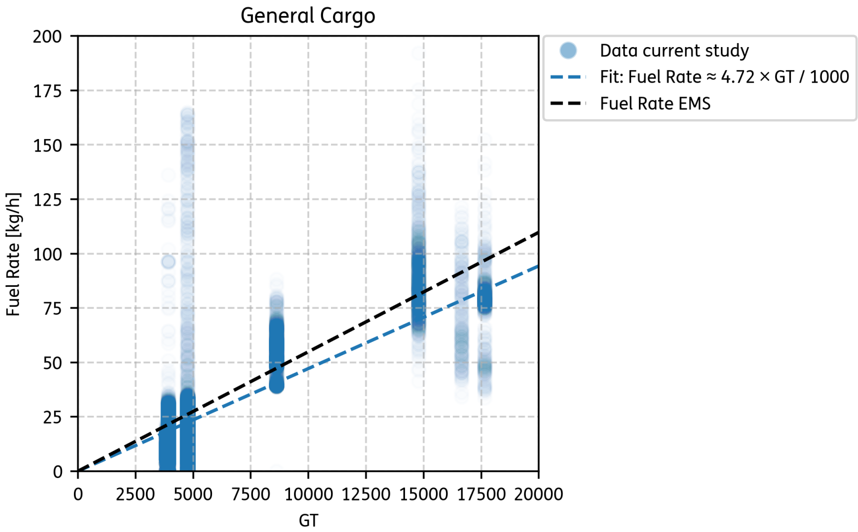

Figure D.1: Fuel rate for power generation versus gross tonnage for general cargo vessels. The figure shows collected data in current study (blue scatter), a linear fit to that data, and the EMS-based relation; the corresponding fit and EMS coefficients are listed in Table D.1.

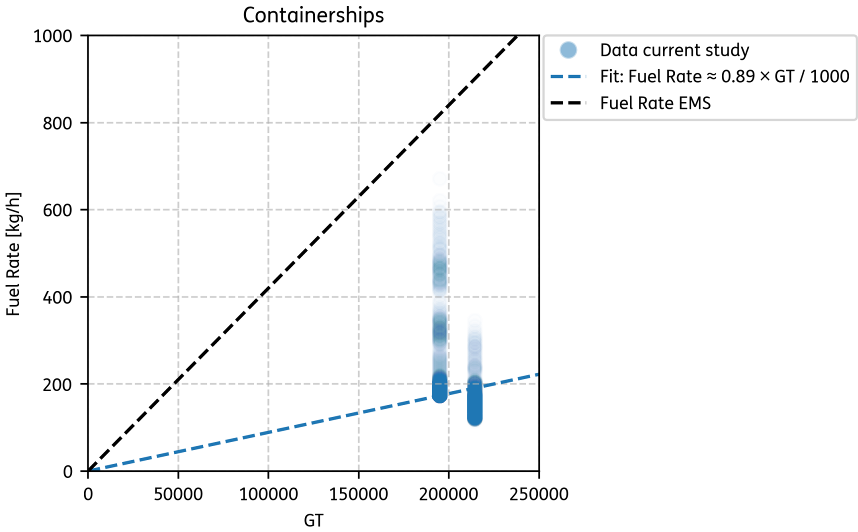

Figure D.2: Fuel rate for power generation versus gross tonnage for container vessels. The figure shows collected data in current study (blue scatter), a linear fit to that data, and the EMS-based relation; the corresponding fit and EMS coefficients are listed in Table D.1.

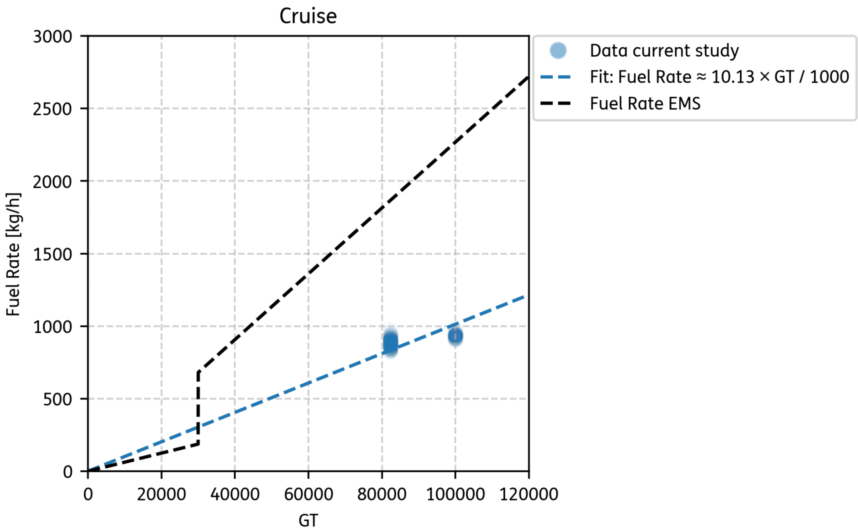

Figure D.3: Fuel rate for power generation versus gross tonnage for cruise vessels. The figure shows collected data in current study (blue scatter), a linear fit to that data, and the EMS-based relation; the corresponding fit and EMS coefficients are listed in Table D.1. The jump in the black dashed line is due to the size distinction in EMS below and above 30,000 GT for passenger vessels.

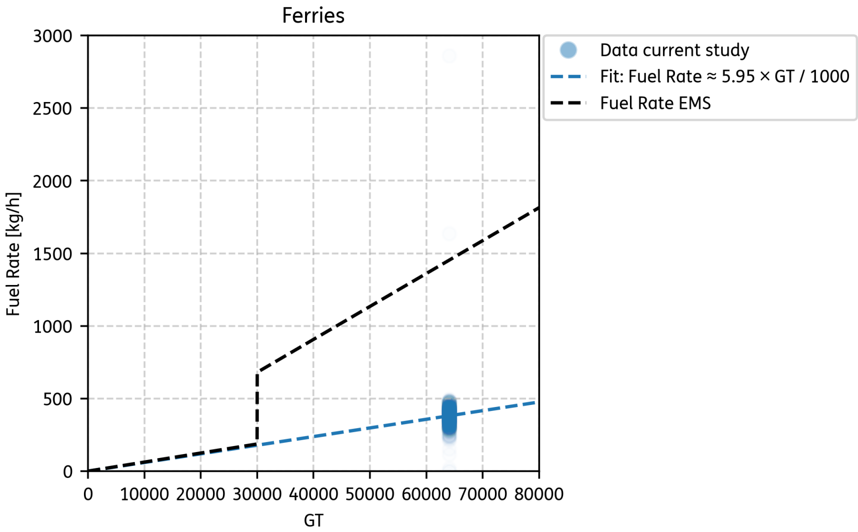

Figure D.4: Fuel rate for power generation versus gross tonnage for ferries. The figure shows collected data in current study (blue scatter), a linear fit to that data, and the EMS-based relation; the corresponding fit and EMS coefficients are listed in Table D.1. The jump in the black dashed line is due to the size distinction in EMS below and above 30,000 GT for passenger vessels.

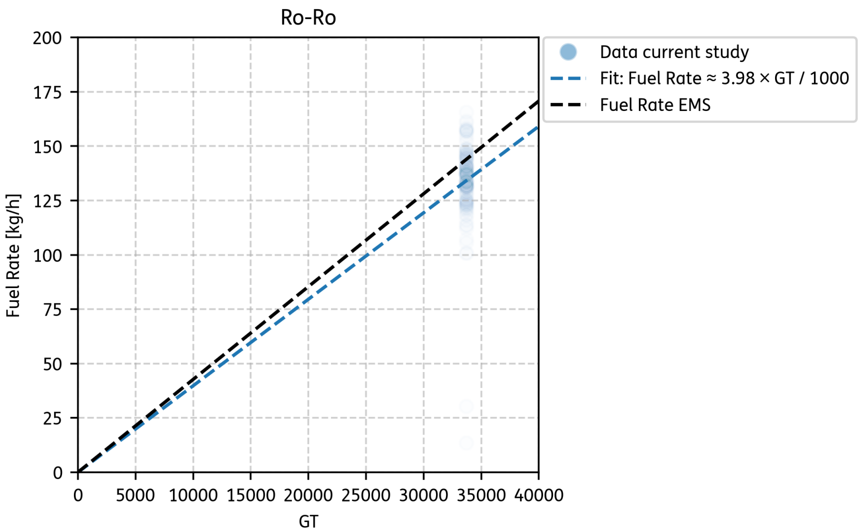

Figure D.5: Fuel rate for power generation versus gross tonnage for Ro-Ro vessels. The figure shows collected data in current study (blue scatter), a linear fit to that data, and the EMS-based relation; the corresponding fit and EMS coefficients are listed in Table D.1.

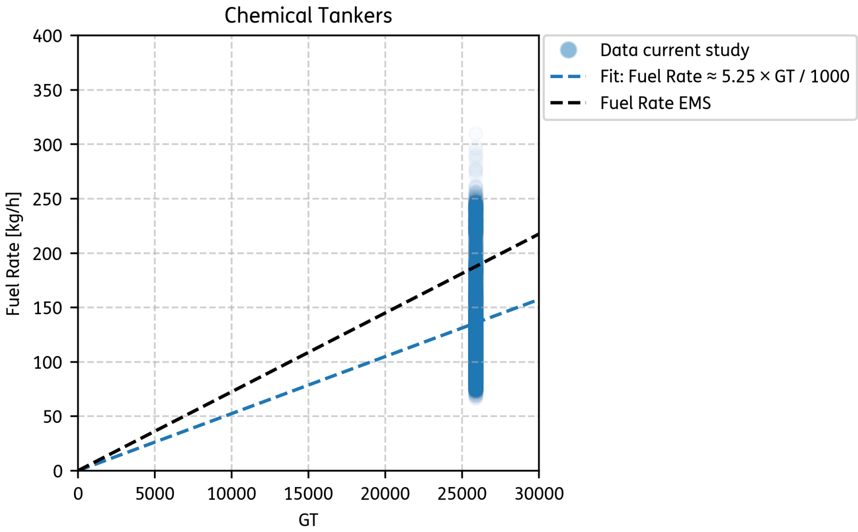

Figure D.6: Fuel rate for power generation versus gross tonnage for chemical tankers. The figure shows collected data in current study (blue scatter), a linear fit to that data, and the EMS-based relation; the corresponding fit and EMS coefficients are listed in Table D.1.

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