Port Energy Demand Model for Implementing Onshore Power Supply and Alternative Fuels

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Abstract

A feasibility study was conducted on the energy and peak power demand of ships for utilising the Onshore Power Supply (OPS) and transitioning to using alternative fuels. The port of Plymouth was adopted as a case study. Four types of ships, Ro-Pax, Tanker, Bulk Carrier and General Cargo, were in operation at the port. A representative vessel was selected for each ship type to simulate the average ship's cargo capacity and engine power. One year of real port operations, including material handling equipment and trucks, were simulated. The peak power and annual energy demand for the OPS system were calculated to be 5.95 MW and 7.1 GWh, respectively. Implementing an OPS system saved 83.6% of total CO_2. Fuel volumes were calculated for conventional and alternative fuels, the volume of liquid hydrogen was around 3.5 times that of the conventional fuel, whereas methanol required less mass and volume than ammonia and hydrogen.

Keywords: Maritime decarbonisation, Real port and ship data, ARENA simulation, Alternative fuels, Onshore Power Supply, Greenhouse emissions.

1. Introduction

While the emissions of ocean shipping have substantial implications at the national level, ports play a distinctive role in shaping local and regional emissions and air pollution scenarios. The increasing sea traffic congestion in ports, driven by increasing demand, and the multitude of port-related operations such as loading, unloading, bunkering, and road transport within the port area collectively give rise to a carbon-intensive zone. The detrimental effects of port-related operations are felt acutely in the local environment, impacting air quality and subsequently causing severe health problems for nearby communities (Azzellino et al., 2013; Alzahrani et al., 2021). The gravity of these environmental concerns is not confined to port boundaries. Research by Corbett et al. (2007) indicates that approximately 70% of ship-induced emissions are released within approximately 216 miles of the coast, while in the United Kingdom, an alarming 1 million tonnes of CO_2 are emitted from ships while at berth in ports (Environment, 2022). Shockingly, as a result of air pollution originating from shipping activities in European waters, it is estimated that 50,000 premature deaths occur annually (Brandt et al., 2011). On a global scale, shipping is responsible for a significant share of environmental emissions, contributing 10-15% of global SOx and NOx emissions and 2-3% of global CO_2 emissions. Without prompt intervention, these percentages are poised to rise significantly by 2050 (Zis and Psaraftis, 2019; Bjerkan and Seter, 2019). Furthermore, ports serve as the central nexus for cargo transport, leading to substantial air pollution stemming from various land transport vehicles and port machinery. Often, these machineries rely on comparatively dirty fuels without adequate exhaust treatment systems, running incessantly. This results in the release of harmful air pollutants, including Carbon Dioxide (CO2), Sulphur Dioxide (SO2), Nitrogen Oxides (NOX), Particulate Matter (PM), Ultrafine particles (UFPs), and Black Carbon (BC), all of which pose severe threats to human health (NABU, 2015).

On the other hand, as stated by Bjerkan and Seter (2019), there is a limited number of publications in the literature focusing on port sustainability, found under different names such as port energy environmental plan (Acciaro et al., 2014a), green port program (Acciaro et al., 2014b), plans for environmental protection, climate protection, climate initiative (Schipper et al., 2017), plan for prevention and reduction of pollution, green port plan (Anastasopoulos et al., 2011) and clean air plans (Anastasopoulos et al., 2011; Gibbs et al., 2014). However, the most important and internationally known action is the World Port Climate Declaration, derived from the World Port Climate Initiative (WPCI). This initiative points out the specific objectives such as a) reducing CO2 from deep sea vessels calling at ports, b) exploring the reduction of CO2 from port operations, c) exploring how to reduce CO2 from inland shipping and other modes of transport, d) exploring how to promote alternative energy sources and e) Calculating the CO2 footprint of ports (Fenton, 2017).

Furthermore, the International Maritime Organization (IMO) indirectly reduces local pollution by promoting sustainable transportation and cleaner fuels. IMO has been pivotal in orchestrating efforts to curb emissions from international shipping, but regulating emissions within ports remains complex (Notteboom et al., 2019). It is imperative to recognise the profound influence wielded by local and regional regulations, often instigated by specific environmental and public health concerns, on port operations. These localised regulations exert significant sway over energy consumption, emission reduction strategies, and the overarching sustainability of ports (Fageda et al., 2018). Recently, IMO has updated their climate target for reducing greenhouse gas (GHG) emissions from shipping, aiming for a 20% reduction by 2030 and a 70% reduction by 2040. The strategy also introduces a goal for scalable zero emission fuels (SZEFs) to make up 5% of shipping fuel demand by 2030, with hopes of reaching 10%, but there is concern that the strategy allows for 'near zero' emission fuels, potentially slowing the transition to net zero (Petroni et al, 2023).

The energy landscape within ports represents a crucial focus within the maritime transport industry, prompting growing scholarly and policy interest. Some research emphasises the pivotal role of ports as critical nodes in the global supply chain, underlying the need for a closer examination of their energy consumption and environmental implications. This issue, as articulated by Roos and Neto (2017), the European Sea Ports Organization (ESPO, 2019), and Canbulat (2021), is a critical aspect of seaport operations. The sources of energy used in ports are pivotal for the adoption of cleaner resources and the pursuit of decarbonisation targets in these critical maritime hubs.

In recent years, the importance of recognising and managing energy-related activities within and around ports has grown due to factors such as emissions control, corporate environmental responsibility, energy trades, and a business focus on energy efficiency. While some port authorities have successfully implemented energy efficiency policies to promote environmentally friendly shipping activities, others have been slow to act. However, collaboration among seven port authorities from five Mediterranean countries has resulted in the development of a port energy management plan for various zones, signalling a growing interest in the topic (Canbulat, 2021).

According to Acciaro et al. (2014a), effective energy management in future ports can deliver significant productivity benefits and increase revenue streams, thereby enhancing the port's competitive position. The authors point to the examples of Hamburg and Genoa ports, which have successfully organised and rationalised their energy needs but note that their energy management plans are based on city strategies. Therefore, there is a need for more port-specific energy management strategies that consider each port's unique characteristics and requirements.

Sdoukopoulos et al. (2019) observe that European port authorities have been actively working to develop effective strategies to create green ports in recent years. As the shipping industry faces increasing pressure to reduce its environmental impact, port authorities must develop comprehensive energy management plans that not only reduce emissions but also enhance energy efficiency and sustainability.

Alongside emerging energy efficiency measures for ships, there are tools and technologies for transitioning to sustainable ports. Bjerkan and Seter (2019) presented a well-structured review describing these tools and technologies. With a broad categorisation, all technologies and tools are divided into four groups, (i) *port management and policies* (i.e., port plans, management of environment and energy, monitoring, concession agreements), (ii) *power and fuels* (i.e., electrification, wind, solar, wave and tidal energy, methanol and hydrogen, LNG), (iii) *sea activities* (i.e., speed reduction, efficient vessel handling) and (iv) *land activities* (i.e., technological shift: trucks and drayage, modal shift, efficient truck operations, automation and intelligence). Selecting the most appropriate measures and tools for a target port needs comprehensive feasibility studies, considering parameters such as visiting ship statistics and particulars, energy type and availability, modes of transport within and around the port, and available land area for facilities, storage and port equipment. In order to make a comparison between these measures and tools, a life cycle assessment (LCA) analysis should ideally be conducted, although that is out of the scope of this paper. In this paper, a feasibility study was conducted using the developed port energy demand model for one UK port (Plymouth) on what is needed to provide OPS and a future transition to implementing alternative fuels in ports. Therefore, this study falls in the category of *power and fuels* based on Bjerkan and Seter (2019).

Moreover, life cycle analysis of alternative fuels is important, and decisions should be made based on LCA considering parameters such as what energy is used to generate fuels and how it is transported to the end users. To the best of the author’s knowledge, there is no life cycle analysis model that exists which can make a decision on the best alternative fuel based on the specific requirements of the target port. This can be attributed to the fact that tank-to-wake LCA models heavily rely on the existing data covering feedstock extraction, processing, transport to conversion site, conversion to product fuel, bunkering and finally combustion in a ship. It is possible to conduct this kind of analysis for conventional fuels whereas due to the lack of data on most elements listed LCA models have not been developed yet. However, it is important to note that initial attempts started to take place on that front, for instance, IMO Marine Environmental Protection Committee (MEPC) published a report (MEPC 80/7/4) (2023) which sets out the IMO's framework for assessing well-to-wake GHG emissions for alternative fuel pathways. This study assumes that all alternative fuels are completely generated using green energy to investigate what are the emissions sources and their distributions in the port. Further study should investigate the required capacity and cost of power plants that can generate green energy to produce alternative fuels as well as develop an LCA model aligned with the IMO's tank-to-wake LCA framework

The studies in the literature attempted to predict the power and energy requirements of ports by categorising them into three groups such as large ports (over 2000 calls in a year), medium ports (500-2000 calls in a year) and small ports (under 500 calls in a year) based on the number of port calls (Chase et al., 2020; Raucci et al., 2019). However, this prediction solely on port calls can mislead the port authorities and investors as port energy demand strongly correlates with the ship type and ship operational characteristics. For example, a RoPax vessel may require over 4 MW power demand, whereas this number is only around 0.4 MW for a standard commercial ship. When berthing times are also taken into account, energy demand may show huge varieties. Therefore, port energy demand predictions based on port calls are vague and cannot be taken as a basis for investment decisions. The problem is a port-specific issue, requiring a tailor-made assessment for the target port.

At the regional level, the European Union (EU) has issued a directive (EPRS, 20221; EPC, 2014) that mandates that port facilities be included in national policy frameworks. This directive requires member states to invest in onshore power supply (OPS) systems for vessels, particularly in Trans-European Transport Network (TEN-T) Core Network ports, by 31 December 2025. Additionally, the European Sea Ports Organisation (ESPO) has published the Green Guide (ESPO, 2012) and the ESPO Environmental Report (ESPO, 2019) to support port authorities in engaging in air quality management, including the provision of OPS facilities (Martínez-López et al., 2021). In the study conducted by Bullock (2020), it was elucidated that the implementation of shore-power has the capacity to entirely mitigate local air pollution emanating from vessels during their berthing phase and contribute to the reduction of greenhouse gas emissions. This is achieved by connecting ships to electricity grids during their time at the dock, thereby removing the necessity of utilising their diesel engines while berthing in ports. Shore-power, as an established and currently accessible technological solution, is experiencing a burgeoning adoption on a global scale; however, it remains comparably infrequent within the UK.

The working principle of an OPS is connecting the ship to the local electricity grid while the ship is at berth, with the ship switching off its auxiliary engines during this period. In general, the auxiliary engine is used for so-called 'hotelling' activities, such as providing shipboard heating, ventilation and air-conditioning, as well as powering shipboard cargo-handling machinery in some cases. These auxiliary engines typically burn fossil fuels within the port. Berthing times show variety based on the ship and, hence, cargo type. Required energy demands for bunkering (re-fuelling) and hotelling activities, as well as other port activities, are calculated to understand the needed volume for any potential alternative ‘future’ fuels to meet this demand.

The estimated cost of renovating OPS for cruise and container vessels is approximately $1 million per vessel, with higher costs for port infrastructure, such as $10 million for one cruise berth at the Port of Halifax and maintenance costs of $10.3 million for each berth at the Port of Long Beach. Implementing the OPS system can reduce carbon emissions in UK ports by 10% (Zis et al., 2014). The Port of Kaohsiung in Taiwan has successfully reduced CO_2 emissions by 57.2%, NOx by 49.2%, and SO2 by 63.2% through the use of OPS (Chang and Wang, 2012). In addition to environmental advantages, OPS has economic benefits for countries with an energy price of less than USD 0.19 per kWh, as electricity usage and maintenance costs can be reduced by up to 75% (Yiğit and Acarkan, 2018). However, the energy efficiency of OPS is not yet known based on the International Maritime Organization (IMO) study (IMO, 2016a), although OPS has more available energy sources and utilises low-carbon or renewable energy sources in a highly productive manner.

Between 2000 and 2010, only 12 ports implemented OPS (WPCI, 2017, cited in Innes and Monios, 2018). Today, 69 ports worldwide use OPS as seen in Fig. 1, with Europe and North America being leaders in the technology. In the last decade, more EU countries have implemented this technology, and this trend is expected to continue with the ports of Bremen in Germany and the Port of Flam in Norway (Maritime Executive, 2020). However, a recent research report by the British Ports Association (BPA) indicated that none of the ports in the world has implemented OPS without public support or subsidies (BPA, 2019). Analysis conducted by Arkevista on BPA revealed that the overall power consumption of vessels at berth in the United Kingdom was over 641 gigawatt-hours of electricity in 2019, accounting for about 0.5% of the total energy demand in the country. Challenges to implementing OPS include uncertain energy planning, potential lack of demand, and high electricity costs (twice that of other countries), which makes it difficult to compete with marine fuel costs in the UK.

Thus, it is necessary to evaluate each port and ship combination in every country for investment or government support to enhance the efficiency and feasibility of port operations.

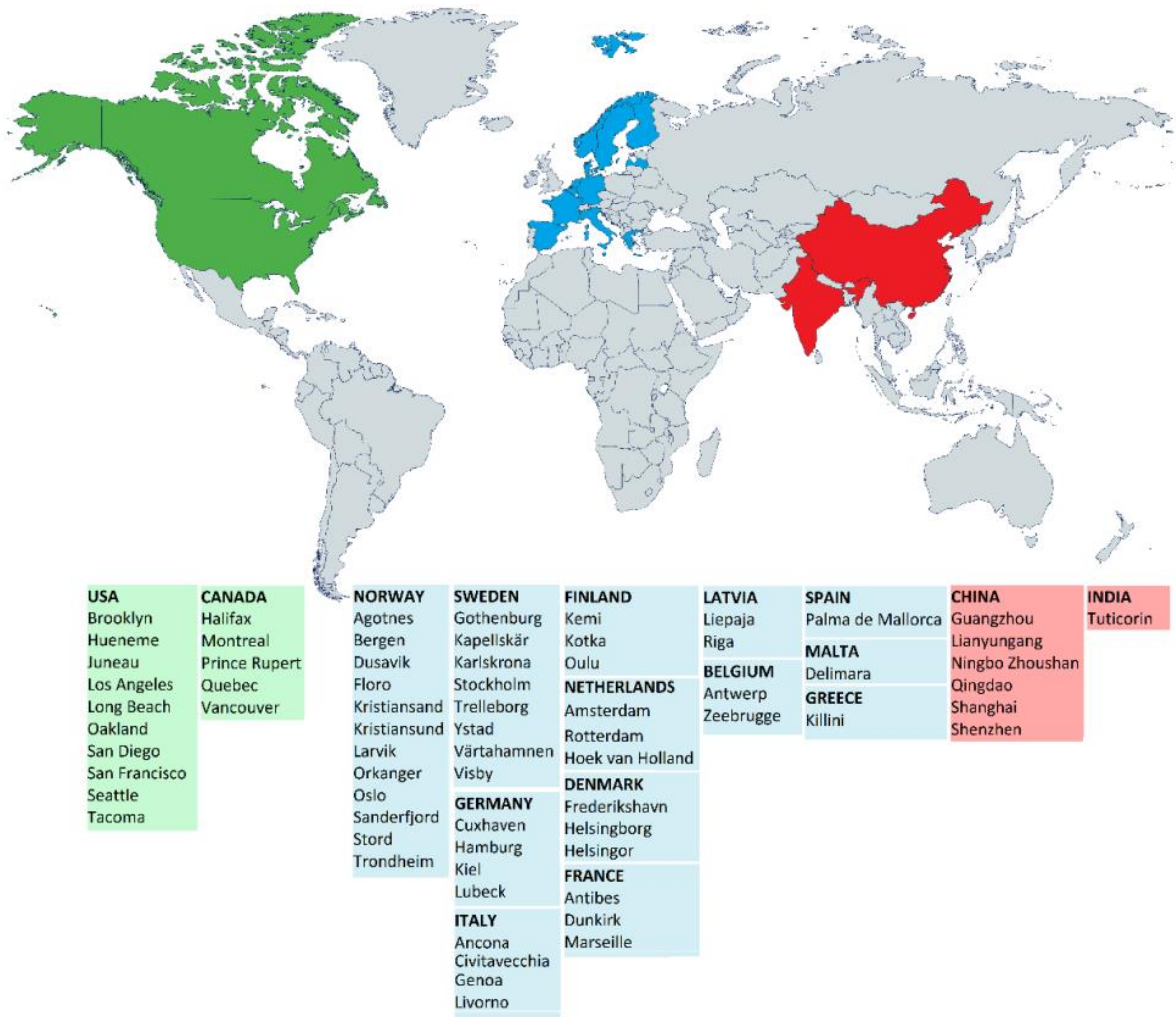

Fig. 1 Available OPS facilities in ports around the world in 2020 (Canbulat, 2021) (Data collected from WPCI, 2017, Killiniport (2020), Innes and Monios (2018), World Ports Sustainability Program (2020)).

On the contrary, the implementation of onshore power supply (OPS) systems in ports faces significant challenges that revolve around availability, cost, and technological problems. Scholars have classified these challenges based on their nature (Zhang, 2016; Ssali, 2018; Sciberras, Zahawi, and Atkinson, 2015) and are presented below:

- There is a high capital expenditure required for port operators to build and maintain shore structures for OPS implementation.

- There is a high capital cost for shipowners when retrofitting vessels with OPS systems, which may not be financially viable.
- Ships do not have standardised voltage and frequency specifications. While some ships use a 60 Hz frequency, most ports operate on a 50 Hz grid.
- The cost of electricity on the shoreline is higher than the availability of auxiliary engines, which may discourage shipowners from using OPS.
- OPS supply is still limited worldwide (Ssali, 2018).
- Connectors and cables used in OPS are not standardised globally.
- Proper policies for OPS implementation have not been established.
- The use of high voltage electricity supply poses health and safety issues and requires load requirements around ports.

In their 2020 research, the BPA (2020) concluded that onshore power supply (OPS) is likely to be a component of the emissions reduction mix for ships at berths in UK ports in the future. However, there are significant challenges to implementing shore power in the UK, which include:

- The primary obstacle is the high capital cost, necessitating public support to help meet the prohibitive costs, especially concerning energy networks and generation, especially electricity network capacity, which needs to be quantified.
- The electricity price must be competitive for UK ports since it is considerably higher than in other countries that offer shore power at their ports.
- The BPA identified demand as a risk, claiming that vessels calling in the UK do not consistently demand shore power. Currently, unlike EU directive, UK does not have a

policy or similar directive on shore power implementation. This increases the investment risks

Nevertheless, the UK Chamber of Shipping (UKCoS, 2021) is convinced that using shore power in ports can substantially and rapidly reduce local air pollution and noise and lower greenhouse gas emissions.

The provision of onshore power supply (OPS) is considered a sustainable solution for the maritime industry, owing to its potential to charge battery-powered short-sea vessels. While several European countries have implemented high-voltage port connections since 2000, the UK has been slow to invest in shore power infrastructure, with only two commercial ports currently providing this service. Given the UK's commitment to achieving net-zero greenhouse gas (GHG) emissions by 2050, the International Maritime Organization's GHG Strategy, and the European Union's Fit for 55 policies, electrification is expected to play a vital role in the decarbonisation of the maritime industry.

According to the research conducted by the BPA and UKCoS, it is important to evaluate the feasibility of onshore power supply (OPS) to determine the appropriate incentives for encouraging ships to use OPS or other potential energy sources, taking into account the energy and peak power demands of ships.

1.1 Aim of this research

To the best of the authors' knowledge, no study exists that proposes a scientific method that can be used for predicting port energy requirements on a target port, considering port traffic and ship-specific port operation flow. This study proposes a novel port energy demand model considering the energy demand of vessels at berths, material handling equipment and, terminal trucks and port-related land-based transportation activities with a holistic approach. The model can be utilised at any port and provides a detailed distribution of power and energy demand analysis, enabling the required feasibility investigations on the initial and operational costs of the possible net-zero solution. This can give a clear idea, provide better alignments, and help stakeholders understand what is needed. Moreover, the model provides detailed fuel consumption and GHG emissions predictions for the target port.

This paper delves into the multifaceted aspects of energy consumption in ports and the associated environmental consequences. It aims to analyse current initiatives and recommend strategies to mitigate the environmental impact of ports further, offering valuable insights into the ongoing pursuit of sustainable maritime practices.

This study contributes to the acceleration of the transition to net-zero fuels and decarbonisation in the maritime industry by focusing on the assessment of peak power and energy demand of berthed ships and their associated port operations, including trucks and material/cargo-handling equipment as listed below:

i) Reducing emissions, benefiting local communities and the port hinterland by calculating the power capacity needed for an OPS system.

ii) Mitigating GHG emissions in line with set targets, combating the climate crisis.

iii) Rationalizing energy use due to scarcity and high costs, aiding in energy efficiency.

iv) Assessing alternative fuel demand for ship energy needs and bunkering infrastructure planning.

v) Accurate electricity demand estimation for OPS requirements and emission savings in the maritime sector, aiding decarbonisation.

Moreover, this study employs discrete event simulation (DES), a widely utilised modelling approach in decision support tools for the shipping, logistics, and supply chain management industries (Seay and You, 2016). A wealth of literature exists regarding simulation studies in the shipping industry. For instance, using DES, Legato and Mazza (2001) developed a simulation model for berth planning and resource optimisation at a container terminal. Woo and Oh (2018) summarised the application areas of simulation in the shipbuilding industry. Several simulation software and techniques, such as Simul8, AutoMod, and Arena (Wales and AbouRizk, 1996), are employed in DES. Recently, Canbulat (2021) conducted a comprehensive literature review by analysing over 500 research outputs on the DES Arena application in ship and port operations. The researcher discovered that while research on the DES Arena application in container ports is available, only a limited number of publications exist in the literature for the Arena application on other types of ports. Canbulat et al. (2022) demonstrated that the DES Arena application is a unique and capable tool for analysing port energy consumption. The research explores the utilisation of DES Arena application in ship and port operations to analyse port energy consumption and simulate various scenarios for enhanced efficiency. The model can be used at any port and offers a comprehensive power and energy demand analysis, enabling stakeholders to make informed decisions for energy management and emissions reduction.

In this study, a year of port operation is simulated using a discrete event simulation method, implemented in the ARENA software. Peak power and energy demand are calculated based on this simulation. The port of Plymouth, located on the south coast of Devon, southwestern England (UK), at the entrance of the English Channel (Latitude 50° 22’ N, Longitude 04° 09’W within Plymouth Sound) is selected as a case study in this work. The selection of this port as a case study is principally motivated by its commitment to achieving net-zero emissions, thereby aspiring to establish a pioneering presence in the region. Additionally, the proximity of the port of Plymouth to the urban centre makes it a pertinent subject of study, as the research aims to yield outcomes that positively contribute to mitigating local air pollution.

2. Methodology

The prime requirement to implement the OPS system and alternative fuel transition scenarios is an extensive power requirement analysis for the ships and associated port facilities. Auxiliary power requirements are considered for the OPS system, whereas ship propulsion (bunkering) is considered when alternative fuel scenarios are analysed. The port of Plymouth provides services for RoPax, Tanker, Bulk Carrier and General Cargo vessels. Bunkering is presently only provided for RoPax vessels, although providing bunkering services to all ship types is proposed in the alternative fuel scenarios, where their volumetric energy density is less than current fuels and hence likely to require more frequent bunkering. A methodology provided by Gutierrez-Romero et al. (2019) is adopted in this study. The methodology adopted follows the framework:

1. A database is created for the ships berthed at the port. One year of ship data between 2020-2021 is taken. The name and type of the ship, deadweight ton (DWT) capacity, IMO numbers, entry and departure dates, and the time at berth are retrieved from Marine Traffic (www.marinetraffic.com). The data is filtered based on the ship type in order to make a disaggregated power analysis for each type of vessel.
2. Following a field observation visit to the port, four process flows are generated for RoPax, Tankers, Bulk Carriers, and General Cargo vessels. The process flows include ship operation steps such as cargo loading and unloading operations and truck and other material handling equipment (e.g., cranes and wheel loaders) operations. At the same time, the past berth call history of the port was analysed. The process flow and data analysis results are combined to build a discrete event simulation model for the port in Rockwell Automation ARENA Simulation Software (Automation, 2022).

3. Once one year of port operation is simulated using discrete event simulation in ARENA, port operation process timings and possible queuing times of the processes, i.e., truck waiting times and material handling waiting times in terms of the hour (h), were obtained.
4. A statistical analysis was next conducted to select a representative vessel for each ship type. The analysis was made based on the DWT distribution of the same ship category. As the distribution trend was defined, an average ship capacity was found, and a representative ship from the same database was selected to represent each target ship type.
5. Once representative ships are defined for each ship type, detailed ship particulars such as main dimensions, main engine, auxiliary engine, service speed, fuel consumption (at service speed), tank capacities, previous routes, endurance, port calls per year, hotelling hours per call are collected from different resources such as ship companies' websites, Marine Traffic (www.marinetraffic.com), FleetMon (www.fleetmon.com) or Vesselfinder (www.vesselfinder.com).
6. Based on the obtained timings (h) from the simulation, all power-consuming elements within this process are multiplied by the operation times, energy demand in kWh and peak power demand in kW is calculated by considering the load factor of each element.
7. The fuel consumption and GHG emissions of each element in the process were calculated.
8. Bunkering calculations and related energy consumption are calculated for the alternative fuel scenarios based on the representative ships' voyage scenarios.

2.1 Analysis of Marine traffic in Port of Plymouth

The port of Plymouth is selected as a case study in this work as it is a representative UK port. Plymouth is a medium-size UK port, ranked 21st in 2021 amongst other UK ports (DfT, 2021).

The port is divided into three basins: Millbay docks, Victoria wharves and Cattedown wharves. Victoria Wharves delivers services for Bulk carriers and General cargo vessels, while Cattedown Wharves provide services for Tankers and General cargo vessels. Millbay is dedicated to RoPax vessels. Only RoPax and commercial cargo vessels are considered in this study. The marine traffic analyses were conducted for a one-year period between 2020 and 2021. Fig. 2 presents the pilotage chart for the port and illustrates all wharves.

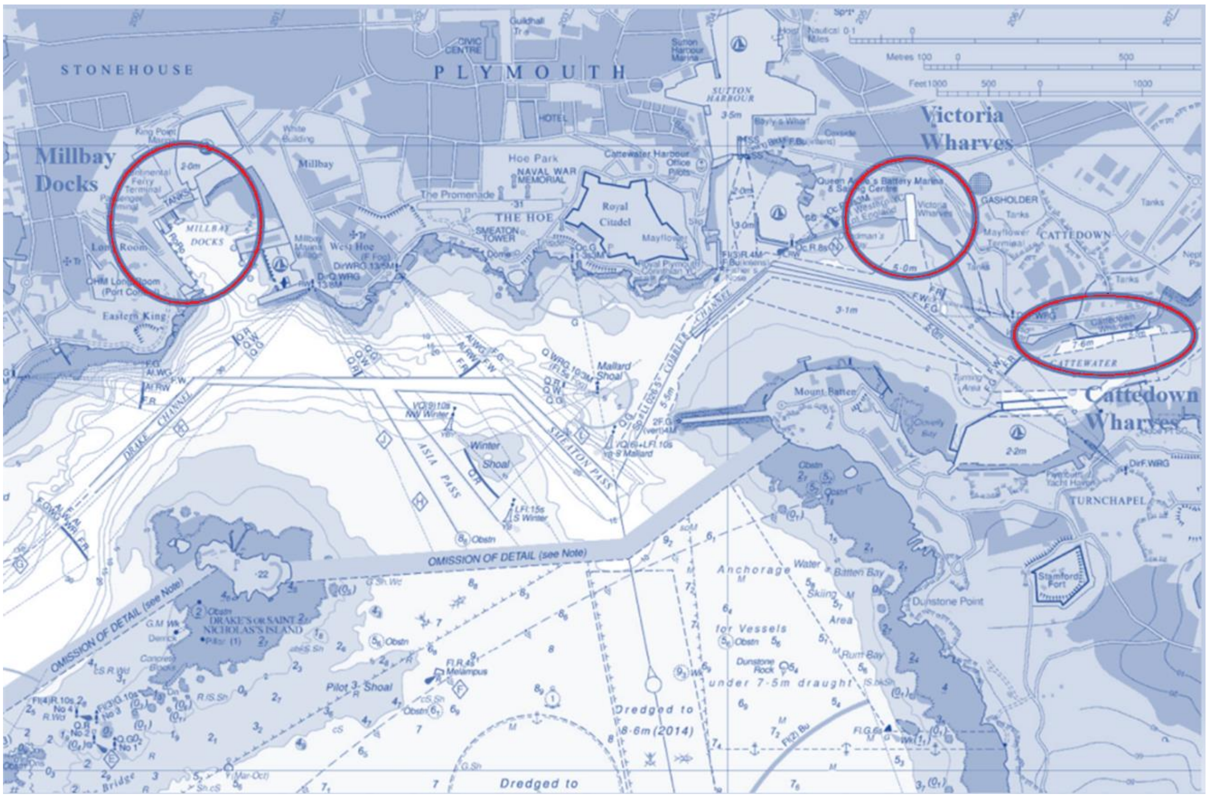

Fig. 2 Pilotage chart of Port of Plymouth (Adapted from Harbour Guides (2015)).

- Millbay Wharves: Serves to Ropax vessels, which mainly carry people, cars and coaches with limited lorry carrying capacity. There are two berths available here. Ropax vessels mainly carry self-moving cargo, and rarely they get trailers without tractors, but when they do, they use their own tractors to move around this kind of cargo.
- Victoria Wharf: Serves general cargo and dry bulk carrier vessels. This is a single-berth wharf which can serve one vessel at a time. Victoria Wharf has two large mobile cranes and three wheel-loaders to load and discharge ships.

- Cattedown Wharves: Serves to liquid bulk (tankers) vessels and general cargo vessels. It has two mobile cranes and a wheel-loader, and uses them to handle general cargo such as pallets, sacked or boxed goods etc. Also, most of the general cargo vessels have their own cranes to load and unload cargo.

Furthermore, cargo vessels (dry bulk, tanker and general cargo) trigger a series of truck movements to either load or discharge them. The port is located in the heart of the city, therefore, what is important about truck movement is the number of cycles required for each vessel, as each cycle generates certain emissions calculated within this study. From an operational aspect, no shore power applications are currently going on in the port of Plymouth, which means vessels at berth run their auxiliary engines to meet their electricity demand. Again, this causes considerable emission generation right in the middle of the city centre.

The percentage distribution of the number of vessels calling at the port of Plymouth based on vessel types is 27.2% for RoPax, 31.3% for tanker, 4.8% for Bulk carrier and 36.7% for General Cargo. Regarding the cargo type, 38% of total cargo in tonnage is categorised as 'other dry bulk', including coal by-products, fertiliser products, cement, aggregates, wood pellets or wood chips (but not the wood pulp), which are carried by General cargo and Bulk Carrier vessels. Oil products, mainly petroleum derivatives, represent 60.4% of the total cargo, including diesel, gasoline, aviation fuel, reformate gas condensate, and benzene heart cut. Finally, RoPax represents the rest of the total cargo traffic, only 1.6%, in the category of road goods vehicles with or without accompanying trailers. It is important to note that passengers are not considered as cargo in these statistics; therefore, the percentage of RoPax is relatively small, although the number of RoPax vessels calling at the port represents 27.2% of the total ship number (DfT, 2021).

The obtained marine traffic data is used in the discrete event simulation to simulate port operations based on real-world historical data. All port operations are simulated, and the simulation output is provided in the form of statistics such as the annual number of ships calling at the port, total time spent in port and average time at the berth in the following section.

2.2 Discrete Event Simulation

Simulation models are widely used in many areas of science and business. Although modelling may be done for different objectives, the most typical one is forecasting how a system will behave in the future (Robinson et al., 2010). A model's predictive ability can stand on its own or form an integral element of a decision-making procedure by providing insight into how a system will respond to various potential options.

A simulation imitates the operation of a genuine system or process across time. Simulation can be done by hand or on a computer. In both cases, simulation involves data acquisition, or generation, phase along with identifying operational characteristics of the actual system to represent the real world successfully. After a simulation model has been built and verified, it may be used to explore various "what if" scenarios involving the actual system. Simulation modelling may be used as a design tool to forecast the performance of new systems under different sets of conditions, as well as an analysis tool for forecasting the impact of modifications to existing systems (Banks et al., 2014).

In this research, the process flows covering discharging and loading scenarios were generated through field examination and discussions with the port authority. The research team visited Millbay, Victoria and Cattedown Wharves for this purpose Fig. 3 illustrates the RoPax port operation process flow as an example.

After the process flows were developed, the simulation model was created using ARENA software. According to the workflows, the simulation model has defined four ship types as different entities. In other words, the model consists of four sub-models dedicated to each distinct vessel type. In general, all four sub-models contain the simplified simulation steps given in Table 1. In addition to the general steps given in the table, depending on the ship type, specific details distinguish the sub-models from each other (i.e., resources required for operation, material handling equipment and additional steps such as tank cleaning).

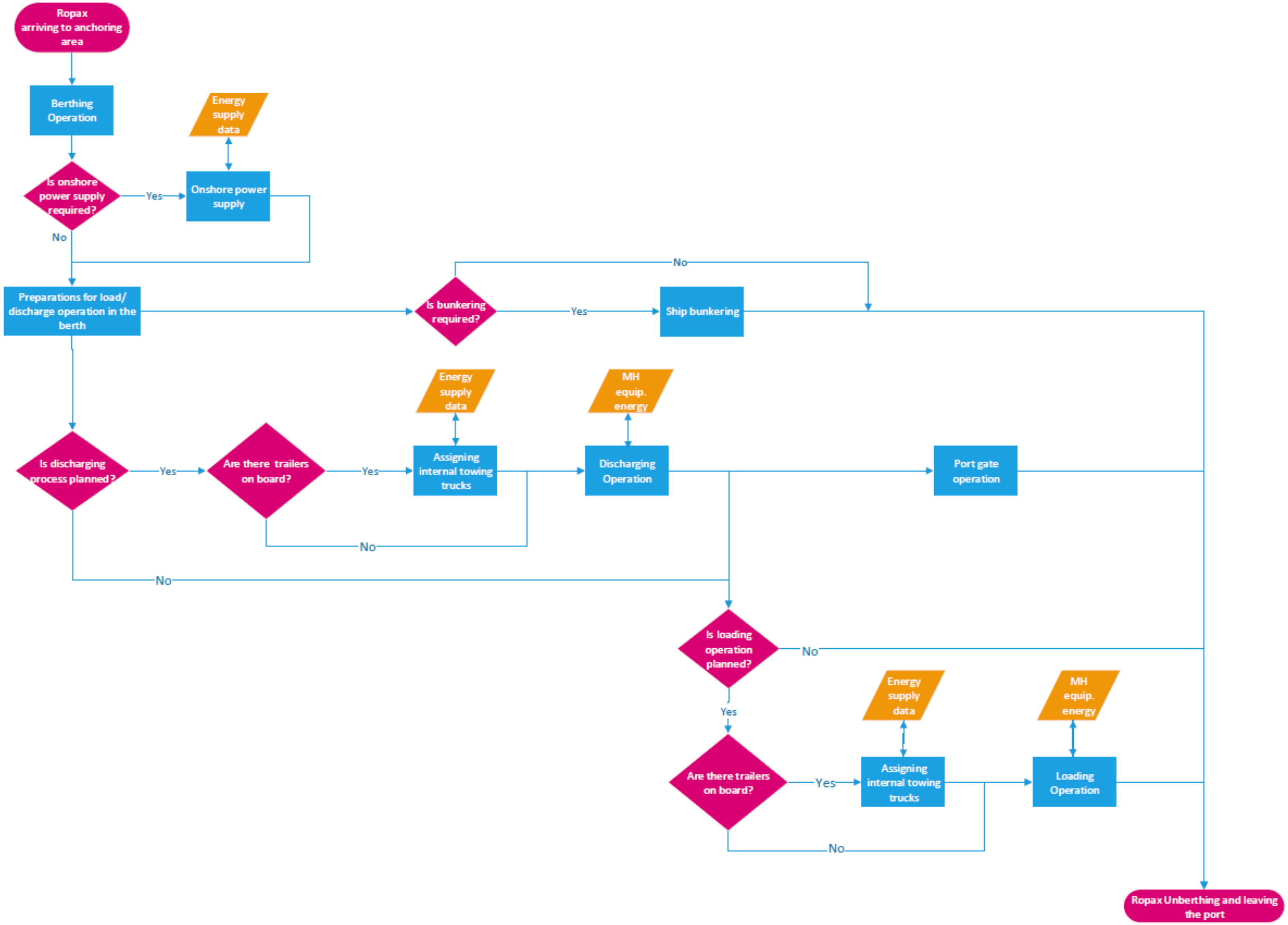

Fig. 3 Designed process flow for RoPax vessels.

Table 1. Simplified simulation steps and definitions.

Step #	**Simplified Simulation Steps**	**Definition / Properties**			
1	Ship arrival	Vessel arrival time interval distribution obtained by historical data. A unique vessel ID is assigned for each individual vessel.			
2	Queue 1	Waiting for a suitable berth slot.			
3	Berthing operation	The vessel seizes the corresponding berth after this point. Operation time distribution obtained by historical data.			
4	Record time 1	After the berthing operation, a timestamp is added for each ship in order to calculate cold-ironing time later on.			
5	Queue 2	Waiting for appropriate material handling equipment (cranes, wheel loaders, or towing trucks, depending on the vessel type).			
6	Discharge/load preparations in the berth	Such as opening cargo hatch covers or doors, arranging onboard material handling equipment (if any), etc. Time distribution is obtained by the experience of professionals at the port.			
Step #	**Simplified Simulation Steps**	**Definition / Properties**	**Step #**	**Simplified Simulation Steps**	**Definition / Properties**
7A	Bunkering decision check	IF YES >>> Go to step 8A IF NO >>> Skip step 8A.	**7B**	Discharging decision check	IF YES >>> Go to step 8B. IF NO >>> Skip step 8B & 9.
8A	Bunkering operation	Time distribution is obtained by the experience of professionals at the port.	**8B**	Queue 3	Waiting for appropriate material handling equipment (cranes, wheel loaders, or towing trucks, depending on the vessel type) for discharge operation.
			9	Discharging Operation	Operation time distribution obtained by historical data. Appropriate hours equipment is in operation.
			10	Loading decision check	IF YES >>> Go to Step 11 IF NO >>> Skip Step 11 & 12
			11	Queue 4	Waiting for appropriate material handling equipment (cranes, wheel loaders, or towing trucks, depending on the vessel type) for loading operation.
			12	Loading operation	Operation time distribution obtained by historical data.
13	Record time 2	After finishing bunkering, discharging, and loading operations, the time is recorded to calculate cold-ironing time.			
14	Release berth and leave	Finally, the vessel leaves the port.			

Probability distributions are generated using historical data obtained from the Marine Traffic website for steps 1, 3, 9, and 12, while professionals' opinions are used for steps 6 and 8A in Table 1. As given in the figure, both square error and goodness of fit tests (Chi-square test) are carried out for each distribution by using ARENA's input analyser module, and a 95% confidence level is achieved overall. Table 2 presents all the distributions obtained from historical data, while the distribution details can be seen in Appendix A. Overall, the average square error of the fourteen distributions given in Table 2 is 2.1%, with the highest error calculated at 8.7%. For the goodness of fit test results, all distributions except one showed that there is not enough evidence to reject the obtained distributions statistically. The only distribution found over the limits of the $\alpha = 0.05$ significance level was actually performed with a 4.1% square error; therefore, it is kept within the analysis. It is important to note that, as seen in Table 2, no loading operation is taking place for Tanker and Bulk Carrier vessels according to the information provided by the port authority.

Table 2. Time distributions obtained from historical records.

Vessel Type	Vessel arrival time interval (h)	Berthing operation time (h)	Discharging operation time (h)	Loading Operation time (h)
RoPax	15 + 444 x BETA (0.25, 2.93)	LOGN (0.859, 0.495)	1 + LOGN (1.02, 1.36)	1 + LOGN (1.02, 1.36)
Tanker	WEIB (48, 1.27)	0.32 + LOGN (0.815, 0.287)	NORM (24.5, 5.43)	N/A
Bulk Carrier	70 + WEIB (220, 0.893)	1 + WEIB (6.96, 0.609)	NORM (37.3, 14.1)	N/A
General Cargo	EXPO (37.8)	WEIB(7.11, 0.584)	NORM (37.9, 18.7)	5 + ERLA (11.6, 2)

Where BETA is beta distribution (Shape parameter alpha 1, Shape parameter alpha 2), WEIB is Weibull distribution (scale parameter beta, scale parameter alpha), EXPO is exponential distribution (mean), LOGN is lognormal distribution (lognormal mean, lognormal standard deviation), ERLA is k-Erlang distribution (exponential mean, Erland parameter k) and NORM is a normal distribution (mean, standard deviation).

Based on this information, the simulation model was run a hundred times to simulate the port operation. As a result, the simulation provided the following: the annual number of ships arriving; average onshore power time per arrival, anchorage times, preparation times, total time spent in port; and all waiting time details for each vessel type. In addition, the simulation also provided utilisation of resources such as berths or material handling equipment. Table 3 summarises the critical outputs of the simulation that will enable precise power, energy, and emission calculations in further sections of this study.

Table 3. Simulation results for 100 runs.

Vessel Type	The annual number of ships call (#)			Total time spent in port per ship call (h)			The average time at berth per ship call (h)		
	Average	Min. Average	Max. Average	Average	Min. Average	Max. Average	Average	Min. Average	Max. Average
RoPax	171	137	211	5.0	4.7	5.6	4.2	3.8	4.8
Tanker	197	171	222	33.6	29.7	40.7	24.7	23.9	25.7
Bulk Carrier	30	18	40	61.9	49.5	81.0	37.9	30.7	44.7
General Cargo	231	196	275	42.7	35.7	49.9	26.0	23.8	29.1

According to the simulation results, the average time at berth for RoPax vessels is 4.2 hours, which is the lowest time. Tanker and General cargo vessels follow this with 24.7 and 26-hours average time at berth per port call, respectively. According to the statistics, Bulk Carriers require the longest time at the berth, with 37.9 hours on average. It is important to note that the total times at the port in Table 3 also cover the queuing time before the ship is berthed.

2.3 Selection of Representative Ships

Once the database is created, an analysis is carried out to define a representative ship for each ship type. The representative ship is selected to represent the power requirements of an average ship which belongs to one of the ship types calling at the port. This selection is made based on the DWT capacity of the ships for each vessel type based on the assumption that there is a correlation between the DWT of the ship and the power requirement. For two cases, however, since there are not many different RoPax (only 2 ferries) and Bulk Carrier vessels (7 vessels) calls at the port, the representative ship is selected according to the ship which requires the highest installed engine power.

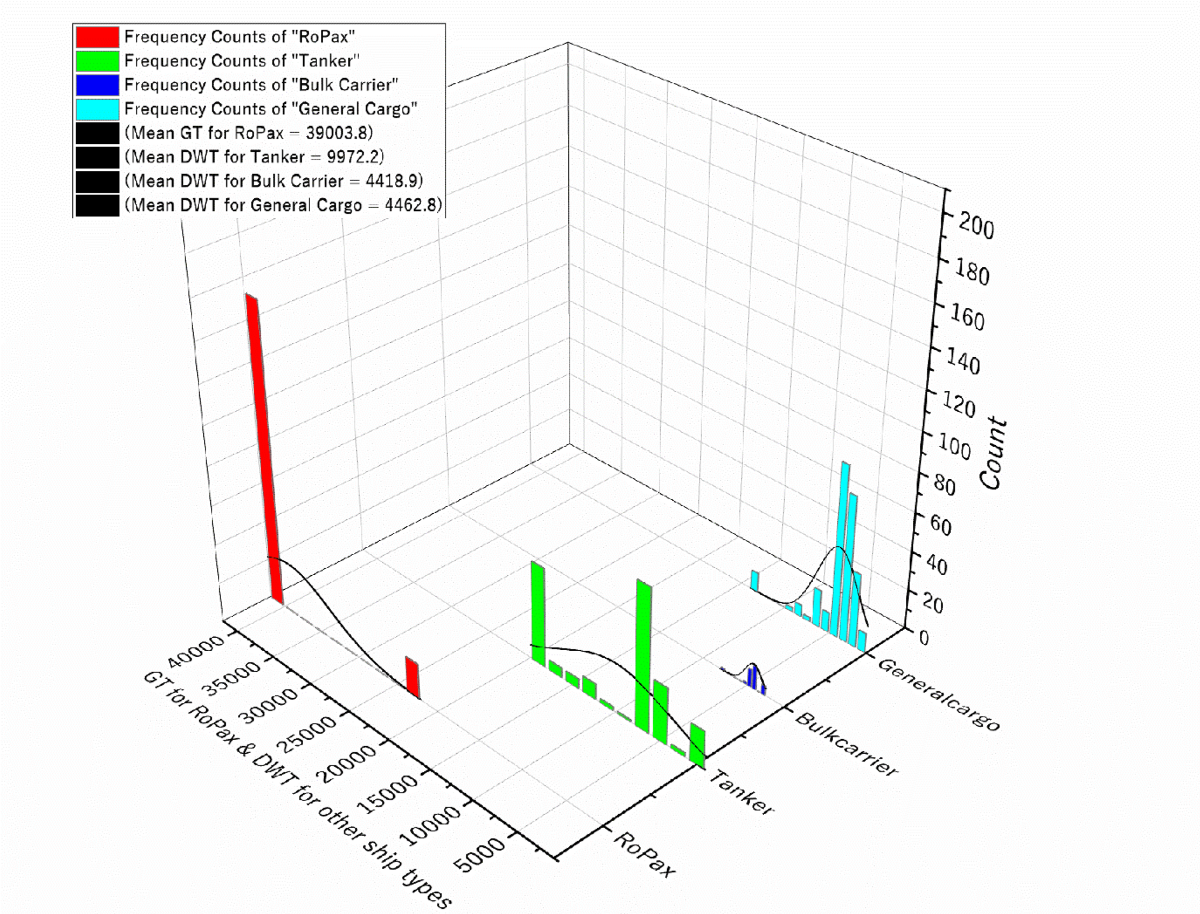

Fig. 4 Statistical Analysis of the four ship types.

Fig. 4 shows the distribution of the ships calling at Plymouth port according to the ship size in terms of DWT for commercial vessels and Gross Tonnage (GT) for the RoPax ferries. The frequency counts of each ship type are given in the figure. The distribution is analysed, and the mean values for each ship type are determined to be used in selecting the representative ships. As shown in Fig. 4, the mean GT value for the RoPax vessel is calculated to be around 39000. As seen in Fig. 4, only two different-sized ferries delivered services for Plymouth during the considered period. It was found that the mean DWT values for commercial vessels are 9972 DWT for tankers, 4419 DWT for bulk carriers, and 4463 DWT for general cargo vessels.

Based on this analysis, a representative ship for each ship type is selected based on the calculated mean DWT values among the ships in the data. Table 4 gives the ship particulars of the selected representative ships. As mentioned, only two RoPax vessels of different sizes are calling at the port. As seen in Fig. 4, the mean GT (~39000) for the RoPax vessel is close to the bigger RoPax vessel in size, which is 41700 GT; therefore, this vessel is selected to represent RoPax vessels. Based on the same approach, vessels with 4216 DWT for Bulk Carrier and vessels with 4497 DWT for General Cargo vessels were selected as representative ships among the same vessel data for each type. The mean DWT value for the tanker was 9972; however, as illustrated in Fig. 4, a very limited number of ships fall in this size range. For this reason, to represent the tanker-type vessels based on the real ship data, the size range of around 7500 DWT vessels is selected, and a real ship from this category is selected to be a representative ship with a 7479 DWT. It is important to note that tankers in this size range represent 37.4% of the total tanker calls.

Table 4. Particulars of the selected representative ships.

Ship Type	**Ro-Pax**	**Tanker**	**Bulk Carrier**	**General Cargo**
Ship Size	41700 GT	7479 DWT	4216 DWT	4497 DWT
Installed Main Engine Power	43200 kW	3840 kW	1530 kW	1950 kW
Installed Auxiliary Engine Power	7200 kW	900 kW	596 kW	522 kW
Service Speed	27 knots	14.2 knots	11 knots	11 knots
Auxiliary Engine load factor	0.64	0.67	0.22	0.22
Auxiliary Engine specific fuel consumption	184 g/kWh	197 g/kWh	238 g/kWh	238 g/kWh
Main Engine specific fuel consumption	177g/kWh	178 g/kWh	188.7 g/kWh	188.7g/kWh
Port calls per year	171	197	30	231
Hoteling hours per call	4.2 hours	24.7 hours	37.9 hours	26 hours
Hoteling hours per year	718.2 hours	4865.9 hours	1137 hours	6006 hours

2.4 Calculation of Energy & Power Requirements

2.4.1 Onshore Power System Energy and Power Demand

Detailed energy and power requirement calculations are conducted based on the operation timings obtained from the discrete event simulation, representative ship particulars, truck features, and material handling equipment. Millbay and Cattedown have 2 berth capacity, whereas Victoria Wharves can provide service for only 1 ship at a time. However, it is important to note that although Millbay has a 2-berth capacity, only one berth is used according to the data. This was confirmed by the Millbay port management. The peak power and energy demand were calculated, assuming all berths in the port were occupied simultaneously.

$$EDOPS_{Total} = \sum_{i}^{K} EDOPS_{annual\,(i)} = AEP \times LF_i \times N_{annual(i)} \times h \times 10^{-3}, \quad (1)$$

where $EDOPS_{annual\,(i)}$ is the annual energy demand (MWh) for onshore power at the port, *AEP* is installed auxiliary engine power (kW), LF_i is load factor (%), $N_{annual(i)}$ is the annual number of ships called at the port, and h is the operating hours of the auxiliary engine at the port (hotelling time). The subscript *i* indicates the vessel type.

Based on Equation (1) and the assumption that peak power demand is equal to the total power demand of the berths while all berths are occupied simultaneously, the power demand (MW) can be calculated using,

$$PPD_{total} = \sum_{i}^{K} PPD_i = AEP \times LF_i \times 10^{-3}, \quad (2)$$

where subscript *K* represents the number of vessel types, and PPD (MW) is power demand.

At present, the ships at berth use their auxiliary engines while they are at the berth. In addition, installed auxiliary power is not required at its full capacity, so a load factor is needed to calculate the required power. The auxiliary engine load factors for each ship type were unavailable for the representative ships in this study. Therefore, the load factors provided by

EPA (Agency, 2017) for each type of vessel derived from the California Air Resources Board's (CARB) Ocean-Going Vessel Survey (CARB, 2005) were used, as shown in Table 4. The auxiliary engine fuel consumption can be calculated based on Equation (3), which is also used in CARB (2007) and Corbett and Comer (2013).

$$FC_{AE(i)} = AEP \times LF_i \times SFOC_{AE} \times N_{annual(i)} \times h \times 10^{-6}, \quad (3)$$

where $FC_{AE(i)}$ is the annual fuel consumption of the auxiliary engine (t) and $SFOC_{AE}$ is the specific fuel consumption of the auxiliary engine (g/kWh).

2.4.2 Energy Demand for Trucks

Annual truck energy demand is calculated based on the truck cycle parameter: the number of required truck operations per ship within the port area. This number is calculated considering the representative ships' cargo volume and trucks' cargo-carrying capacity. Following this, truck operating times are calculated to find the fuel consumption of trucks. Truck fuel consumption is calculated by

$$FC_{Trucks(i)} = T_{cycle(i)} \times N_{annual(i)} \times TFCH_i \times TOH, \quad (4)$$

where $FC_{Trucks(i)}$ represents the fuel consumption of a truck dedicated to each vessel type (litre), $T_{cycle(i)}$ is the number of required truck cycles per ship, $TFCH_i$ is the truck fuel consumption per hour (litre/hour), and *TOH* represents the truck operating hours per cycle. It is worth noting that the subscript of *i* is used in this equation as truck features may show variety based on the vessel type. The parameters used in truck energy demand calculations, as described by Equation 4, are presented in Table 5. It is important to note that T_{cycle} , and $TFCH$ values are provided by the port authority, whereas *TOH* is calculated based on the provided information on distance made by trucks and their average speed.

Table 5. The parameters used in truck energy demand calculations.

Vessel Type	T_{cycle}	$TFCH$ (litre/h)	TOH(hour)
RoPax	2	5.8	1
Tanker	200	6.27	0.25
Bulk Carrier	150	6.27	0.33
General Cargo	150	6.27	0.33

Following Equation (4), annual truck energy demand can be calculated by multiplying the fuel consumption value with a constant of 10.9. The constant of 10.9 represents the conversion value of kWh per tonne for diesel oil (DEFRA, 2012), (DUKES, 2021). This conversion is shown by,

$$EDT_{Total} = \sum_{i}^{K} EDT_{annual(i)} = FC_{Trucks(i)} \times 10.9 \times 10^{-3}, \qquad (5)$$

where $EDT_{annual(i)}$ is the annual energy demand of trucks (MWh).

2.4.3 Energy Demand for Material Handling Equipment

The energy demand of the Material Handling Equipment (MHE) is calculated based on the information provided by the port authority. Cranes and wheel loaders are the MHE used in the port. It is important to note that MHE is used only in Bulk Carrier and General Cargo operations, as this equipment is not involved in RoPax and Tanker operations.

$$FC_{MHE(i)} = N_{annual(i)} \times WLFCH_i \times WLOH + CFCH_i \times COH, \qquad (6)$$

where $FC_{MHE(i)}$ stands for fuel consumption of MHE (litre), $WLFCH_i$ is the wheel loader fuel consumption per hour (litre/h), $WLOH$ is wheel loader operating time (h), $CFCH_i$ is crane fuel consumption per hour (litre/h), and COH is crane operating time (h). It is important to note that there is no parameter in terms of the number of cranes or wheel loaders, as this is included by the $WLOH$ and COH parameters. The subscript *i* indicates that the specific fuel consumption of wheeled loaders and cranes may show variety from berth to berth, depending on the features of the equipment. Table 6 gives the operating hours and consumption rates of the MHE provided by the port authority and machine specifications documents.

Table 6. Material Handling Equipment Operating Times and Fuel Consumption Rates.

Ship Type	Bulk Carrier	General Cargo
COH (hour)	19	13
$CFCH$ (litre/hour)	24	24
$WLOH$ (hour)	26.5	18.2
$WLFCH$ (litre/hour)	20	20

In addition, it is assumed that MHE work at a load factor of 1.0, hence no-load factor parameter is included in Equation (6). The total energy demand of the MHE can be described in Equation (7) in a similar manner to Equation (5),

$$EDMHE_{Total} = \sum_{i}^{K} EDMHE_{annual(i)} = FC_{MHE(i)} \times 10.9 \times 10^{-3}, \quad (7)$$

where $EDMHE_{annual(i)}$ is the annual energy demand of MHE (MWh).

2.5 Calculation of required fuel volume for alternative fuel scenarios

The calculation of the required alternative fuel mass and volume is made considering the average cruise range of the representative vessels, by adopting the methodology proposed by McKinlay et al. (2021). This calculation can be described by,

$$M = \frac{R_D \times C_D \times u_{HFO} \times \eta_{HFO} \times (1 + S_m)}{24 \times S_S \times u_x \times \eta_x} \quad (8)$$

Where M is fuel mass (t), R_D is ship average cruise range (NM), C_D is daily fuel consumption (t), S_m is safety margin (%), S_S is service speed, u_{HFO} is the gravitational energy density of Heavy Fuel Oil (HFO) (MWh/kg), η_{HFO} is the system efficiency for HFO (%) ,u_x the gravitational energy density of the target alternative fuel (MWh/kg) and η_x the system efficiency for the target alternative fuel.

Following this, alternative fuel volume can be calculated using,

$$V = M\left(\frac{1000}{\rho}\right), \quad (9)$$

where V is fuel volume (m^3), and ρ is fuel density (kg/m^3). It is important to note that the system efficiency for HFO is calculated based on the specific fuel consumption of the main engine installed in the selected representative ships, rather than using the average ranges given by McKinlay et al. (McKinlay et al., 2021). Equation (10) describes the calculation of η_{HFO} using the energy density of HFO,

$$\eta_{HFO(i)} = \frac{1}{SFOC_{ME(i)} \times u_{HFO}}, \tag{10}$$

where $SFOC_{ME}$ is the specific fuel consumption of the main engine (g/kWh). The u_{HFO} is taken as 0.0116 (MWh/kg). It is of note that $SFOC_{ME}$ remains the same when it is converted to the MWh/kg. The subscript *i* represents the varying system efficiency depending on vessel type.

Following this approach, weekly, monthly or annual bunkering requirements are calculated. A theoretical cruising range is defined for each vessel type, and the parameters given in Equation (7. Required fuel volume calculations were made based on the assumption that the ships calling at the port had no fuel remaining when they reached the port.

2.6 Emissions calculations

The emission calculations were made based on the calculated fuel consumption for auxiliary engines, material handling equipment and trucks. Emissions factors for each pollutant, provided by the IMO (Faber et al., 2020), are used in the calculations. Equation (11) describes the emission calculations as,

$$TPE_{i,j,k} = \left(FC_{AE(i)} + FC_{Trucks(i)} + FC_{MHE(i)}\right) \times EF_{j,k}, \tag{11}$$

where $TPE_{i,j}$ is the total port emissions (kg), and EF_j are emissions factors (kg pollutant/tonne fuel). The subscript *i* represents the vessel type, the subscript j represents the pollutant type, and subscript k is the fuel type. The emissions calculations are made for the pollutants of Carbon dioxide (CO_2), Methane (CH_4), Nitrous Oxide(N_2O), Nitrogen Oxides (NO_x), Carbon

Port Energy Demand Model for Implementing Onshore Power Supply and Alternative Fuels

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Abstract

A feasibility study was conducted on the energy and peak power demand of ships for utilising the Onshore Power Supply (OPS) and transitioning to using alternative fuels. The port of Plymouth was adopted as a case study. Four types of ships, Ro-Pax, Tanker, Bulk Carrier and General Cargo, were in operation at the port. A representative vessel was selected for each ship type to simulate the average ship's cargo capacity and engine power. One year of real port operations, including material handling equipment and trucks, were simulated. The peak power and annual energy demand for the OPS system were calculated to be 5.95 MW and 7.1 GWh, respectively. Implementing an OPS system saved 83.6% of total CO_2. Fuel volumes were calculated for conventional and alternative fuels, the volume of liquid hydrogen was around 3.5 times that of the conventional fuel, whereas methanol required less mass and volume than ammonia and hydrogen.

Keywords: Maritime decarbonisation, Real port and ship data, ARENA simulation, Alternative fuels, Onshore Power Supply, Greenhouse emissions.

monoxide (CO), Non-methane volatile organic compounds (NMVOC), Sulphur oxide (SO_x), Particulate Matter (PM), Fine Particulate Matter (particles with a diameter of 2.5 micrometre or less) $PM_{2.5}$ and Black Carbon (BC). It is important to note that the effect of engine type on the emissions factors was ignored, which means the same conversion values (kg pollutants per tonne fuels) provided by IMO (Faber et al., 2020) were used without considering the engine category, tier and model year. Fuel emission factors (g/Litre diesel) for trucks and material handling equipment were adopted from Wang et al. (Wang et al., 2019). Although Equation (11) describes the total port emissions, the same approach can calculate vessel-induced emissions during the cruising period. If this is the case, the main engine's fuel consumption can be included in the equation.

3. Results

The power and energy requirements of the port were calculated following the approach described in Section 2.4. One year of discrete event simulations were conducted and the required ship and port-related operation timings obtained. Power and energy demand for the OPS system and energy demand for material handling equipment and trucks were calculated. The total annual energy demand of auxiliary engines, trucks and material handling equipment was calculated to be around 10.7 GWh. Analyses showed that the highest energy demand is for the ships' auxiliary engines, with 66.29% of total energy demand. This is followed by the energy demand of MHE, with 18.94% of the total demand and trucks, with 14.77% of the total demand.

3.1 Calculation of Power and Energy Requirements for OPS system

The power and annual energy demand of an OPS system that would provide onshore electricity to all vessels calling at the port were calculated. Energy demand per ship, depending on vessel types and annual fuel consumption of auxiliary engine use while ships are at berth are also obtained.

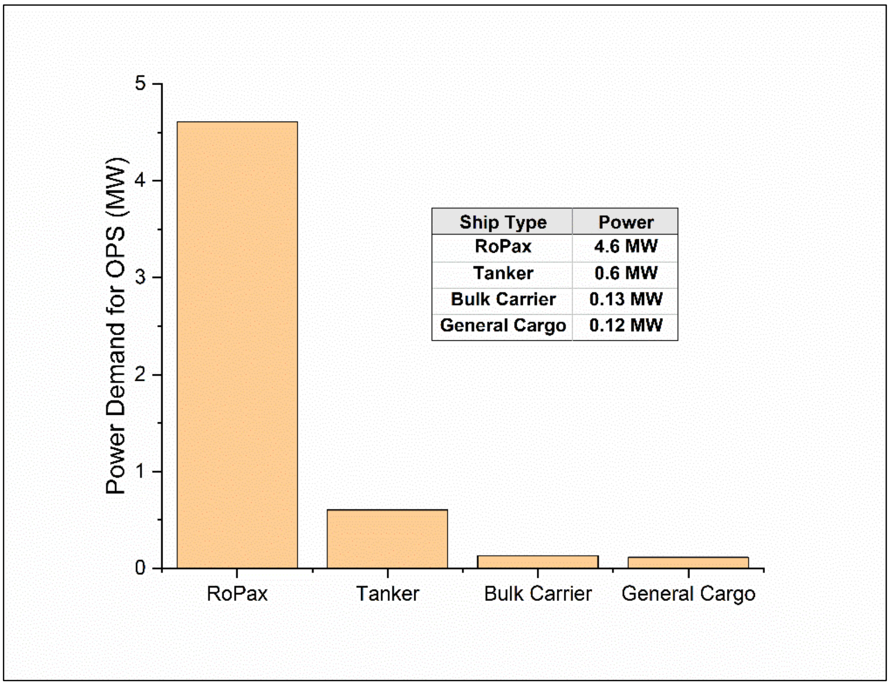

Fig. 5 Power demand for OPS for each ship type.

Fig. 5 illustrates the calculated power demand for OPS, depending on the ship type calling at the port. The peak power demand is estimated to be 5.95 MW, considering the port's berth capacities. The highest power demand occurs in the berth allocation scenario of two tankers, one RoPax and one Bulk Carrier simultaneously. The load factors and auxiliary engine powers used for this calculation are in Table 4.

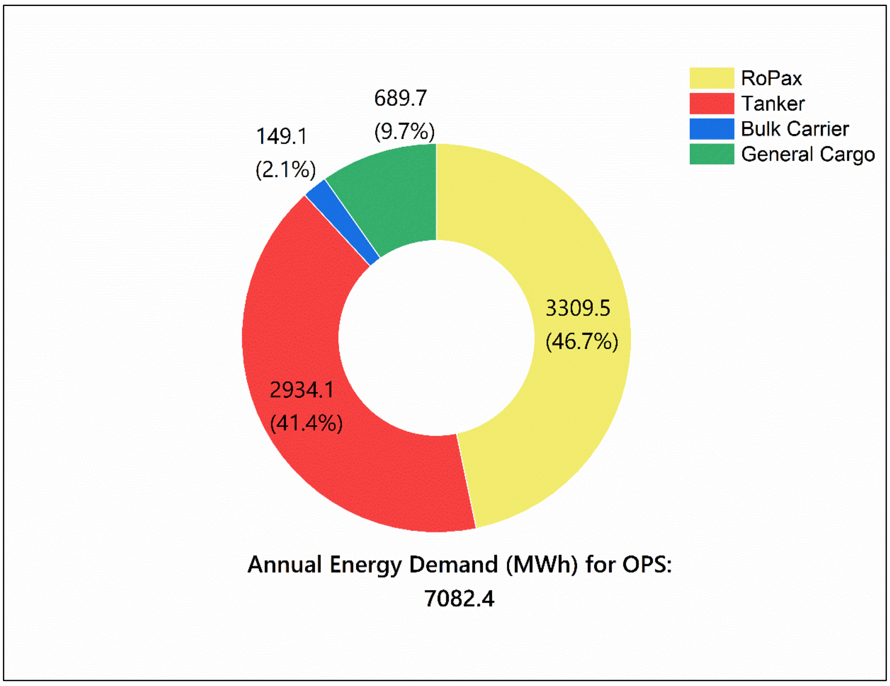

Fig. 6 Annual Energy Demand for OPS, depending on ship type (MWh).

As seen in Fig. 6, the total energy demand for OPS was calculated to be around 7 GWh for a year. According to the results, RoPax-type vessels are the highest energy consumers, with 46.7% of total demand, or around 3.3 GWh consumption for a year. Tankers follow this with 2.9 GWh energy consumption, 41.4% of the total demand. The annual energy need for General Cargo vessels is calculated to be around 0.69 GWh, which is 9.7% of the total demand. As expected from the limited number of Bulk Carriers calling at the port, the energy demand of the Bulk carriers is only 0.15 GWh, with 2.1% of the total demand.

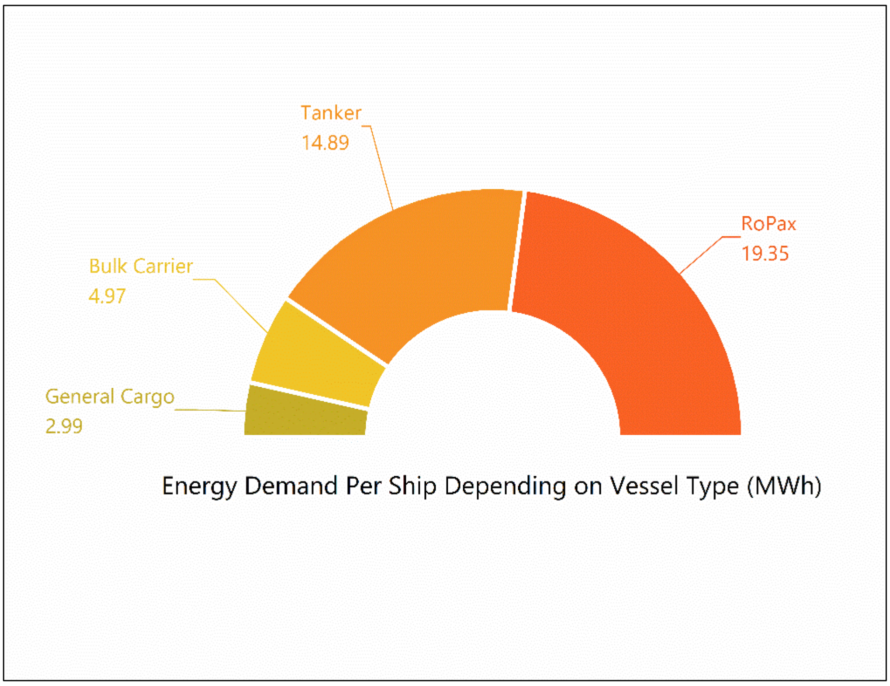

Fig. 7 Energy Demand Per Ship Depending on Vessel Type (MWh).

Fig. 7 presents the annual energy demand per ship, depending on vessel type. As expected, the vessels with highest specific energy demand are RoPax and Tanker vessels, with 19.35 MWh and 14.89 MWh per ship respectively. Interestingly, the energy demand of a Bulk Carrier type vessel is higher, with 4.97 MWh, compared to that of General Cargo, with 2.99 MWh. This can be attributed to the fact that the auxiliary engine operating time of Bulk Carriers is much higher than the General Cargo vessels, although they have similar auxiliary engine power capacity and engine load factors.

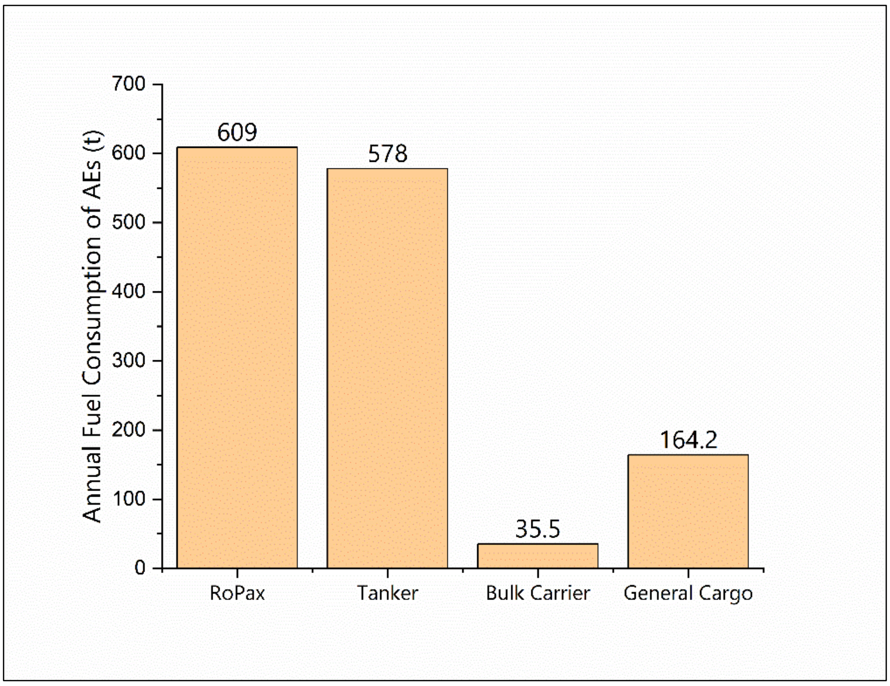

Fig. 8 Annual Fuel Consumption of Auxiliary Engines (t) for each vessel type.

Fig. 8 illustrates the annual fuel consumption of ships while they are at berth. The total auxiliary engine fuel consumption is 1386.6 tonnes. It can be seen in Fig. 8 that RoPax and Tanker type vessels burn the highest fuel volumes with 609 tonnes and 578 tonnes, respectively, equivalent to 43.9% and 41.7% of total consumption. This is followed by General Cargo vessels with 164.2 tonnes of fuel consumption, 11.8% of total consumption and Bulk Carrier vessels with 35.5-tonne fuel consumption, just 2.6% of total consumption.

3.2 Calculation of Trucks' Energy Demand

The annual energy demand of trucks needs to be included to analyse the total energy requirement of port operations. Based on the approach given in Section 2.4.2, the annual energy demand of trucks is presented in this section. The parameters used in the calculation are given in Table 5.

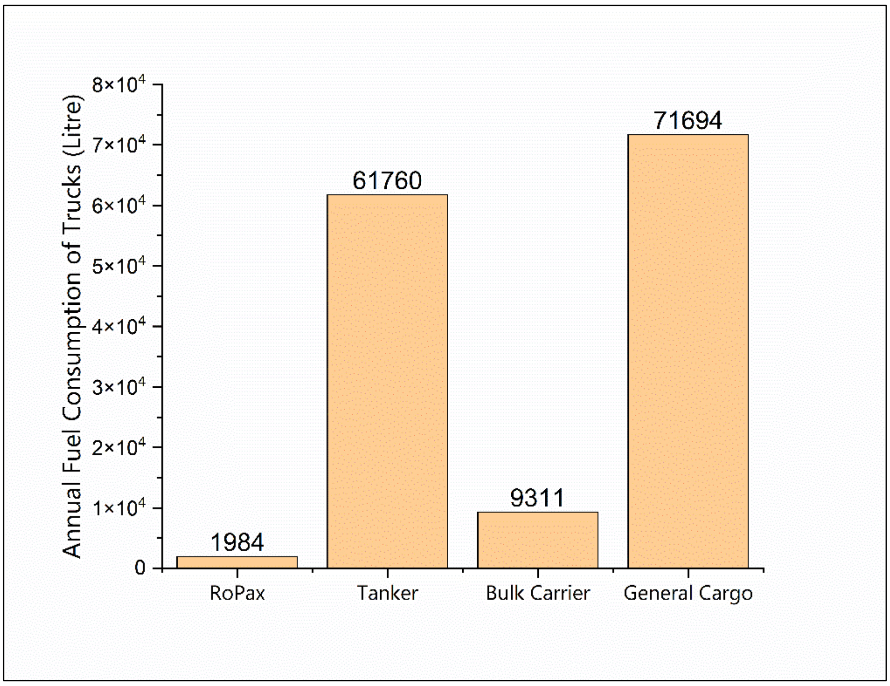

Fig. 9 Annual fuel consumption of Trucks in litre for each vessel type.

Fig. 9 shows the annual fuel consumption of trucks dedicated to each vessel type. It can be seen in Fig. 9 that the annual fuel consumption of trucks dedicated to General Cargo and Tanker vessels is the highest, with 71694 and 61760 litres of diesel. The fuel consumption of the trucks dedicated to Bulk Carrier operations is 9311 litres of diesel, which is comparatively low as expected due to the limited number of Bulk Carrier calls. It is apparent from Fig. 9 that trucks that took place in RoPax operations consumed only 1984 litres of diesel. This can be explained by the fact that only two truck cycles are needed per RoPax vessel, as shown in Table 5. The equivalent energy demands for the calculated fuel consumption values are 22 MWh for RoPax vessels, 673 MWh for Tankers, 101 MWh for Bulk Carriers and 781 MWh for General Cargo vessels. The annual total energy demand for trucks is calculated to be 1578 MWh.

3.3 Calculation of Energy Demand for Material Handling Equipment

Annual energy demand and fuel consumption of MHE are calculated based on the approach given in Section 2.4.3. The parameters given in Table 6 are used in the presented calculations. The results showed that the annual fuel consumption of MHE dedicated to the General Cargo vessels is around 156156 litres of diesel, whereas this number is 29562 litres of diesel for Bulk

Carrier vessels. Annual energy calculation of the MHE indicated that 1702 MWh is needed to meet the energy demand of the General Cargo vessel's MHE. The energy need of the MHE of Bulk Carriers is calculated to be 322 MWh. The annual total energy demand for MHE is calculated to be 2024 MWh.

3.4 Total GHG emissions and Possible Reductions in GHG Emissions with the implementation of OPS System

Implementing the OPS system is expected to significantly reduce GHG emissions and improve the air quality of the region where the port is located. The GHG emissions of the port operations within the drawn boundaries are calculated using Equation (11), following the approach described in Section 2.6. Table 7 shows the annual pollutant emissions that occurred in the port. The amounts of CO_2 emissions are comparatively high compared to the other pollutants, as conventional diesel mainly consists of carbon (85%-87%).

Table 7. Pollutant emissions in tonnes for each type of ship at the port during the period of 2020-2021.

Ship Type	Pollutant type (tonnes/year)									
	CO_2	CH_4	N_2O	NO_X	CO	NMVOC	SO_X	PM	$PM_{2.5}$	BC
RoPax	1957.49	0.0312	0.1105	34.545	1.641	1.475	0.835	0.548	0.505	0.231
Tanker	2015.75	0.0545	0.1333	33.136	3.493	1.816	0.813	0.52	0.48	0.220
Bulk Carrier	216.1	0.0179	0.0248	2.236	1.348	0.355	0.062	0.032	0.294	0.013
General Cargo	1126.17	0.1027	0.1373	10.622	7.787	1.975	0.304	0.148	0.136	0.062
Total	**5315.5**	**0.206**	**0.406**	**80.54**	**14.27**	**5.62**	**2.02**	**1.25**	**1.151**	**0.527**

Notably, pollutant emissions in the port include emissions due to the fuels burned by the auxiliary engines of the ships, trucks, and material handling equipment. The total CO_2 emissions of the port for a year were calculated to be 5315.5 tonnes. This is followed by 80.5 tonnes of NO_x, 14.27 tonnes of CO, 5.62 tonnes of NMVOC, 2.02 tonnes of SO_x, 1.25 tonnes of PM, 1.15 tonnes of $PM_{2.5}$, 0.527 tonnes of BC, 0.406 tonnes of N_2O (125.86 tonnes CO_2eq) and 0.206 tonnes of CH_4 (4.33 tonnes CO_2eq).

Table 8. Percentage of CO_2 emissions distribution among Auxiliary Engine (AE), Trucks and Material Handling Equipment.

Emissions Source	**RoPax**	**Tanker**	**Bulk Carrier**	**General Cargo**
Auxiliary Engine	99.7%	91.9%	52.6%	46.7%
Trucks	0.3%	8.1%	11.3%	16.8%
MHE	No MHE Operation	No MHE Operation	36.0%	36.5%

Table 8 shows the percentage of CO_2 emissions distribution induced by AE, Trucks and MHE for each vessel type. The results indicated that the port's dominant source of CO_2 emissions is auxiliary engine-induced CO_2 emissions, with 99.7% for RoPax and 91.9% for Tanker, 52.6% for Bulk Carrier and 46.7% for General Cargo. The percentages of CO_2 emitted due to truck operations are 0.3% for RoPax, 8.1% for tanker, 11.3% for Bulk Carrier and 16.8% for General Cargo vessels. Interestingly, MHE-induced emissions comprise 36% and 36.5% of total CO_2 emissions for Bulk Carriers and General Cargo vessels, respectively.

As can be seen from Table 8, the implementation of an OPS system at the analysed power capacity can cut 99.7% of total CO_2 emitted by RoPax and 91.7% of tanker based CO_2 emissions while 52.6% of Bulk Carrier generated CO_2 and 46.7% of General Cargo based CO_2 can be saved. This means the auxiliary engines of the ships emit 83.6% of total CO2 and, therefore, can reasonably be saved by implementing an OPS system. For this specific case, 16.4% of total CO_2 emissions are emitted from MHE and trucks with the calculation based on Table 7 and Table 8.

One of the most interesting outcomes to mention here is that the implementation of an OPS can only cut nearly 50% of CO_2 emissions for Bulk Carriers and General Cargo vessels. Therefore, to achieve net-zero targets, the port needs to acquire battery-powered trucks and electric-powered MHE as well as additional infrastructure for charging trucks.

3.5 Calculation of Alternative Fuel Volumes

Alternative fuel volume calculations were made for hydrogen, ammonia and methanol fuels based on the foresight that these fuels have the potential to take the place of conventional carbon-intensive fuels. The methodology proposed by McKinlay et al. (2021) was followed to calculate the required volume for providing a bunkering service for the ships calling at the port. The common point appearing from the results was that the required volume of fuel for each alternative fuel scenario is larger than for the conventional fuel. This means more storage volume would be required at ports and ships if alternative fuel scenarios are to be realised.

Table 9 compares the calculation results for diesel and alternative fuel scenarios. The efficiency percentage ranges for alternative fuels are adopted from McKinlay et al. (2021) and the upper boundary for efficiencies was used in this study, similar to McKinlay et al. (2021). However, the diesel propulsion system's efficiency is calculated for each case using Equation (10). Energy density, fuel density and safety margins used in the calculations can be seen in Table 9.

The weekly bunkering requirements are calculated based on the representative ships' average cruise range. It is assumed that ships calling at the port arrive with empty fuel tanks. It is important to note that R_D for RoPax vessels are calculated based on the time schedule of the ferry company. As explained, two RoPax vessels are operated from the port. The RoPax vessels provide service on two routes: Plymouth to Roscoff (97 NM) and Plymouth to Santander (478 NM). Fuel consumption of other RoPax vessels was also considered while calculating the cruise range for a RoPax vessel. The fuel calculations for the RoPax vessel were confirmed by the company which runs the RoPax operations. For other commercial vessels, the required fuel volume calculations were made based on the assumption that the port will provide a fuel volume equivalent to that of the seven days of a ship cruising at indicated service speed. This can easily be changed within the model to investigate different scenarios.

Table 9. Comparison of results for Diesel, Hydrogen, Ammonia and Methanol fuel scenarios.

Fuel Type	**Diesel (HFO)**	**Hydrogen (Liquid, -252°C)**	**Ammonia (-34°C)**	**Methanol (15°C)**
Efficiency (%) η_x	➢ RoPax:48.7% ➢ Tanker:48.4% ➢ BulkCarrier:45.6% ➢ General Cargo: 45.6%	60%	60%	60%
Gravitational Energy density (MWh/kg) u_x	0.0116	0.0333	0.0052	0.0055
Fuel Density (kg/m^3) ρ	950 @14.85°C	71 @ -252°C	681.9 @ -34°C	796 @ 15°C
Safety Margin (%)	25	25	25	25
Fuel Mass per vessel (tonne)	➢ RoPax:280 ➢ Tanker:123 ➢ BulkCarrier:52 ➢ General Cargo:66	➢ RoPax:79.1 ➢ Tanker:34.8 ➢ Bulk Carrier:13.9 ➢ General Cargo:18.5	➢ RoPax:506.7 ➢ Tanker:223.1 ➢ Bulk Carrier:89 ➢ General Cargo:118.7	➢ RoPax:479.1 ➢ Tanker:210.9 ➢ Bulk Carrier:84.2 ➢ General Cargo:112.2
Fuel Volume per vessel (m^3)	➢ RoPax:295 ➢ Tanker:129.5 ➢ BulkCarrier:54.7 ➢ General Cargo:69.5	➢ RoPax:1114.5 ➢ Tanker:491 ➢ Bulk Carrier:196 ➢ General Cargo:261	➢ RoPax:743.1 ➢ Tanker:327.1 ➢ Bulk Carrier:130.5 ➢ General Cargo:174	➢ RoPax:602 ➢ Tanker:265 ➢ Bulk Carrier:106 ➢ General Cargo:141

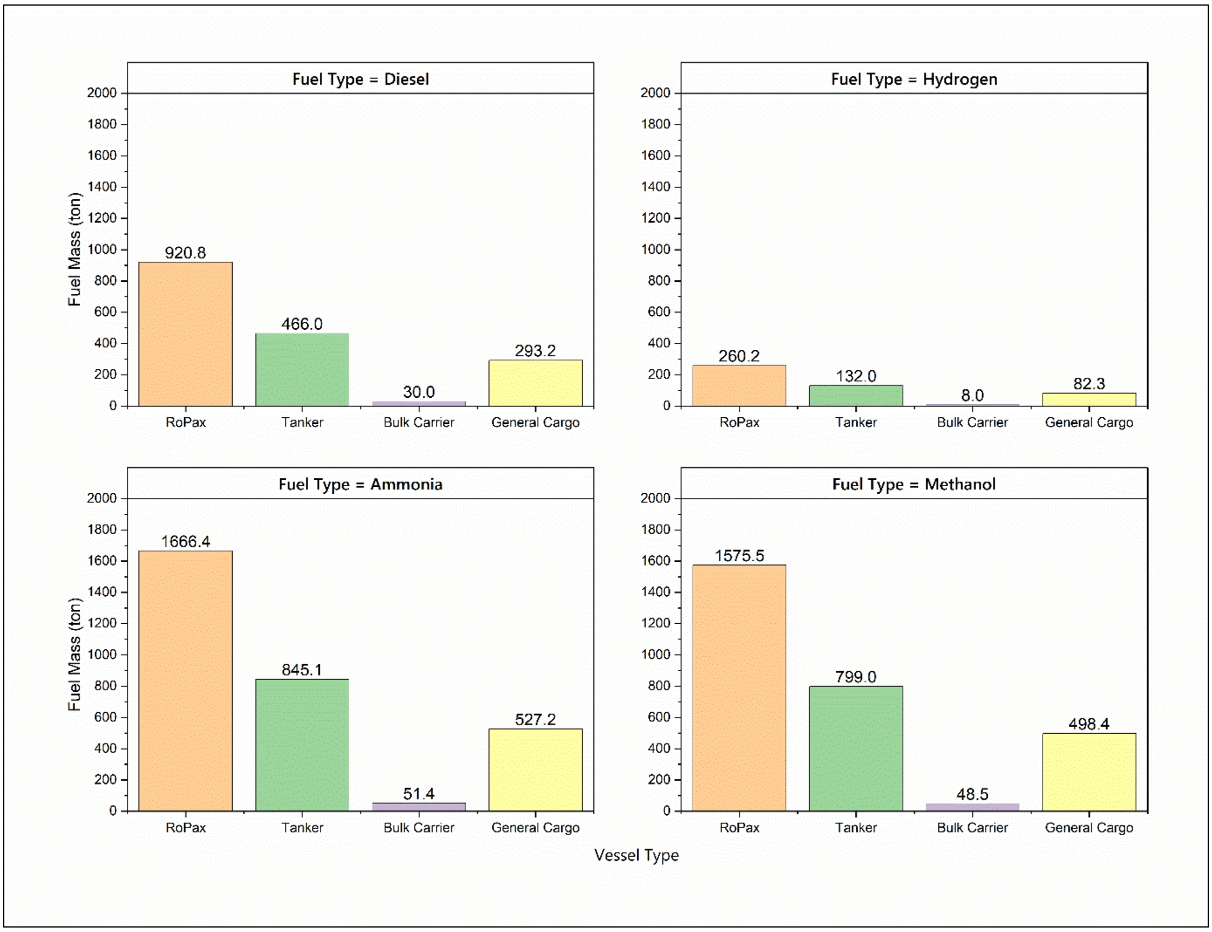

Fig. 10 Weekly Bunkering Scenario Fuel Mass Comparisons for Diesel, Hydrogen, Ammonia and Methanol for Each Vessel Type.

Fig. 10 compares the required fuel mass calculated for the weekly bunkering scenario for each vessel type, whereas Fig. 11 shows the equivalent fuel volumes required at the port for the bunkering purpose. It is important to note that Table 9 provides fuel mass per vessel and fuel volumes per vessel. To calculate weekly fuel demand, weekly port calls statistics were used to multiply with the fuel volumes per vessel and fuel mass per vessel. The average port calls per week can be calculated in Table 3.

As seen in Fig. 10, hydrogen is advantageous in terms of mass as it can provide the same amount of energy with less fuel mass than other fuels. On the other hand, ammonia and methanol need a large amount of fuel mass compared to diesel and hydrogen. This can be attributed to hydrogen's gravitational energy density being comparatively higher than the other fuels, as shown in Table 9. The required fuel masses for a weekly diesel fuel bunkering are

920.8 t for RoPax, 466 t for tanker, 30 t for Bulk Carrier and 293.2 t for General Cargo. These numbers altered to 260.2 t, 132t, 8 t and 82.3 t for Hydrogen, and 1666.4 t, 845.1t, 51.4 t and 572.2 t for Ammonia and 1575.5 t, 799t, 48.5t and 498.4t for Methanol, respectively.

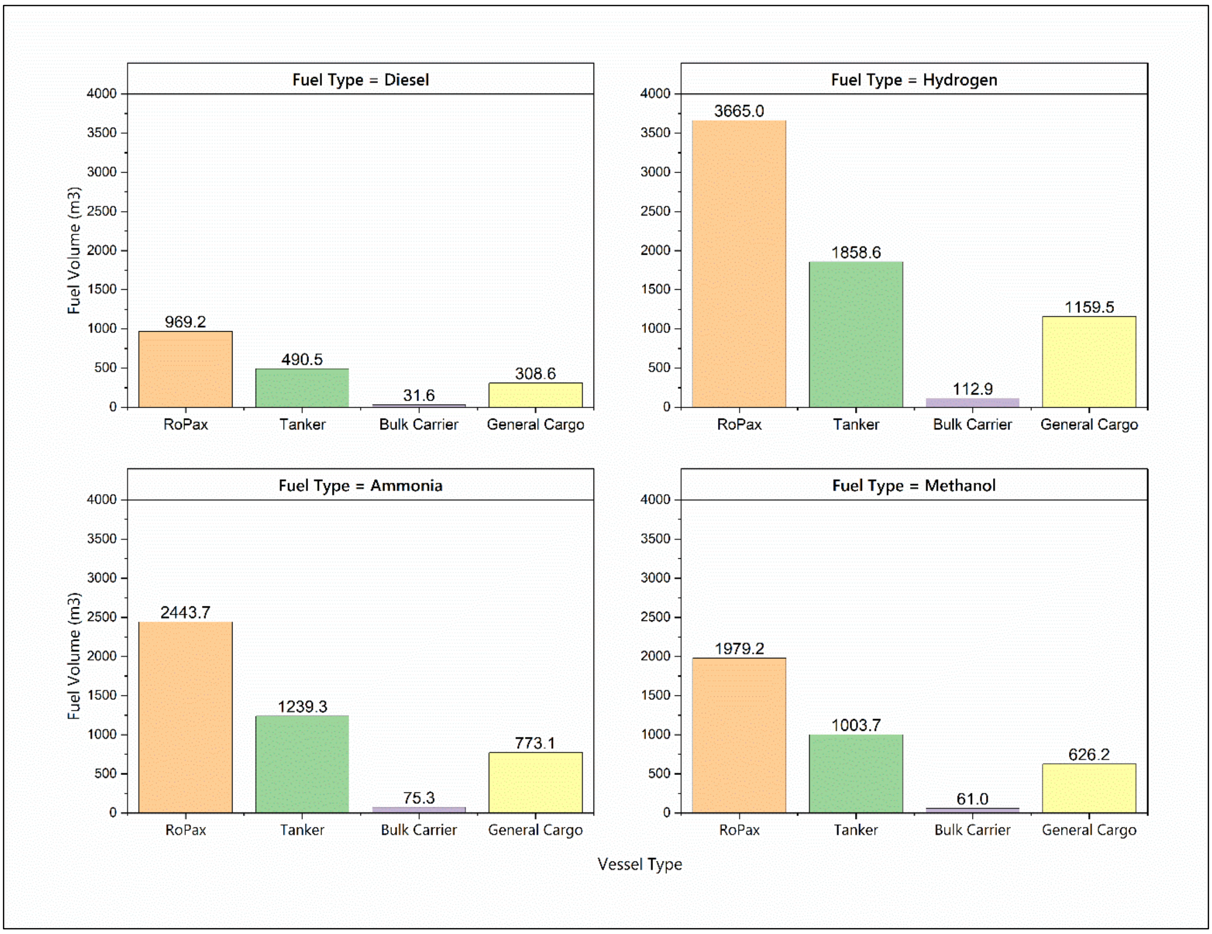

Fig. 11 Weekly Bunkering Scenario Fuel Volume Comparisons for Diesel, Hydrogen, Ammonia and Methanol for Each Vessel Type.

From a volume perspective, hydrogen does not remain as advantageous as when considering the mass of the fuels. As shown in Fig. 11, the required hydrogen volume is around 3.8 times the diesel fuel volume and ~1.85 times the Methanol and ~1.50 times the Ammonia (McKinlay et al. 2021). This is simply due to having the lowest volumetric energy density among the alternative fuels. For hydrogen bunkering, the required volumes are 3665 m^3 for RoPax, 1858.6 m^3 for tanker,112.9 m^3 for Bulk Carrier and 1159.5 m^3 for General Cargo vessels. These values have changed to 2443.7 m^3,1239.3 m^3,75.3 $m^{3,}$ and 773.1 m^3 for ammonia bunkering and 1979.2 m^3, 1003.7 m^3,61 m^3 and 626.2 m^3 for methanol bunkering, respectively.

4. Conclusions

Reducing port-based emissions is critical, aiming to achieve zero-emission maritime transport. This study focused on two solutions; i) implementation of an Onshore Power Supply system for cutting auxiliary engine emissions at the port and ii) transition to alternative fuels for bunkering purposes, with three candidates being selected: hydrogen, ammonia and methanol. Marine traffic data for the port of Plymouth (UK) was investigated as a case study for the period of 2020-2021. The number of port calls, total time at port and total time at berth for each vessel are obtained. The vessel types calling at the port were defined. Through statistical analysis, one representative ship was selected from each group for emissions calculations. All port operations were simulated using a discrete event simulation approach and operation timings obtained. High-level disaggregated power-energy demand, fuel consumption and Greenhouse Gas emissions predictions were made. Based on the representative ships' bunkering needs, the weekly fuel demand for the port was calculated for Heavy Fuel Oil (HFO), hydrogen, ammonia and methanol fuels. Based on these investigations, the main findings of this study are:

- The results revealed that annual port calls are 231, 197, 171 and 30 for General Cargo, Tanker, RoPax and Bulk Carrier, respectively. When the average berth time per call is analysed, Bulk Carrier vessels have the highest berth time with an average of 37.9 h per call, whereas this value changes to 26 h for General Cargo, 24.7 h for tanker and 4.2 h for RoPax vessels.
- The peak power demand is 5.95 MW, considering the maximum possible power-consuming berth allocation scenario: two Tankers, one RoPax and one Bulk Carrier simultaneously.
- RoPax and Tanker vessels have the highest energy consumption at the port, with 19.35 MWh/per vessel and 14.89 MWh/ per vessel energy consumption rates. Although the average berth time for RoPax is relatively low (only 4.2 h), the power capacity of

auxiliary engines of RoPax vessels makes them the highest energy-consuming vessel type among other vessel types in this study.

- Total annual energy demand is calculated to be around 10.7 GWh consisting of 7082 MWh from AE, 2024 MWh from MHE and 1578 MWh from Trucks.
- The main pollutant is CO_2, with around 98% of total emissions. Implementing an OPS system could save 83.6% of total CO_2 emissions in the port. In order to achieve net zero targets, additional actions need to be taken in ports such as electrifying all material handling equipment and trucks and providing an adequate number of charging facilities for these.
- Due to hydrogen's low volumetric energy density, using hydrogen as an alternative fuel onboard ships is commonly seen as not feasible in the first instance. The results showed that the required volume of hydrogen is around 3.5 times that of the conventional fuel, which may be practical for certain vessel types, particularly considering the light weight of hydrogen may make upper deck storage viable. On the other hand, methanol required less mass and volume than ammonia and hydrogen.

This case study has demonstrated that a discrete event simulation in conjunction with statistical analysis of port traffic can be used to predict onshore power supply system requirements for ports having a complex mix of vessel types, cargo and equipment. Such detailed predictions are essential to estimate the degree to which local electricity grids need to be upgraded to reduce in-port emissions from vessels and associated land-side operations. The detailed distribution of power demand between vessel types, berths and source of power (ships' auxiliary engines, material handling and trucks) allows for consideration of fair means to pay for such Onshore Power provision within a port.

It is well known that hydrogen is one of the essential materials that need to be used in the production of ammonia (Haber-Bosch process) and methanol (Synthesis), meaning more energy will be required in these processes. Moreover, there are also energy losses within the ammonia and methanol production stages. For this reason, we believe that hydrogen is a more likely replacement for conventional fuels for ships to provide a realistic net zero supply chain.

Another important outcome from this research is that considering the required volume of alternative fuels, future ship designs will change, resulting in ships having higher fuel tanks and sophisticated storage equipment to operate on these fuels. Further studies are needed for port area allocation for fuel storage requirements, and health and safety standards are required for implementing the net zero transition at the ports in a standardised and safe way. Future research may examine the investment required for each alternative fuel and its associated risks.

Finally, this study is anticipated add to a rapidly developing literature on maritime transport decarbonisation which aims to provide a holistic approach to a complex issue. The recent publication by Sung et al.(2022) demonstrates that innovative thinking, as the proposed Blue Visby solution, could be advantageous compared with other well-known concepts as the just in time. However, even if an innovative vessel arrival system is in place, it still needs to examine the ports' capability to offer green energy not only for vessels but also to all the transportation modes interacting with cargo movement. Therefore, this research will help provide evidence with real data on how it could be achieved, and potential constrains of alternative fuels that they may have, but also opportunities. Furthermore, our research emphasises the vital requirement for robust data collection and monitoring systems within ports for the precise evaluation of power demands and the influence of Onshore Power Supply (OPS) technology, particularly for validation and comparative purposes. This underscores the imperative for future research initiatives that centre on establishing such systems, thereby bolstering the sustainability and efficacy of maritime operations and their analytical endeavours.

5. Appendix

Appendix A

Time distributions obtained				
Vessel Type	**Vessel arrival time interval (h)**	**Berthing operation time (h)**	**Discharging operation time (h)**	**Loading Operation time (h)**
RoPax	15 + 444 x BETA (0.25, 2.93)	LOGN (0.859, 0.495)	1 + LOGN (1.02, 1.36)	1 + LOGN (1.02, 1.36)
Tanker	WEIB (48, 1.27)	0.32 + LOGN (0.815, 0.287)	NORM (24.5, 5.43)	N/A
Bulk Carrier	70 + WEIB (220, 0.893)	1 + WEIB (6.96, 0.609)	NORM (37.3, 14.1)	N/A
General Cargo	EXPO (37.8)	WEIB(7.11, 0.584)	NORM (37.9, 18.7)	5 + ERLA (11.6, 2)

Chi-square goodness of fit test - Corresponding p-value				
Vessel Type	**Vessel arrival time interval (h)**	**Berthing operation time (h)**	**Discharging operation time (h)**	**Loading Operation time (h)**
RoPax	<0.05	0.9099	0.7005	0.7005
Tanker	0.0632	0.2133	0.0844	N/A
Bulk Carrier	0.6504	0.0736	0.0536	N/A
General Cargo	0.0584	0.2091	0.2328	0.0755

Square errors of the obtained distributions				
Vessel Type	**Vessel arrival time interval (h)**	**Berthing operation time (h)**	**Discharging operation time (h)**	**Loading Operation time (h)**
RoPax	4.1%	0.0%	0.5%	0.5%
Tanker	0.3%	4.8%	4.4%	N/A
Bulk Carrier	1.5%	2.4%	8.7%	N/A
General Cargo	0.4%	0.1%	1.0%	1.0%

Appendix B

The references of emission factors

Diesel consumption emission factors of trucks and MHE (Wang et al., 2019)

exhaust emissions	factor: g/ L diesel
CO_2	2632.8
CO	32.311
SO_2	0.3486
NOx	5.7602
HC	19.588
CH_4	0.415
VOC	6.9388
HCHO	0.5561
N_2O	0.4731
Pb	0.4067

Emissions factors used in this study for top-down estimation (unit: kg pollutant/tonne fuel) (IMO, 2020)

Pollutants	Fuel Type	The Fourth IMO GHG Study						
		2012	2013	2014	2015	2016	2017	2018
CO_2	HFO	3,114	3,,114	3,114	3,114	3,114	3,114	3,114
	MDO	3,206	3206	3,206	3,206	3,206	3,206	3,206
	LNG	2,750	2,750	2,749	2,749	2,750	2,753	2,755
CH_4	HFO	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	MDO	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	LNG	5.31	6.00	7.35	8.48	10.20	11.22	11.96
N_2O	HFO	0.17	0.17	0.17	0.17	0.18	0.18	0.18
	MDO	0.18	0.18	0.18	0.18	0.18	0.18	0.18
	LNG	0.08	0.08	0.08	0.09	0.09	0.10	0.10
NO_x	HFO	78.61	77.18	76.19	76.98	76.71	76.67	75.90
	MDO	53.12	52.51	52.14	57.68	57.45	57.62	56.71
	LNG	5.60	5.90	5.82	5.99	7.46	10.95	13.44
CO	HFO	2.84	2.83	2.84	2.86	2.86	2.87	2.88
	MDO	2.48	2.47	2.47	2.58	2.58	2.60	2.59
	LNG	1.88	2.07	2.38	2.64	3.10	3.57	3.97
NMVOC	HFO	3.14	3.13	3.13	3.17	3.18	3.19	3.20
	MDO	2.16	2.15	2.15	2.39	2.39	2.42	2.40
	LNG	0.81	0.88	0.99	1.09	1.26	1.44	1.59
SO_x	HFO	46.63	44.80	45.31	47.90	50.44	50.83	50.83
	MDO	2.74	2.54	2.35	1.56	1.56	1.56	1.37
	LNG	0.03	0.03	0.03	0.03	0.03	0.03	0.03
PM	HFO	7.11	6.96	7.01	7.26	7.48	7.53	7.55
	MDO	0.97	0.96	0.94	0.92	0.92	0.92	0.90
	LNG	0.11	0.11	0.11	0.11	0.11	0.11	0.11
$PM_{2.5}$	HFO	6.54	6.41	6.45	6.68	6.88	6.93	6.94
	MDO	0.90	0.88	0.87	0.84	0.84	0.85	0.83
	LNG	0.10	0.10	0.10	0.10	0.10	0.10	0.10
BC	HFO	0.26	0.27	0.27	0.26	0.26	0.26	0.26
	MDO	0.43	0.43	0.43	0.37	0.37	0.37	0.38
	LNG	0.019	0.019	0.019	0.019	0.019	0.019	0.019

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.

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