Facilitating "green practices" within the Irish maritime industry from use of cleaner alternative technologies

By Ketan Gore, B.E. (Hons), M.Sc.

A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy (PhD)

School of Business
Maynooth University
Maynooth, Co. Kildare

October 2023

Head of Department: Prof. Joseph Coughlan
Supervisors: Dr Patrick Rigot-Müller, Prof. Joseph Coughlan

DECLARATION

I, Ketan Gore, as the author of this thesis, hereby declare that, except where duly acknowledged, this thesis is entirely my own work and has not been submitted for any degree or qualification in any other university or country.

Signed: ______________________________ Date: 14th October 2023

Doctoral Candidate: Ketan Gore

We hereby certify that all the unreferenced work described in this thesis and submitted for the award of Doctor of Philosophy, is entirely the work of Ketan Gore. No portion of this work contained in this thesis has been submitted in support of an application for another degree or qualification to this or any other institution.

Signed: _____________________ Date: 14th October 2023

Supervisor: Dr Patrick Rigot-Müller

Signed: _______________________ Date: 14th October 2023

Supervisor: Prof. Joseph Coughlan

ACKNOWLEDGEMENT

First, and most sincerely, I would like to thank my supervisors Dr Patrick Rigot-Müller and Prof Joseph Coughlan, for their invaluable support, encouragement and understanding throughout my doctoral journey. The door to their offices were always open whenever I ran into a trouble spot or had a question about my research or writing. They consistently allowed the emanating doctoral research to be my own work but steered me in the right the direction whenever he thought I needed it. Thank you for providing me with this opportunity, giving me faith in my abilities, and helping me to strengthen my passion for the field.

I would like to thank the members of Annual Review Committee: Dr Ali Nazarpour and Dr Jon Gruda, for their continuous support and constructive feedback, which helped further shape and enhance my research work. Further, I am incredibly grateful to all the faculty members at the School of Business who have been a great source of encouragement. Also, I particularly want to express sincerest appreciation to my fellow PhD colleagues: Kanishka and Javad, for providing unconditional assistance and motivation, while always being there for me through the ups and downs of this PhD journey.

Finally, I must express my very profound gratitude to my parents back home in India for providing me continuous encouragement throughout my study period and through the process of researching and writing this thesis. This accomplishment would surely not have been possible without them. Thank you.

TABLE OF CONTENTS

ABSTRACT

Marine shipping, which is considered as the backbone of international trade, predominantly relies upon dirty fossil fuels for its operation. Tougher regional and global environmental regulations are now challenging the industry to take action – in line with the Paris Agreement goals. In the form of three research papers (two published and one conference paper), this thesis quantifies environmental benefits and financial costs of switching to cleaner alternative technologies. Hence, providing a "guiding tool" for policymakers for implementing best-case practices within the industry. Owing to its maritime dependency, proven vulnerability to shipping emissions and its reluctance for compliance with the established regulations, Ireland was selected as the research case study.

Paper-1 investigated the NPV of Shore Side Electricity (SSE) adoption utilising the existing (2019) and future (2030) Irish energy mix. The future electricity supply is anticipated to be "cleaner" due to an increase in the uptake of renewable energy sources, which is expected to boost the present (2019) NPVs. The paper finds that cost-effectiveness will be higher if the ten most frequently visiting ships switch to shore side power. Paper-2 estimated and compared the NPV of three blended biofuels (FAME, HVO and FT-Diesel), against the relatively popular options of scrubbers and low-sulphur oil, used to mitigate pollutants. To comply with the proposed Atlantic-ECA regulation, blended FAME was found to be the most cost-effective option using NPV. Paper-3 analysed the NPV of four low-carbon marine fuel technologies: LNG, Methanol, Green Hydrogen, and Green Ammonia. LNG had the highest NPV, followed by methanol and hydrogen, with ammonia showing a negative NPV, due to high operational costs. To meet the future decarbonization targets, Green Hydrogen will be the most suitable alternative over LNG and methanol respectively.

The three papers in this thesis combine to provide a range of policy initiatives for the Irish government to contemplate while developing its maritime action plan. Ireland needs to consider how it can rapidly progress to meet the near- and long-term emission goals and how it can influence other partners to do so. This thesis provides clear evidence about practicality of different green technologies, to help the government make informed decisions.

NOMENCLATURE

SO_x	Sulphur Oxides	ETS	Emission Trading System
NO_x	Nitrogen Oxides	ESPO	European Sea Ports Organisation
$PM_{2.5}$	Particulate Matter (2.5 µm)	ME	Main Engine
CO_2	Carbon dioxide	AE	Auxiliary Engine
GHG	Green House Gases	COVID	Coronavirus Pandemic
NPV	Net Present Value	IMDO	Irish Maritime Development Office
SSE	Shore Side Electricity	UK	United Kingdom
FAME	Fatty Acid Methyl Esters	MSD	Medium Speed Diesel
HVO	Hydrotreated Vegetable Oil	HSD	High Speed Diesel
FT- Diesel	Fischer- Tropsch Diesel	CSO	Central Statistics Office
IMO	International Maritime Organisation	NISRA	Northern Ireland Statistics and Research Agency
EU	European Union	BeTa	Benefits Table
LNG	Liquified Natural Gas	CAFE	Clean Air for Europe
MEPC	Marine Environment Protection Committee	NEEDS	New Energy Externalities Development for Sustainability
RO	Residual Oil	CPI	Consumer Price Index
HFO	Heavy Fuel Oil	AIS	Automatic Identification System
VLSFO	Very Low Sulphur Fuel Oil	IEA	International Energy Agency
UNCTAD	United Nations Conference on Trade and Development	EGCS	Exhaust Gas Cleaning System
OECD	Organisation for Economic Cooperation Development	SEAI	Sustainable Energy Authority of Ireland
ECA	Emission Control Area	PEM	Proton Exchange Membrane
MGO	Marine Gasoline Oil	BOG	Boil Off Gas
MDO	Marine Diesel Oil	TEN-T	Trans-European Network

LIST OF TABLES

LIST OF FIGURES

CHAPTER ONE: INTRODUCTION

1.1. Research Background

Marine shipping, which has been recognised as an energy-efficient means of transportation due to its large carrying capacity and low fuel consumption per ton transported, is still one of the significant sources of air pollution at the global level (Zhang et al., 2019). Shipping operations were responsible for total 11.4 million tonnes of sulphur oxide (SO_x), 20.2 million tonnes of nitrogen oxide (NO_x), 1.5 million tonnes of particulate matter ($PM_{2.5}$) and 919 million tonnes of carbon dioxide (CO_2), in 2018 (International Maritime Organisation [IMO], 2020). In 2022, the total CO_2 emissions were estimated to be around 1,017 million tonnes, with the highest contribution coming from bulkers (28%), followed by tankers (27%) and containers (25%), with remaining 20% being made up by passenger, Roll/on-Roll/off (Ro-Ro), offshore and service ships (United Nations Conference on Trade and Development [UNCTAD], 2023). At the European Union (EU) level, shipping emitted 1.25 million tonnes of NO_x, 70,000 tons of $PM_{2.5}$, 255,000 tonnes of SO_x, and 127.6 million tonnes of CO_2 in 2021 (European Environment Agency [EEA], 2023a, EEA, 2023b). Within the EU member states, Ireland has witnessed the highest growth rate (since 1990) in terms of maritime emission footprint (EEA, 2023a, EEA, 2023b).

The predominant source of emissions from marine shipping is the exhaust gas from burning diesel fuel in the combustion engines (Alver et al., 2018). Upon ignition in the engine, a mix of air and fuel releases mechanical energy which is harnessed for propulsion and produces hot exhaust gases as a by-product (Lindstad et al., 2015). The most important pollutant species being emitted include SO_x, NO_x, CO_2 and $PM_{2.5}$, due to their significant share in the total emissions (IMO, 2020). Amongst these pollutants, CO_2 is a Greenhouse Gas (GHG) of immense significance to climate change, whereas SO_x, NO_x and $PM_{2.5}$ pose serious health risks to the population residing near the coastline

(Chatzinikolau et al., 2015, Lindstad et al., 2020). Academic studies, in recent years, have been examining the existential threat of shipping air emissions, through the calculation of external costs, which indicates the damages imposed by marine ship emissions on the local environment and human health in monetary terms (Nunes et al., 2019, Tovar and Tichavska, 2019, Progiou et al., 2021, Spengler and Tovar, 2021).

Through the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI, the IMO has adopted stricter regulations aiming to reduce SO_x emissions by introducing Emission Control Areas (ECAs) and changing the existing marine fuel sulphur limit for ships (Nunes et al., 2017a, IMO, 2019). The ECA sulphur directive requires all vessels operating inside Sulphur Emission Control Areas (SECA) to utilise fuel oil with a sulphur content of no more than 0.1% m/m (mass by mass) (Gu and Wallace, 2017). Presently, there are four designated ECAs in the world: i) Baltic Sea, ii) North Sea, iii) North American Area (covering designated coastal areas off the United States and Canada) and iv) United States Caribbean Sea area (around Puerto Rico and the United States Virgin Islands) (IMO, 2019). At the 79th meeting of The Marine Environment Protection Committee (MEPC 79), the IMO adopted the amendments under MARPOL Annex VI to also designate Mediterranean Sea, as a whole, under ECA regulation, which is likely to come into effect on 1st of May 2025 (IMO, 2022a). Also, at the 80th MEPC in 2023, further three ECA proposals (Canadian Arctic, the North-East Atlantic Ocean and the remaining Norwegian coast not already covered by existing ECAs) were submitted, with formal applications to be made at 81st MEPC (IBIA, 2023). Outside of SECAs, all operating vessels must employ fuels with a sulphur limit of no more than 0.5% m/m from the 1st of January 2020 (IMO, 2019). Three alternatives that can be used to comply with the IMO-2020 sulphur limit are currently available on the market. The first approach is to use fuel oil which is inherently low enough in sulphur

(Very Low-Sulphur Fuel Oil (VLSFO) with 0.5% sulphur limit outside ECAs and Marine Gasoline Oil (MGO) with 0.1% sulphur limit inside ECAs (Zhu et al., 2020). On the other hand, the shipowner may install Exhaust Gas Cleaning Systems (EGCS), also known as "scrubbers", which absorb the majority of the sulphur content in the exhaust, and therefore enables the ship to keep using cheap Heavy Fuel Oil (HFO) (i.e., Residual Oil (RO)) inside and outside of SECA (Gu and Wallace, 2017, IMO, 2019). The last option is to consider alternative fuel types containing low or zero sulphur, for example, hydrogen, ammonia, Liquified Natural Gas (LNG), methanol and biofuels (IMO, 2019).

For mitigating NO_x emissions, Tier III legislation has been introduced by IMO which requires all the vessels built after the 1st of January 2016 to adhere to a stringent NO_x emission limit within ECAs (Whall et al., 2010). Such ECAs with Tier III NO_x emission limits in place are known as Nitrogen Emission Control Areas (NECA), which require the use of technologies such as Selective Catalytic Reduction (SCR) or Exhaust Gas Recirculation (EGR) (Karl et al., 2019, Zhao et al., 2021). In parallel to the IMO, the EU has also been prioritizing to improve the air quality levels in port areas (ESPO, 2019). This stems from the fact that port-based shipping emissions are a dominant source of urban pollution in coastal areas, having detrimental impact on the population residing near the coastline and the built environment (Castells Sanabra et al., 2014, Viana et al., 2014, Tichavska and Tovar, 2015a). To alleviate port-based emissions, the EU has mandated ships berthing in EU ports for more than 2 hours to either use MGO or switch to Shore Side Electricity (SSE) (Castells Sanabra et al., 2014, Urdahl, 2020). In addition to minimizing sulphur and nitrogen emissions, there has also been an increased attention from the international (IMO) and regional (EU) regulatory authorities to reduce the extent of GHG emissions from shipping.

The IMO previously set a target to reduce GHG emissions by 50% by 2050, compared to 2008 levels, which was recently revised to reach net-zero GHG emissions closer to 2050 (IMO, 2023). This includes commitment to ensure a higher uptake of alternative zero and near-zero GHG fuels by 2030, as well as indicative checkpoints for 2030 and 2040 (IMO, 2023). The EU, as part of its “Fit for 55” package, aims to reduce CO_2 emissions by 55% by 2030, compared to 1990 levels (EPRS, 2023). Most recently, the IMO delegation reached a consensus on taxing carbon emissions from shipping, although, no agreement has been made on the amount of tax to be paid (per ton or carbon) (Gerretsen, 2022). The EU-based maritime sector is also regulated under Emission Trading Scheme (EU-ETS), which will require vessels to report 50% of their CO_2 emissions on voyages into or out of the EU, and 100% of their CO_2 emissions on voyages between the EU ports (NAPA, 2022), The reported carbon emissions will then need to be verified and paid for, with payment obligations being phased over three years (Tan and Ryan, 2022).

Despite the fact that the newest global engine (Tier III) and fuel (IMO-2020) regulations have been proclaimed to reduce SO_x, $PM_{2.5}$ and NO_x emissions to an extent (MIT, 2021), such measures are less likely to steer the maritime industry towards the ambitious decarbonization targets. This is primarily because existing directives do not supress the demands for fossil fuels within the industry, with nearly 99% of global ships preferring diesel-based combustion procedure as of 2022 (UNCTAD, 2023). This can be seen from the UNCTAD (2023) report, which stated that global shipping CO_2 emissions have risen by nearly 10% in 2022 (1,017 million tonnes) against 2018, despite the significant disruption caused by the Coronavirus Disease 2019 (COVID-19) pandemic in 2020-21. A similar trend can also be seen in the EU, where the “international shipping - 2021” SO_x, $PM_{2.5}$ and NO_x emissions have dropped by 57%, 24%, and 10%, respectively, since

2018, while the CO_2 emissions have largely remained flat within the same period (in the range of 125 – 135 million tonnes) (EEA, 2023a, EEA, 2023b). Hence, it is of utmost importance for the global maritime sector to shift away from the use of fossil fuels for combustion if they strive to achieve the "net-zero" targets by or around 2050. There continues to remain uncertainty within the sector surrounding the best alternatives available, with the onus for technological investments being on shipowners, ports and the energy-producing industry. In light of this, the role of researchers becomes increasingly prevalent to analyse the financial costs and the requisite environmental benefits of investing into cleaner technologies. This analytical procedure could justify the selection and outlining of best-case solutions for compliance with the existing directives and to achieve the impending emission targets.

1.2. Review of relevant literature

While the impetus behind the foundation of stringent regulations and ambitious targets is to reduce (while aiming to eliminate) the environmental harm caused by shipping emissions, such obligations will also impose large costs on shipping companies (Ammar, 2019, Perčić et al., 2022). The selection of cleaner alternatives will depend upon the trade-off between the benefits achieved against the total costs invested (Innes and Monios, 2018, Helgason et al., 2020). Here, the benefits attained would be the saved external costs from the use of alternative technologies, when compared against the baseline operation (use of diesel fuel oils), with the total invested costs being the capital and operational costs of using the required technologies (Yu et al., 2019, Dai et al., 2019). External costs are the negative impacts derived from air pollution which are quantified and then monetised to indicate the total health and environmental damage inflicted by air emissions (Tichavska and Tovar, 2017, Spengler and Tovar, 2021). Estimation of external costs will be helpful for varied reasons, since it can indicate the total environmental costs associated with specific shipping activities, which will allow for better decisions to ensure that the achieved benefits of new operational conditions exceed the baseline environmental costs (Dragović et al, 2018, Nunes et al*.,* 2019). Depending on ship-movements (port-based and sea-based), distinct low-emission technologies have been presented for shipowners to implement. For port-based emissions, the EU has regulated visiting ships to switch to MGO or SSE while berthing, with SSE utilization being mandated in Ten-T network ports from 2030 (European Parliament, 2005 European Council, 2023a). For sea-based emissions, the IMO has proposed shipowners to switch to low-sulphur fuel (MGO), install "end of pipe" technology (scrubber), or to employ alternative fuel technologies which can also lower GHG emissions in consolidation with SO_x emissions (IMO, 2019, IMO, 2021).

SSE is a “land-to-ship electricity" connection that replaces the AEs to supply power to the ship when at berth, thus ameliorating negative environmental impacts of fuel-based sources (Yu et al., 2019, Dai et al., 2020). Within the academic literature, studies have been analysing the financial and environmental cost-benefits of implementing SSE technology. Here, the costs mainly refer to the installation of SSE "port-side" and "ship-side" infrastructure (retrofit - CAPEX) and the supplied electricity charges from the grid (OPEX) (Zis, 2019). While the benefits include avoided environmental external costs and saved diesel fuel costs from operation of AEs (Spengler and Tovar, 2021). Ballini and Bozzo (2015) reported total financial costs of €37 million for “port-side” SSE installation in the Copenhagen cruise port and external costs savings of €2.8 million annually. The conducted analysis was targeted at 60% of berthing cruise ships, resulting in a payback period of 12-13 years. Tseng and Pilcher (2015) estimated total external costs savings of $2.8 million for 60 container ships berthing in the Kaohsiung port using SSE, alongside an increase in financial costs per ship of $6,920. Innes and Monios (2018) reported “port-side” installation costs of €7.4 million in a medium-sized port (Aberdeen-UK) and assessed that total external costs savings could be up to €1.4 million annually, resulting in Net Present Values (NPVs) of €1.2 million (10 year period) and €8.7 million (25 year period). Dai et al. (2019) reported negative NPVs in range of −1.3 billion to −2.9 billion Chinese Yuan (CNY) for SSE usage by containerships in Shanghai port, for three adoption rates, incorporating CO_2 emission trading only. Yu et al. (2019) estimated an average payback period of less than 4 years for the use of SSE by containerships visiting Dalian port, with the total external cost savings being $128 million annually. Winkel et al. (2016) estimated the total external cost savings with the prospective use of SSE across several European (including Irish) ports to be €2.94 billion, while for a similar scenario, Stolz et al. (2021) indicated significant achievable reductions in shipping emissions.

In line with IMO -2020 and -ECA directive, scholarly literature has also been focusing on the measurement of cost-effectiveness of potential fuel sulphur limit compliance solutions. Jiang et al. (2014) found that the use of MGO when applied on fixed-route container ship will be more viable against scrubber via the NPV methodology. Although an increase in the price spread between MGO and HFO will improve the NPV of scrubbers over MGO. Lindstad et al. (2015) showed that the use of MGO will be more financially profitable over scrubber utilization within ECA waters, if the annual fuel consumption is less than 1,000 and 1,500 tonnes, for ships with small (4,000 kW) and large (12,000 kW) engine sizes, respectively. Panasiuk and Turkina (2015) estimated larger cash outflows in the initial year of scrubber instalment, with possibility to recoup the invested costs within 1 year, due to the use of cheaper RO fuel. Abadie et al. (2017) reported lower financial costs of installing scrubber than MGO, when a ship has longer remaining lifetime and spends most of its time at sea while sailing in ECAs. However, it was noted that fuel consumption values are higher with scrubber installation, resulting in higher CO_2 emissions. Gu and Wallace (2017) and Fan et al. (2020) indicated that the scrubber installation will be more profitable for ships that have a higher density of movements, i.e., spend considerable amount of time sailing within ECAs. Zhu et al. (2020) reported higher NPV for scrubber utilization against MGO, when applied on container ship sailing between Far East and Europe. Although, financial attractiveness of installing scrubber would be highly dependent upon the changes in fuel price spread between HFO and MGO. Zhao et al. (2021) found that use of open-loop scrubbers in combination with Exhaust Gas Recirculation technology will be the most financially viable combination for compliance with SECA+NECA regulation. While the viability of installing scrubbers will depend on the fuel price spreads between HFO-MGO and the remaining lifespans of the ships.

To achieve the EU-2030 and IMO-2050 shipping decarbonization targets, distinct alternative fuel technologies such as LNG, Methanol, Hydrogen, and Ammonia, have been discussed. Ammar (2019) found that the use of dual-fuel methanol engines reduced ship air emissions significantly, although the financial costs of operating diesel fuel engine was lower. Sustained benefits from slow steaming and avoiding any additional technological investment costs (e.g., catalytic converters) will help pay back the dual-fuel investment costs within 12 years. Helgason et al. (2020) reported conventional (gas-based) methanol to have higher financial and environmental cost-competitiveness over renewable-based methanol and HFO, with renewable-based methanol only expected to be more cost-competitive post 2040s. Cariou et al. (2021) analysed the impacts of carbon tax, regulated through EU ETS, when implemented on ~2,500 oil tankers operating within Europe between 2017-2019. It was found that ships operating on intra-European trade routes and having a higher number of voyages are expected to have lower payback periods for switching to new-built LNG systems, due to higher carbon tax savings. Some studies have also conducted a Life-Cycle Assessment (LCA) to analyse the economic and environmental impact of alternative fuel technologies. Perčić et al. (2020) found that battery-powered ships had lowest life-cycle emissions and costs, amongst the available alternative technologies (electricity, methanol, hydrogen, LNG, dimethyl ether and biofuel), alongside HFO. Perčić et al. (2021) also conducted LCA and Life-Cycle Cost Analysis (LCCA) for similar fuels as in Perčić et al. (2020), with battery remained the most environmentally friendly option, the most cost-effective option varied for each different ship type considered (passenger, container, dredger). Alongside the financial costs, the studies of Perčić et al. (2020) and Perčić et al. (2021) also included the carbon emission costs in their LCCA analysis. Perčić et al. (2022) conducted LCA and LCCA analysis for the use of hydrogen and ammonia fuels (produced from varied sources) in combination with fuel cells. The results showed that green hydrogen had the lowest life-cycle GHG emissions, although, it was also the least cost-effective option. While Lindstad et al. (2021) found that fossil-based (grey) hydrogen had the highest life-cycle CO_2 output, with green hydrogen having the lowest. Switching to green hydrogen or green ammonia is shown to be cheaper to use than the other hydrocarbon-based renewable fuels such as E-LNG or E-methanol.

Table 1.1 provides a summary of various parameters (capital and operational costs, ship emissions, saved fuel, external and carbon tax costs) considered within the literature concerning the cost analysis of employing alternative measures.

Table 1.1. Literature concerning the cost-benefit analysis of low-carbon technologies

Study	Measure	Costs			Benefits		
		Ship emission	Capital Costs	Operation costs	Saved Fuel	Saved External	Saved Carbon tax
At-Berth							

Tzannatos (2010a)	SSE	✓	✓	✓		✓	
Ballini and Bozzo (2015)	SSE	✓	✓			✓	
Ölçer and Ballini (2015)	SSE	✓	✓			✓	
Tseng and Pilcher (2015)	SSE	✓	✓	✓		✓	
Wang et al. (2015)	SSE	✓	✓	✓		✓	
Winkel et al. (2016)	SSE	✓				✓	
Vaishnav et al. (2016)	SSE	✓	✓	✓	✓	✓	
Innes and Monios (2018)	SSE	✓	✓			✓	
Dai et al. (2019)	SSE	✓	✓	✓			✓
Yu et al. (2019)	SSE	✓		✓	✓	✓	
Zis (2019)	SSE	✓	✓	✓		✓	
Dai et al. (2020)	SSE	✓					

Stolz et al. (2021)	SSE	✓					
Spengler and Tovar (2021)	SSE	✓				✓	
At-Sea							
Jiang et al. (2014)	Scrubber and MGO	✓	✓	✓		✓	
Panasiuk and Turkina (2015)	Scrubber and MGO		✓	✓			
Abadie et al. (2017)	Scrubber and MGO	✓		✓			✓
Gu and Wallace (2017)	Scrubber and MGO		✓	✓			
Ammar (2019)	Methanol SCR	✓	✓	✓			
Fan et al. (2020)	Scrubber and MGO	✓	✓	✓			
Helgason et al. (2020)	Methanol	✓		✓		✓	
Zhu et al. (2020)	Scrubber and MGO		✓	✓			
Cariou et al. (2021)	LNG	✓	✓				✓

Dai et al. (2021)	LNG	✓	✓	✓		✓	
Lindstad et al. (2021)	MGO, LNG, Ammonia Hydrogen Methanol	✓	✓	✓			
Perčić et al. (2021)	MGO, LNG, Ammonia Hydrogen Methanol Biodiesel Battery	✓	✓	✓			✓
Zhao et al. (2021)	Scrubber, MGO, SCR, EGR		✓	✓			
Perčić et al. (2022)	Hydrogen and Ammonia	✓	✓	✓			✓
Tan et al. (2022)	Scrubber and MGO	✓	✓	✓			

Despite the extensive literature surrounding the cost-feasibility analysis of low-emission ship technologies, as evident in Table 1.1, gaps remain to be addressed. Firstly, while conducting cost-benefit analysis, studies have rarely assessed both the capital and operational costs of using low-carbon technologies, in combination with the collected benefits via saved fuel, external and carbon tax costs. Secondly, very few studies have considered the impact of saved baseline (diesel) fuel costs and carbon tax costs, when analysing the cost-effectiveness of technologies. Also, the estimation of benefits from saved external costs arising from the use of low-carbon alternative fuel technologies seems less understood within the literature. As per Helgason et al. (2020), it is important to consider external costs when evaluating the feasibility of using alternative technologies, as their exclusion from regulatory frameworks will reflect little incentive for maritime firms to reduce their emission footprint by investing in such technologies. Thirdly, except for Perčić et al. (2021), there has been limited research which analysed the cost-viability of using biofuels as an alternative to traditionally-utilized measures such as scrubbers or MGO. However, Perčić et al. (2021) did not consider the financial and environmental benefits via saved baseline fuel and external costs, respectively. Fourthly, except for Innes and Monios (2018), SSE-based studies have not analysed the impact of the future energy mix for grid supply, which is an important aspect when evaluating the profitability of long-term investments. Taking into consideration that several changes are expected in the use of energy sources within the EU as part of proposed Green Deal. However, Innes and Monios (2018) did not consider the supplied electricity costs while estimating the cost-feasibility of SSE. To address these gaps in the literature and to assist the stakeholders with the selection of most suitable technology to be implemented at different modes of operation, this research aims to conduct a rigorous cost-benefit analysis of different alternative solutions. Also, despite the fact that all emissions from the use of MGO by vessels during stays in EU ports are included within the EU ETS (NAPA, 2022), the electricity supplied at berth remains exempted from Energy Taxation Directive (ESPO, 2022). Further, it is expected that any benefits generated in terms of carbon taxes savings from the use of SSE at berth will effectively be offset by the taxes on supplied electricity at berth, hence, we have not considered the carbon tax costs while analysing the cost-effectiveness of using SSE.

1.3. Proposed Methodology - Thesis

Within this PhD thesis, the financial and environmental performances of low-emission technologies were evaluated and compared against the established baseline (diesel fuel) scenario. In which, to analyse the requisite shipping emissions for baseline and green technology-based scenarios, "bottom-up" methodology has been utilized. There are namely two main methods for deriving shipping emissions, top-down (fuel-based) and bottom-up (activity-based) (Tichavska et al., 2019). The top-down approach refers to estimating ship exhaust emissions based on a combination of data such as marine fuel sales (quantity and type) and fuel-related emission factors (Lee et al., 2021). This approach is relatively simple and can quickly obtain the results of emission inventories (Chen and Yang, 2024). It is commonly used by several countries to prepare domestic and international emission inventories (Nunes et al., 2017b). Although, a major concern about this methodology is statistical difficulty in segregating fuel delivery to various vessel types in a region (Merien-Paul et al., 2018). Furthermore, since reporting of fuel bunker sales in some regions are not mandatory (Merien-Paul et al., 2016), the figures from data bases may not always be representing accurate fuel consumption. Also, the top-down methodology is considered inaccurate as it does not account for the actual movement of ships, as opposed to bottom-up approach (Lee et al., 2021, Chen and Yang, 2024). The bottom-up approach is built on detailed information of ship specifications (IMO number, ship type and dimensions, engines characteristics and fuel type) plus survey and operational data (travel distances, maximum speed, port calls, estimated ship operations, ship tracks and real time operations) (Nunes et al., 2017b). Due to bottom-up approach using more precise input parameters, it is widely adopted within the literature (Nunes et al., 2017a, Dragović et al, 2018, Tichavska et al., 2019, Lee et al., 2021, Spengler and Tovar, 2021, Ay et al., 2022).

In consolidation with shipping emissions, evaluation of external costs is an important step for feasibility analysis where the costs to establish technologies to mitigate a specific environmental burden are compared with benefits (averted damages) (Jiang et al., 2014). There are mainly two proposed approaches for the quantification of external costs, bottom-up and top-down. The bottom-up approach calculates the external costs of air pollution starting from emissions, followed by concentrations, exposure, biophysical impacts and valuation of the economic costs and is more appropriate to apply to marginal cost valuation (more precise and accurate, with potential for differentiation) (Chatzinikolau et al., 2015). The top-down approach estimates the external costs using cost factors from reference bottom-up studies (mostly for the US and the EU) and is more convenient to assess average costs (Tichavska and Tovar, 2017, Nunes et al., 2019)

The Impact Pathway Approach (IPA) developed as a part of the ExternE project approved by the EU has been attributed as the most detailed methodology for calculating site specific air emissions external costs (Spengler and Tovar, 2022). Several EU funded studies such as the Benefits table database (BeTa), Clean Air for Europe (CAFE), and the New Energy Externalities Development for Sustainability (NEEDS) have employed this bottom-up approach to providing localised cost factors for different EU member states, including for Ireland (Holland and Watkiss, 2002, Holland et al. 2005, Korzhenevych et al. 2014). While it has been accepted that bottom-up approach provides. more localized and precise estimate of external costs, due to extensive modelling and complex data requirements, the top-down methodology has been widely adopted within the literature (Dragović et al, 2018, Nunes et al., 2019, Spengler and Tovar, 2021, Spengler and Tovar, 2022). Hence, following the widely agreed scholarly approach, this thesis utilises the cost factors as being provided by BeTa, CAFE and NEEDS, to quantify the impacts of implementing low-emission technologies for reducing the ship-based externalities.

To analyse the cost-effectiveness of implementing low-emission technologies, the NPV methodology was adopted. The NPV is commonly adopted financial tool used in capital budgeting and investment planning to analyse the profitability of a projected investment or project (Fernando, 2024). The idea behind NPV analysis is to determine all the future cash inflows and outflows associated with an investment, where, the future cash flows of any project are discounted into "present value" amounts via discount rate that represents project's cost of capital and risks (Gallant, 2024). The resulting number after subtracting future cash flows from the initial cash outlay required is the final NPV of any project (Fernando, 2024). Positive NPV indicates that the project will generate more value than the initial capital investment, while a negative NPV implies that the project would result in a loss (Faster-Capital, 2023). The impetus for conducting NPV analysis is mainly because it allows for a more realistic assessment of profitability, by including time value of money and risks associated for investors while facilitating any project, which is excluded while doing payback and Internal Rate of Return (IRR) analysis (Dai et al., 2022). Due to relative advantages of NPV over payback over IRR analysis, it has been the most popular analytical procedure adopted for evaluating cost-effectiveness of low-emission marine technologies in the literature (Jiang et al., 2014, Innes and Monios, 2018, Yu et al., 2019, Fan et al., 2020, Zhu et al., 2020, Zhao et al., 2021, Zis et al., 2022).

1.4. Research question and objectives

The overarching research question is to examine *how marine shipping sector can transition away from the use of fossil fuels towards low-emission technologies for compliance with existing directives and to achieve overarching near- and long-term emission targets.* The compiled research question can further be broken down into sub-research questions, in line with the identified literature gaps and the determined objectives of this research thesis: -

Q1. how much cost-competitive will the EU-2030 mandate of shore-side electricity utilization be against the consumption of MGO at berths?

RO. The cost-benefit analysis of SSE utilization has been prevalent within the academic literature (Ballini and Bozzo, 2015, Winkel et al., 2016, Vaishnav et al., 2016, Innes and Monios, 2018, Dai et al., 2019, Yu et al., 2019, Zis, 2019). Albeit, with the exception of Innes and Monios (2018), the relevant SSE-based literature haven't analysed the impact of the future energy mix for grid supply, which is an important aspect when evaluating the profitability of long-term investments. Considering that several changes are expected in the use of EU-based energy sources owing to "Green-Deal", in consolidation with the use of SSE becoming a mandate from 2030 at Ten-T ports (for passenger and container ships), the profitability of SSE utilization is expected to fluctuate accordingly. However, Innes and Monios (2018) did not consider the supplied electricity costs while estimating the cost-feasibility of SSE, which is also expected to alter in line with the grid energy mix. Hence, the objective-1 of this research is to "*analyse the profitability of using SSE against MGO under baseline (2019) and future (2030) Irish grid energy mix, highlighting cost-viability of SSE mandate under FuelEU directive"*.

Q2. how biofuels can be prospective alternative solutions over scrubbers and MGO for compliance with upcoming Atlantic-ECA regulations?

RO. As per IMO -2020 and -ECA directive, shipowners have been mandated to switch to low-sulphur fuel oil (MGO), install scrubbers or to use other potential alternatives like LNG and biofuels. In line with the established directives, several academic studies till date have analysed the cost-effectiveness of requisite compliance solutions (Jiang et al., 2014, Panasiuk and Turkina, 2015, Abadie et al., 2017, Gu and Wallace, 2017, Fan et al., 2020, Zhu et al., 2020, Zhao et al., 2021, Perčić et al., 2021). Although, it was found that the academic research has been fairly limited till date in terms of analysing the potential use of biofuels as low-sulphur alternative, with studies mainly focusing on traditionally employed measures such as scrubbers and MGO. Further, as biofuels are also being discussed as "transitional" low-carbon alternatives to the currently utilized diesel fuels. it becomes increasingly prevalent to analyse their cost-viability. Hence, the objective-2 of this research is to *"derive cost-effectiveness and practicality of switching to biofuels against traditional ECA compliant solutions of Scrubbers and MGO"*

Q3. how feasible will be the utilization of low-carbon alternative fuel technologies by marine shipping sector to achieve the near- and long-term emission targets?

RO. In parallel to fuel sulphur limit directives, the IMO (alongside EU) have further established decarbonization targets for the maritime sector. Various low-to-zero carbon fuel technologies such as LNG, Methanol, Hydrogen, and Ammonia, have been discussed widely within the academic and scientific society, to help steer the maritime industry towards the set carbon targets (Ammar, 2019, Helgason et al., 2020, Perčić et al. 2020, Cariou et al., 2021, Lindstad et al., 2021, Perčić et al., 2021, Perčić et al., 2022). Despite the increased attention being paid by researchers on such alternative fuel technologies, it was observed that studies have been limited till date which evaluated the cost-effectiveness of such measures while including the external costs alongside the requisite financial costs. The exclusion of external costs from cost-feasibility studies abandons any impetus for shipowners to switch to alternative technologies (Helgason et al., 2020). Hence, the objective-3 of this research is to "analyse the cost-feasibility of switching to low-carbon alternative fuel technologies, to help marine shipping sector achieve the established decarbonization targets".

Based on the established primary and sub-research questions (Q1,Q2,Q3), in conformity with the determined objectives (RO.1, RO.2, RO.3), the following research framework has been delineated (Figure 1.1), providing an essential pathway for this thesis to build upon.

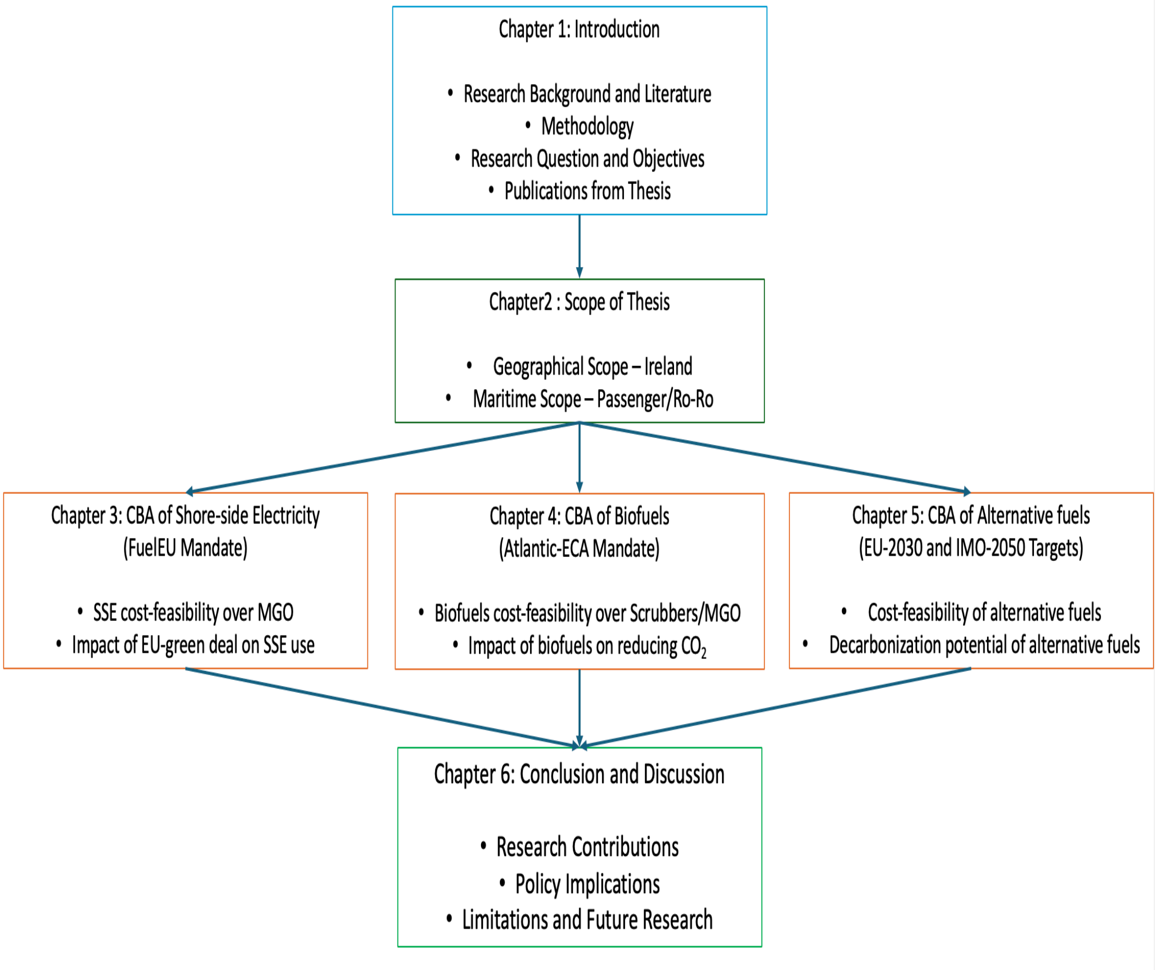


Figure 1.1. Proposed framework for this Thesis

1.5. Publications from the thesis

It is worth noting the publication status of the papers presented as chapters in this thesis, as presented in Table 1.2. To establish the quality of publications, leading business schools follow the Chartered Association of Business Schools (CABS) journal list, with journal rankings measured on the scale of highest (4*) to lowest (1). The CABS 2021 rankings for the published journals has also been provided in Table 1.2. The mentioned studies have been presented as separate chapters in the thesis, as per the given order in Table 1.2.

Table 1.2. Overview of thesis studies publication status

Paper and Chapter	Citation	Status and Ranking
Paper – 1 Chapter – 3	Gore, K., Rigot-Müller, P. and Coughlan, J., 2023. Cost-benefit assessment of shore side electricity: An Irish perspective. J. Environ. Manage. 326, 116755. https://doi.org/10.1016/j.jenvman.2022.116755	Published (CABS – 3)
Paper – 2 Chapter – 4	Reducing emissions from ships: The costs and benefits of emission abatement approaches. Gore K., Rigot-Müller, P., Coughlan, J., 2022. 30th Conference of the International Association of Maritime Economists, Busan.	Conference Paper
	Gore, K., Rigot-Müller, P. and Coughlan, J., 2023. Reducing emissions externalities from ships: The role of biofuels	Working Paper
Paper – 3 Chapter – 5	Gore, K., Rigot-Müller, P., Coughlan, J., 2022. Cost assessment of alternative fuels for maritime transportation in Ireland. Transp. Res. Part D Transp. Environ. 110, 103416. https://doi.org/10.1016/J.TRD.2022.103416	Published (CABS – 3)

Paper-1 “Cost-benefit assessment of shore side electricity: An Irish perspective” was published in the Journal of Environmental Management (CABS 3). In this paper, the cost-effectiveness of using SSE for cruise and ferry ships berthing in Irish passenger ports of Dublin and Belfast was investigated. Two different grid energy mix were considered, one dominated by non-renewable sources (year 2019), with other one primarily utilising renewable sources (year 2030) for electricity generation. No changes have been made to the published paper other than reformatting for this thesis. Paper-2 “Reducing emissions from ships: The costs and benefits of emission abatement approaches” was most recently presented as conference paper at the International Association of Maritime Economists (IAME) 2022 summit in Busan, South Korea. This paper was reworked and extended and now is entitled “Reducing emissions externalities from ships: The role of biofuels”. Paper-3 “Cost assessment of alternative fuels for maritime transportation in Ireland” was published in Transportation Research Part D: Transport and Environment (CABS 3). Taking into consideration the decarbonization targets set by the IMO and the EU, this study analysed and compared the cost-effectiveness of future zero-carbon fuels like hydrogen and ammonia and the presently available low-carbon fuels like LNG and methanol. No changes have been made to the published paper other than reformatting for this thesis.

The following Chapter 2 presents the scope of thesis, outlining detailed insights and research impetus for the selected case study, which is Ireland. Chapter 2 showcases how the Irish maritime sector has evolved over the years, which ship category and trade routes dominate the industry and economy, alongside its equivalent progress in meeting the regional (EU) and global (IMO) emission targets.

CHAPTER TWO: SCOPE OF THESIS

2.1. Introduction

Chapter 2 outlines detailed insights into the maritime trade sector for selected case study: Ireland, alongside the impetus behind its selection to analyse the use of clean alternative technologies. This chapter is divided into two distinct sub-sections (2.1 and 2.2). Section 2.1 highlights how the Irish maritime sector has fared and evolved over the years, especially through the period of Coronavirus Disease (COVID-19) pandemic, which initiated a global economic downturn, alongside that of Brexit (Exit of UK from the EU), which prompted economic adjustments within the EU. This sub-section further highlights the probable negative impacts imposed on the local Irish population and its environment from the fossil fuel-reliant shipping, while also understanding the progress Ireland has made in terms of fulfilling global and regional commitments for reducing shipping-based emissions. Section 2.2 analyses Irish maritime trade based on visiting ship types, handling ports, alongside the region of trade. Such comprehensive examination is of utmost importance as this helps to further narrow down on the ship types which are originating from highly populated port cities while being mostly operated on fixed routes closer to Ireland. Since these visiting ship types could be prioritised towards using cleaner alternative technologies, which could considerably increase local environmental conditions.

2.2 Geographical scope of thesis

The purpose of this thesis is to understand how marine shipping sector can transition away from its use of environmentally harmful fossil fuels, towards cleaner low-emission technologies, which are feasible to implement when comparing the provided benefits and the financial costs. For this research, Ireland was identified as a suitable case study considering the scale of externalities imposed by shipping emissions on the local population (Rutherford and Miller, 2019), alongside the overarching dependence of its local economy on the maritime sector (Lacey et al., 2019).. Irish ports play an indispensable role in facilitating international trade and linking Irish industry to broader EU and global markets (Marine Institute, 2023). In 2021, the direct turnover of the Irish maritime sector was around €1.6 billion. Further, shipping industry generated about €450 million in value added and employed nearly 5,000 people (Ahearne and Cassidy, 2023). Since 2007, the Irish Maritime Development Office (IMDO), which is Irish government's dedicated development, promotional and marketing office for the shipping sector, has been producing an "iShip Index". This quarterly weighted indicator outlines trends within Ireland's shipping industry, and as a result, the wider economy. The iShip index accounts for five separate market segments, highlighting changes (growth/decline) in such segments over the years. Unitised trade includes Lo-Lo (Container trade) and Ro-Ro, while Bulk traffic includes Break, Dry and Liquid. Figure 2.1 indicates a total Irish iShip Index for all primary maritime traffic sectors. The base period of the iShip index is 2019, which was chosen as an appropriate benchmark for the Irish shipping sector in Ireland as it marks the last year before the COVID-19 pandemic or Brexit took hold (IMDO, 2023). It was also a record year for both Ro-Ro and Lo-Lo traffic up to that point, and these markets represent half of all port traffic in Ireland when combined.

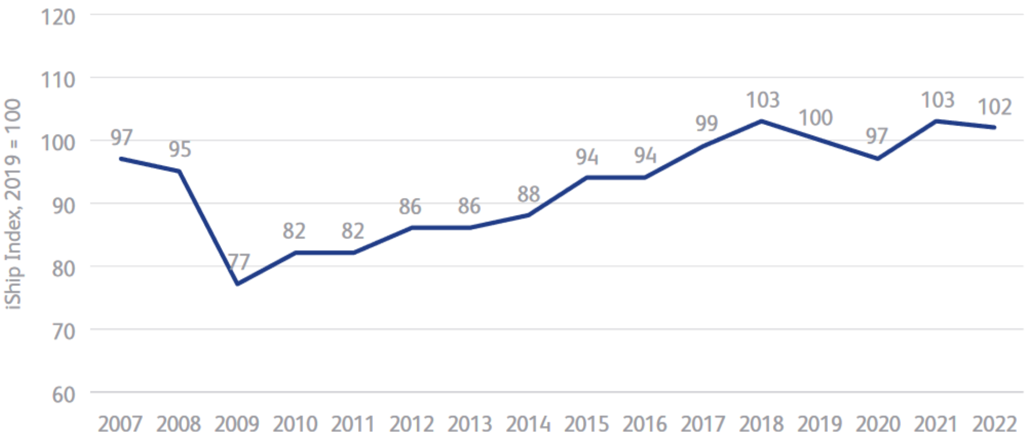


Figure 2.1. Total iShip Index (2007-2022)

Source: IMDO (2023)

The flow of Irish port traffic since 2007 is presented in Figure 2.1. The effects of the global financial crash on the traffic flow is evident between 2008 and 2009. Irish port tonnage fell by 19% during that period as the Irish economy fell into recession. Between 2009 and 2019, port tonnage rose consistently as the Irish economy recovered in consolidation with the increase in regional and international trade. The effects of the COVID-19 pandemic in 2020 was also found to be evident, when the iShip index declined by 3% in that year. In 2022, the iShip index declined by 1% compared to 2021, while it rose by 2% when compared to 2019. When further breaking down the iShip index in Figure 2.1, the changes in unitised trade category index – Lo-Lo and Ro-Ro, were outlined in Figure 2.2.

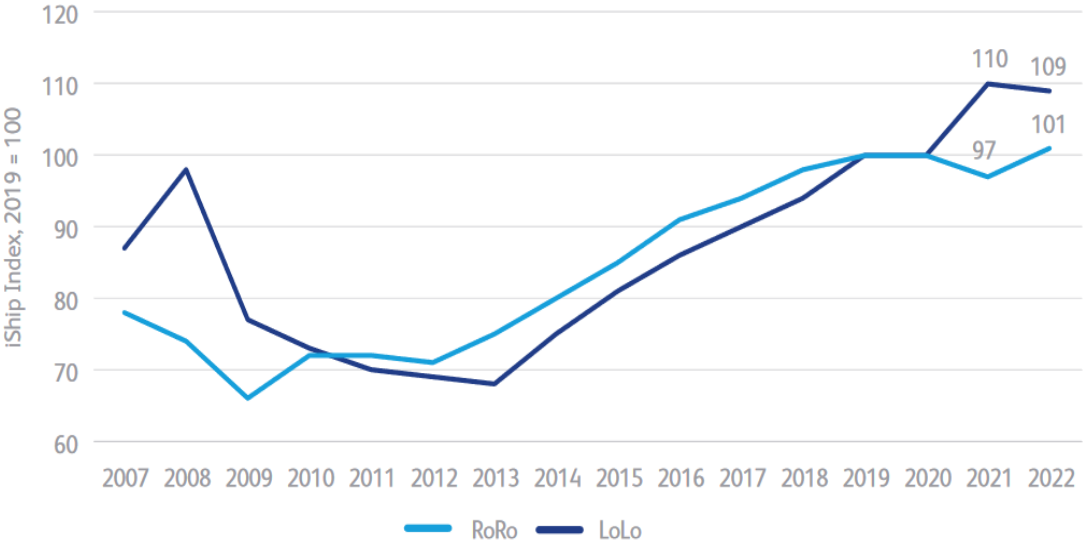


Figure 2.2. iShip Index for Unitised Trade Categories – Lo-Lo, Ro-Ro

Source: IMDO (2023)

Figure 2.2 illustrates that both the Lo-Lo and Ro-Ro market underwent a period of consistent and rapid growth between 2012 and 2019, which represented a recovery from the 2008 global financial crash. This was interrupted by the COVID-19 pandemic in 2020. It is noted that between 2013 and 2016, the Ro-Ro market experienced considerable growth of 6% per year on average. Between 2017 and 2019, growth slowed but maintained a robust annual rate of 3% (IMDO, 2020). Since 2020, Ro-Ro traffic has recorded significant fluctuations, with its traffic being just slightly above those volumes recorded in 2019. The change in trends for the Irish Ro-Ro market mainly resulted from the end of the Brexit transition period. According to the IMDO (2023), in the years leading up to 2021, Ro-Ro units on routes direct to mainland EU ports made up approximately 16%, or one in six Ro-Ro units per year. In 2021, this grew to 33%, or one in three Ro-Ro units. Conversely, Ro-Ro units on routes to UK ports, such as Holyhead, Liverpool, Fishguard and Pembroke, represented 84% of all Ro-Ro traffic share prior to Brexit, which fell down to 67% of the prior amount. In volume terms, post-Brexit traffic on Irish – UK routes declined by roughly 20%, while traffic on Irish – EU routes has doubled. Of the factors that drove this change, the decline in the use of the UK Landbridge has had the greatest impact. Figure 2.2 also demonstrates that until 2019, the LoLo iShip index has averaged 5-6% growth every quarter since Q1-2014, reflecting Pre-Brexit trends (IMDO, 2020). While in 2021 and 2022, the Lo-Lo traffic volumes Post-Brexit were found to outperforming its Pre-Brexit volumes. This is explained as the surge in demand from Irish traders for direct Lo-Lo services to mainland EU ports following the end of the Brexit transition period and has been persistent throughout 2021 and 2022 (IMDO, 2023). The vast majority of Lo-Lo services from Ireland are directed to continental EU ports, with Rotterdam and Antwerp being the two leading ports for Irish container traffic. When Irish exports reach these large European port hubs, many goods are transferred to much larger vessels and continue on to countries outside the EU,. Others may travel to EU Member States, such as the large markets of France, Germany, and Italy. Lo-Lo traffic from the island of Ireland therefore operates as a feeder service to and from large European maritime hubs, where Irish trade can access global markets.

Prior to Brexit, the UK Landbridge was a fast, effective way of accessing these European maritime hubs from Irish ports, and many shipping companies, hauliers and freight forwarders chose to do so. The UK Landbridge is a term used to describe a route to market that connects Irish importers and exporters to regional (EU) and international markets via the UK road and ports network (IMDO, 2018). It is a strategically important means of access to mainland Europe that has been favoured by traders in high value or time sensitive goods because it offers faster transit times than direct routes (IMDO, 2018). However, the introduction of customs controls at UK ports because of Brexit increased transit times and placed additional administrative costs on Irish businesses that reduced their competitiveness in accessing the regional and international markets (IMDO, 2023). Hence, Ro-Ro and Lo-Lo services have increasingly redirected their services away from the UK Landbridge in 2021 and 2022 towards direct services to EU ports for accessing the EU markets, and from there, global markets, in response to changes in the trading environment brought about by Brexit. This outcome was also evident from the study of IMDO (2023), where it was shown that in 2022, 60% of all unitised traffic from Irish ports is directed to and from a mainland EU port, an increment of 10% from roughly 50% pre-Brexit, while the use of UK Landbridge dropped to 40%. Followed by the display of changes in iShip index for unitised trade category in Figure 2.2, the adjustments in the bulk traffic sector within Ireland are outlined in Figure 2.3.

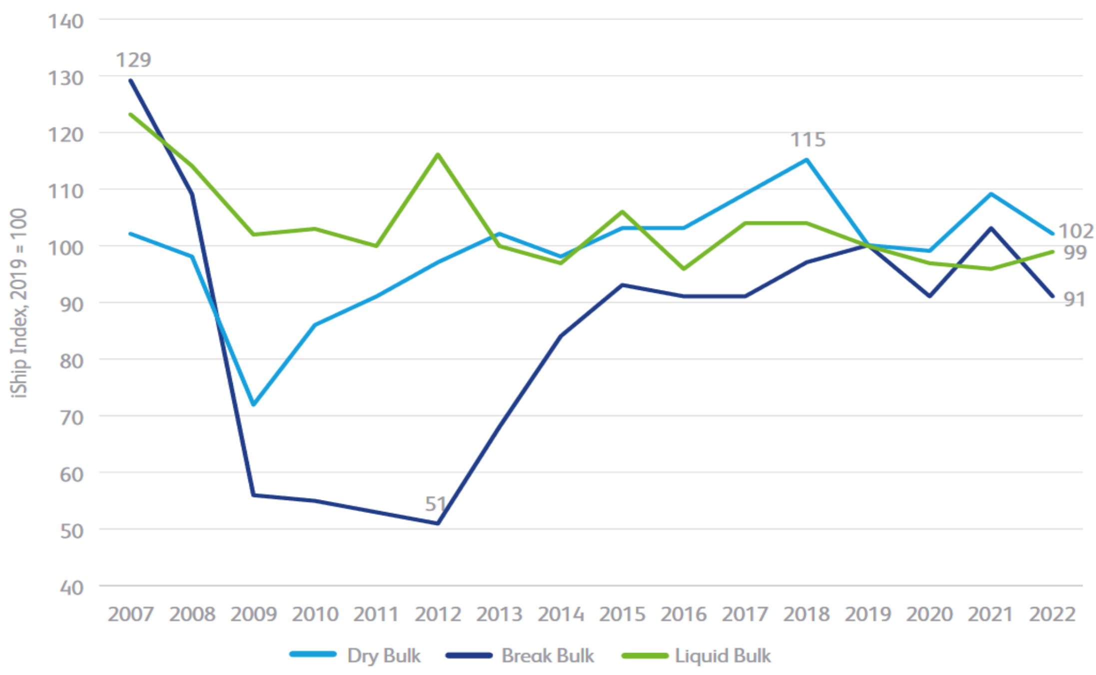


Figure 2.3. iShip Index for Bulk Categories – Dry, Break, Liquid

Source: IMDO (2023)

The iShip Index for Bulk traffic trends has been illustrated in Figure 2.3, where Bulk Port traffic refers to three market segments of port and shipping activity: liquid, dry and break. Liquid bulk is a commodity that ranges from petrol for cars to crude oil or LNG, mainly carried by tanker vessels. Dry bulk refers to raw materials for industrial or agricultural purposes, such as fertiliser, grains, coal, and iron ores. Break bulk is largely made up of non-containerised (i.e., general) cargo (IMDO, 2023). In 2022, break bulk traffic fell sharply by 9% compared to 2019 levels, primarily resulting from widespread increase in the price of building materials in 2022 that had a suppressive effect on demand for such traffic, which stopped the strong momentum attained after 2012 post the collapse of Irish construction sector (IMDO, 2023). While the dry bulk and liquid bulk levels in 2022 were roughly at the same levels as that of 2019, there has been a considerable decline in these segments over the years. Figure 2.4 shows the share of port tonnage held by each bulk segment, at five year intervals.

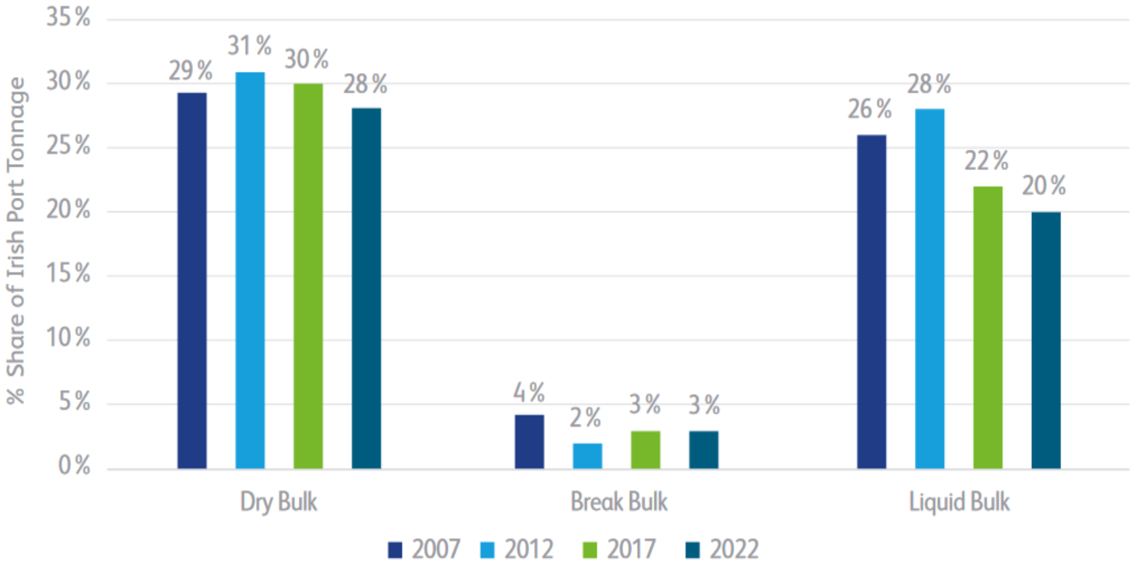


Figure 2.4. Percentage share of Irish port tonnage, at five year intervals

Source: IMDO (2023)

From Figure 2.4, a decline in dry bulk and liquid bulk share by 3% and 8% is observed, respectively, over the decade 2012 – 2022. This is reflective of the changing composition of Ireland's primary energy usage, as in the last decade, Ireland has made increasing use of natural gas and renewable sources for meeting energy demands, while the use of oil and coal has declined by 8.4% and 37%, respectively, over the period of 2016 – 2021, as stated by the Sustainable Energy Authority of Ireland (SEAI, 2022). The decline in imports of coal and petroleum has a significant effect on overall port volumes, particularly at Ireland's core ports (IMDO, 2023).

Along with trade, Irish ports also act as important gateways for its local tourism industry, as several international cruise and regional ferry companies offer connectivity to British, European and International ports (IMDO, 2020). Many shipping operators employ a Ro-Pax model (Ro-Ro ferry), meaning they carry not only freight traffic but passengers and passenger vehicles as well. Between 2009 and 2019, the market concentration of Ro-Ro freight and passenger levels have risen considerably by 18% and 19%, respectively, across the Irish ports (IMDO, 2020). Although, due to COVID-19 pandemic restrictions, a significant decline was witnessed in ferry passenger numbers in 2020 and 2021. For example, a total of 4.7 million passengers arrived in Irish ports on Ro-Ro passenger ships in 2019, which then declined by 56% and 37% in 2020 and 2021, respectively (IMDO, 2023). In 2022, a post-pandemic rebound was evident perhaps due to increased vaccination rates, as the total change compared to 2019 levels contracted by only 5% (IMDO, 2023). Similar to the trends of Ro-Ro freight, an increase in passenger numbers on the Irish–EU routes was evident in 2022 (by 5%) following Brexit transition period compared to 2019 levels (IMDO, 2023). Although, the Irish–UK route remained the most popular Ro-Ro passenger route, as it represented nearly 90% of the total passenger volume and 88% of the total weekly sailings (IMDO, 2023). This is possibly due to the "Common Travel Area" arrangement between the UK and Ireland, which allows citizens of either of the two countries to have the right to travel without any immigration requirements, which is not applicable in case of other EU citizens willing to travel to the UK. Similarly, Ireland has also been a popular destination of embarkment and disembarkment for Cruise passengers. In 2019, 701,140 cruise passengers travelled through the Irish ports, which dropped down by 100% in 2020 and 2021, as there were reportedly no cruise arrivals (Eurostat, 2023a), mainly due to COVID-19 pandemic restrictions. While the cruise tourism rebounded in 2022, the levels were still lower by nearly 29% (c. 500,000 passengers) compared to 2019 (Afloat, 2023, Central Statistics Office [CSO], 2023).

For all the outlined maritime traffic segments, the majority of the ship movements were found to be reported at the important port cities of Dublin, Belfast, Cork, and Limerick, which act as key strategic access points for the entire country along with other small and medium-sized coastal port towns (IMDO, 2020, IMDO, 2023). Dublin, the most populated city of Ireland, is also home to the busiest port in the nation, based on the ship traffic, followed by Belfast (NISRA, 2019, CSO, 2022a, IMDO, 2023). While shipping has been at the forefront of Ireland's economic growth, its attached emissions has impacted the local population negatively, as Ireland occupied 6th position globally in 2015 when it comes to number of premature deaths due to shipping emissions (per 100,000 population) (Rutherford and Miller, 2019). This higher death rate could be attributed to the fact that nearly 40% of the total population resides within 5 km of the coastline, especially in the major port cities of Dublin, Belfast, Cork and Limerick (CSO, 2022b). Figures 2.5 and Figure 2.6 below visualise shipping traffic density across the island of Ireland for 2019 and population density across the island, respectively.

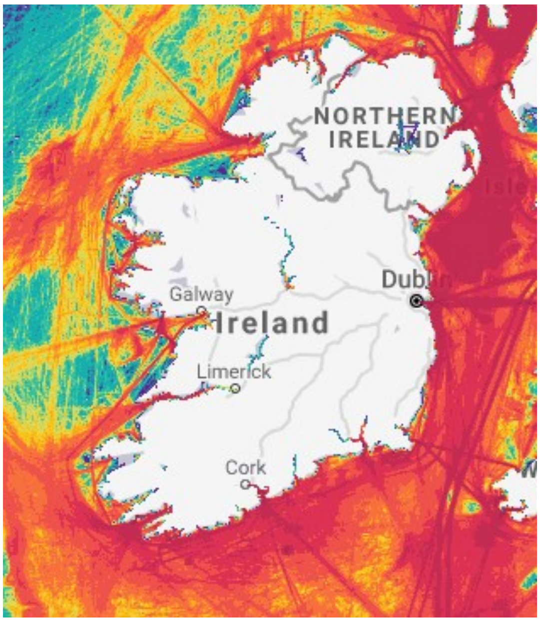


Figure 2.5. Ireland's Shipping traffic density in 2019

Source: Marine Traffic (2020)

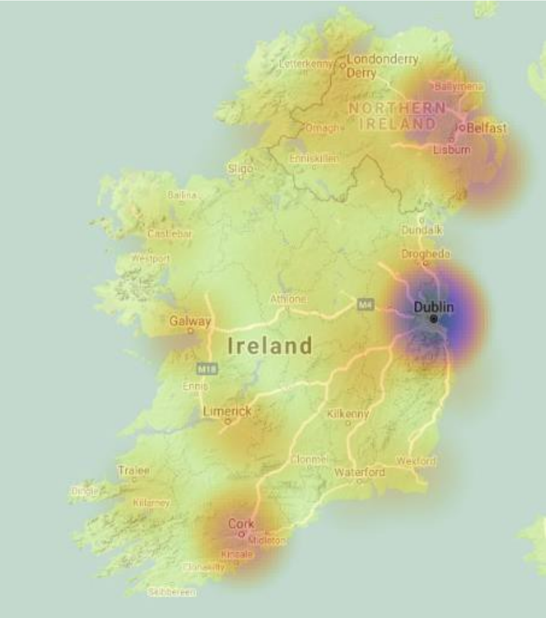


Figure 2.6. Irish population density heatmap in 2019

Source: NISRA and CSO (2014) (updated based on Eurostat (2023a))

To mitigate the negative impacts of shipping emissions on the local Irish population and environment, there is a pressing need for the introduction and promotion of "ow-to-zero emission technologies within the Irish maritime industry. At regional and international level, several steps have been taken by the regulatory authorities to mitigate shipping emissions. The IMO has implemented several ECAs where ships are required to follow fuel sulphur limit of 0.1% by using MGO or other alternative fuels, or by installing scrubbers, while it has set a global fuel sulphur limit of 0.5%. Currently, Ireland is not a part of any ECA, although, at the most recently concluded session of the Marine Environment Protection Committee (MEPC 80), a new "North-East Atlantic ECA" was being proposed, which will include Ireland, alongside Spain, Norway, France, Portugal, and Iceland, possibly coming into effect in early 2027 (Eason, 2023, IBIA, 2023). Also, it has set a target of reaching net-zero GHG emissions close to 2050, which will require an increase in uptake of low-to-zero emission fuels.

As part of its “Fit-for-55” package, the EU has introduced the FuelEU maritime proposal, which outlines limits on GHG intensity for ships and inclusion of shipping within the EU Emission Trading System (ETS). The FuelEU proposal also comprises an obligation for freight and passenger ships to use SSE while moored at the quayside in major EU (Ten-T) ports for more than two hours as of 2030, unless the ships are installed with other low-carbon fuel technologies (European Commission, 2023). Here, the obligation for ports to install shore-side infrastructure will be triggered if they annually receive at least 100 container ship calls and 50 passenger ship calls (European Commission, 2023). As part of Alternative Fuel Infrastructure Directive (AFID), EU Member States are obliged to ensure appropriate number of refuelling points for LNG at maritime ports, to enable LNG seagoing ships to circulate throughout the TEN-T Core Network. In the near future, discussions on the bunkering facilities for hydrogen, ammonia and methanol are also expected to take place (European Parliament, 2023a). The AFID will also require EU member states to create and provide national policy frameworks which should outline national objectives for implementing renewable and low-carbon fuel infrastructure, including both maritime and inland LNG infrastructure. However, the AFID did not impose any mandatory requirements for hydrogen infrastructure, leaving it up to Member States' discretion (BVNA, 2023). Parallel to the EU regulations, the concept of green shipping corridors (zero-emission maritime routes between two or more ports) has also been seen as a major lever towards shipping decarbonization (Fahnestock, 2022). This concept of green shipping corridors was developed at the COP26 summit which resulted in the “Clydebank Declaration”, to which Ireland is a signatory. The 2022 green shipping corridor progress report identifies 21 initiatives worldwide, 12 of them concerning short sea shipping (Global Maritime Forum, 2022). It is expected that by 2026, more than six green shipping corridors will be in operation. Although there is still uncertainty about the energy sources to be used for these initiatives, the main alternative fuels envisaged so far are green- methanol and -ammonia, while green hydrogen, synthetic diesel and electric power are also considered (Global Maritime Forum, 2022).

Despite the regional and international provisions, there has not been any noticeable impact on the roll-out and implementation of low-to-zero emission technologies within the Irish maritime sector till date. The Irish "Climate Action Plan 2023", which has set out the ambitious roadmap to put Ireland on a trajectory for net-zero by 2050, rarely references the impact of maritime emissions on Ireland and any strategic guideline for the fulfilment of EU Fit-for-55 objectives (Government of Ireland, 2023). This is in combination with the fact that Ireland has witnessed a growth of nearly 830% in its "international shipping" CO_2 emissions in 2021 compared to 1990 levels (EEA, 2023b). This is not only significantly higher than the EU-27 growth rate for the similar period (27%), but also, is reportedly the highest growth rate for shipping CO_2 emissions among all the EU member states (EEA, 2023b). Hence, for successful compliance with the set decarbonization objectives, increased attention needs to be paid by the stakeholders involved to help the Irish maritime industry sector transition away from the use of fossil fuels towards low-to-zero emission technologies. Since, this could fundamentally reduce the imposed externalities on the local Irish population and its built environment via ship air emissions.

2.3 Maritime scope of thesis

The island of Ireland has been divided into two separate jurisdictions: the Republic of Ireland and the Northern Ireland. There are total 24 ports on the island, with 18 being in the Republic and the remaining 6 in Northern Ireland. For the considered 24 ports, Table 2.1 indicates total tonnage of goods handled during 2019, classified by five major ship traffic categories of liquid bulk tanker, dry bulk, containers, Ro-Ro, other general cargo, alongside total number of ship arrivals and registered calls. The impetus behind the consideration of year 2019 for this study was mainly due to the occurrence of Coronavirus (COVID-19) pandemic and preparations for Brexit in early 2020s, which placed unprecedented pressure on the Irish maritime industry in the year 2020 and onwards (IMDO, 2021).

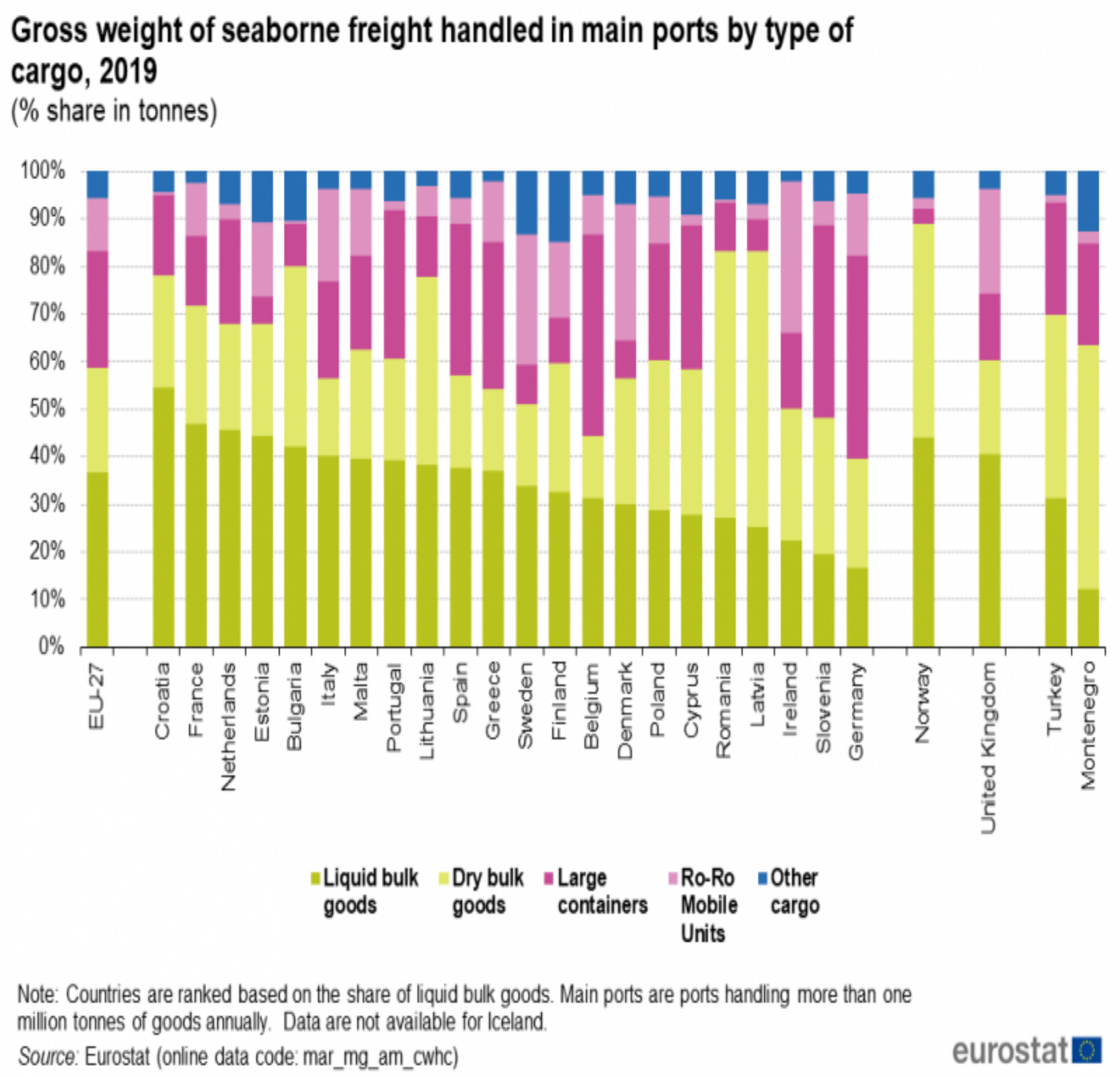
Table 2.1. Total tonnage of goods handled by Irish ports, in 2019, by category of traffic

	Category of traffic				
Port	Liquid bulk tanker	Dry bulk	Container	Ro-Ro	Other General
Republic of Ireland					
Bantry Bay	728	-	-	-	-
Castletown	-	-	-	-	65
Cork	4,882	1,525	1,889	135	271
Drogheda	35	1,197	-	-	299
Dublin	4,652	1,821	5,803	14,041	17
Dundalk	-	78	-	-	-
Galway	370	138	-	-	47
Greenore	-	814	-	-	208
Killybegs	-	29	-	-	65
Kinsale	-	25	-	-	-
New Ross	2	361	-	-	-
Rosslare	-	-	-	2,010	31
Limerick	1,066	8,269	-	-	286
Sligo	-	16	-	-	19
Tralee	-	-	-	-	23

Waterford	-	1,359	317	-	172
Wicklow	-	2	-	-	166
Youghal	-	-	-	-	11
Northern Ireland					
Bangor	-	-	-	-	-
Belfast	2,182	6,677	1,756	7,571	332
Carrickfergus	34	467	-	-	-
Derry	596	1,247	-	-	66
Larne	4	19	-	2,705	39
Warrenpoint	-	455	248	2,323	294
Total tonnage	**14,551**	**24,499**	**10,013**	**28,785**	**2,411**
Ship arrivals	**319**	**276**	**86**	**86**	**743**
Registered calls	**1,762**	**435**	**1,724**	**13,355**	**3,021**

Source: CSO (2020), Refinitiv Eikon (2022), Eurostat (2023b)

From Table 2.1, it is noted that for 2019, total 80,259 tonnes of seaborne freight was handled by 24 Irish ports. When compared on the basis of ship categories, Ro-Ro freight represented nearly 36% (28,785) of the total tonnage, followed by dry bulk goods (31%), liquid bulk tanker (18%), containers (12%), and other general cargo (3%). These figures can largely be attributed to the fact that Ro-Ro vessels also represented nearly 66% of the total calls (13,355) registered at the Irish ports, highest among all the categories, despite the number of ship arrivals being only 6% (86) of the total. Also, it was observed that share of Ro-Ro freight in total tonnage of goods handled by Irish ports in 2019 (31.9%) was the highest recorded figure among all the EU member states (Figure 2.7), reflecting the importance of Ro-Ro ferry traffic in the Irish seaborne transport sector.



Note: Countries are ranked based on the share of liquid bulk goods. Main ports are ports handling more than one million tonnes of goods annually. Data are not available for Iceland.

Source: Eurostat (online data code: mar_mg_am_cwhc)

Figure 2.7. Gross weight of EU seaborne tonnage by ship cargo type (2019)

Source: Eurostat (2021), Eurostat (2023c)

Further, to help determine the most popular trade route for Irish seaborne traffic, for the identified ship traffic categories, Figure 2.8 classifies the total tonnage of goods handled by Irish ports based on the region of trade, in 2019.

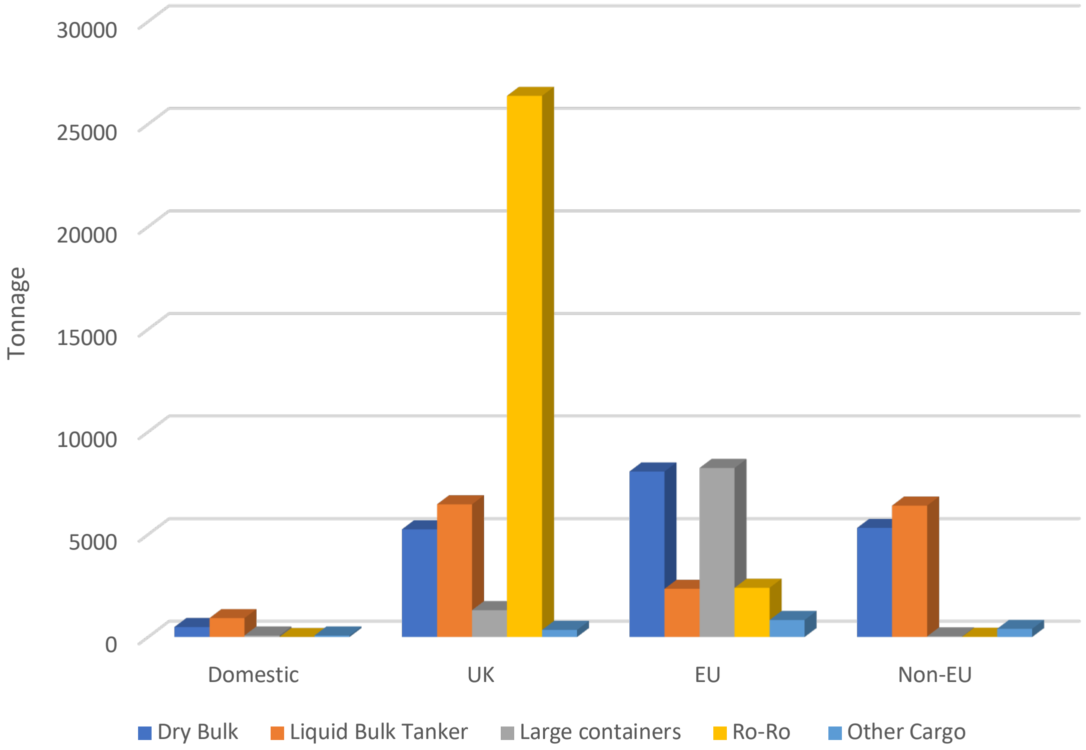


Figure 2.8. Seaborne tonnage handled by Irish ports in 2019, by ship type and region

Source: Eurostat (2023b)

From Figure 2.8, it is observed that nearly 50% (39,747 tonnes) of the seaborne freight trade happened between the Irish and United Kingdom (UK) ports, highest among all the regions. This was followed by its trade with EU countries (32%), non-EU countries (16%), and domestic trade (2%). Among the Irish-UK seaborne trade, Ro-Ro was the most popular ship category, as it represented nearly 66% share of the total trade. Also, it must be noted that Ro-Ro ships operating on Irish-UK route is the most popular combination of ship traffic category and trade route among all the possible options outlined. This information is of increased significance, considering that unlike other categories of ships, Ro-Ro ships increasingly operate on a fixed route between the Irish and UK ports, and hence, pose a notable challenge in terms of emissions, as they are highly likely to impact local population and environment negatively. Hence, determining the significance of Ro-Ro ship category within the Irish seaborne traffic with that of proven high mortality rate and negative impact on the Irish built environment from shipping emissions (Rutherford and Miller, 2019), this ship type needs to be given the utmost priority while discussing the use of low-to-zero emission technologies to help achieve higher societal and environmental benefits, and as a result, the primary focus in this study in terms of cost-benefit evaluation will be on Ro-Ro ship arrivals at Irish ports. Further, alongside Ro-Ro ships, we have also included cruise ships which visited Irish ports in 2019 as case subject for our study "Cost-benefit assessment of Shore Side Electricity: An Irish perspective", considering that such ships spend considerably longer amount of time at berth, and have been known to display higher energy demand at berth when compared to that of cargo ships (Winkel et al., 2016, Spengler and Tovar, 2021).

2.4 Conclusion

To summarise, the Irish maritime sector, across the different trade categories, has been growing steadily post the 2008 financial crisis. Albeit there was some downturn in the sector in 2020 due to the two unprecedented events of COVID-19 pandemic and the Brexit, post which it has been on a recovery track and is expected to reach and further overcome the pre-pandemic and pre-Brexit levels. Also, despite the significance of the maritime sector within the Irish economy and the negative environmental impacts associated with it, it has hardly made any progress till date for achieving the overarching emission targets set by the EU and IMO. If the Irish maritime sector intends to transition away from the use of fossil fuels, it should start prioritising the use of cleaner alternative options within the Ro-Ro ships, as they constitute major share of maritime trade and tend to operate on fixed routes closer to the Irish coastline, with the use of low-to-zero emission technologies within such category expected to reap significantly higher environmental benefits.

Hence, considering the observations in Chapter 2, in the following Chapter 3, as per the FuelEU maritime proposal, the use of SSE was investigated for Ro-Ro Ferry and cruise ships visiting the two most busy and populated port cities of Dublin and Belfast, when compared for its use against the currently utilised MGO fuel at berth. While in Chapter 4, the cost-effectiveness of using biofuels (under IMO-2020 directive), when applied to Ro-Ro ferries operating from Irish ports, was compared against the use of presently available options of MGO and scrubber. Further, in Chapter 5, the cost-effectiveness of implementing LNG, methanol, hydrogen, and ammonia fuel technologies for the Top-20 ships (Ro-Ro ferry and cargo) was analysed, to indicate their potentiality of achieving the future EU-2030 and IMO-2050 emission targets.

CHAPTER THREE

Cost-benefit assessment of Shore side Electricity: An Irish perspective

3.1 Abstract

This study, based on 2019 data, investigates the cost-effectiveness of Shore Side Electricity (SSE) adoption utilising the existing (2019) and future (2030) Irish energy mix, while considering different levels of adoption across six scenarios, incorporating both “port-side” and “ship-side” private costs alongside the benefits from reduced external costs and avoided Auxiliary Engine (AE) fuel costs. Passenger ships calling to the two most populated Irish port cities of Dublin and Belfast were selected as the case study, owing to the significance of such ports and ship types in the Irish maritime economy. For the existing Irish energy mix, the most optimal solution among the discussed scenarios was that of switching the top 10 most frequent passenger ship callers in Dublin and Belfast to SSE, as it reflected the highest Net Present Values (NPV) of €34.06 million and €15.44 million, respectively. The future (year 2030) SSE supply is expected to be “cleaner” due to an increase in the uptake of renewable energy sources, which will further boost the obtained NPVs by 50%. A combination of public funding (by 50%), increment in supplied electricity price by 8.62% (for Dublin) and 10.01% (for Belfast) and an annual ticket price supplement (per passenger seat) by €0.03 (for Dublin) and €0.04 (for Belfast), can create a business case for the identified optimal scenario.

3.2 Keywords

Shore Side Electricity; Ship emissions; External costs; Private costs; Cost-benefit analysis

3.3 Introduction

When at berth, ships use their Auxiliary Engines (AE) to generate electricity for essential ‘hotelling’ services which include communications, lighting, and other onboard equipment (Tzannatos, 2010a, Winkel et al., 2016). In port cities, emissions from these ship-based activities are identified as a significant source of air pollution (Castells Sanabra et al., 2014). It has been acknowledged that approximately 450 different types of pollutants are emitted by marine engines as a part of their internal combustion process, including oxides of sulphur (mainly sulphur dioxide (SO_2)), nitrogen oxides (NO_x), particulate matter (PM) and greenhouse gases (mostly carbon dioxide (CO_2)) (Alver et al., 2018). These pollutants have important implications for not only the environment, but also for the local population residing near the coastline (Tzannatos, 2010a).

Shore Side Electricity (SSE) is seen as an alternative to reduce the emissions of AEs and thus ameliorate the negative effects of fuel-based power sources (Dai et al., 2020). SSE is a “land-to-ship electricity connection that replaces the AEs to supply power to the ship when at berth” (Yu et al., 2019). The EU has been increasingly proactive in promoting the use of SSE, with its first important directive being in 2005, which mandates ships berthing in EU ports for more than 2 hours to use fuel oils with a sulphur content of less than 0.1% (e.g., Marine Gasoline Oil (MGO)), unless they are able to switch to SSE (Castells Sanabra et al., 2014, Zis, 2019). It took one step further in 2014 when it approved the directive 2014/94/EU stating that “Member States shall ensure that the need for shore-side electricity supply for inland waterway vessels and sea-going ships in maritime and inland ports is assessed in their national policy frameworks, where, such shore-side electricity supply shall be installed as a priority in ports of the TEN-T Core Network, and in other ports, by 31 December 2025, unless there is no demand and the costs are disproportionate to the benefits, including environmental benefits” (Innes and Monios, 2018, p.300). Here, the costs mainly refer to the installation of SSE port-side infrastructure and the supplied electricity from the grid (Zis, 2019), with the environmental benefits being the reduced socio-environmental external costs associated with the use of SSE against MGO (Spengler and Tovar, 2021). External costs are the economic consequences of ship exhaust emissions on the local population and environment (Nunes et al., 2019). Along with ports, there are also shipowner costs in the form of ship-side modifications and the payment for supplied power (Winkel et al., 2016), although in return the majority of the fuel costs are avoided. Hence, the choice of deploying SSE requires the comparison of the associated costs and benefits, where the costs are split into "port-side" and "ship-side", with the incurred benefits being the reduced external costs and the saved fuel costs when ships switch to SSE instead of using MGO at berth. Also, when conducting SSE cost-benefit analysis, it is important to consider the energy mix of the supplied electricity, as it will drastically impact the associated socio-environmental benefits (Spengler and Tovar, 2021).

Investigating SSE-related costs and benefits is a key feature of extant literature. Tzannatos (2010a) reported total external costs of €10.8 million and €1.4 million for the use of MGO and SSE by cruise ships berthing in the Piraeus port, respectively, with the total "ship-side" private costs being €5.2 million and €10.4 million, respectively. Ballini and Bozzo (2015) reported total private costs of €37 million for "port-side" SSE installation in the Copenhagen cruise port and external costs savings of €2.8 million annually, for SSE usage by 60% of berthing cruise ships, resulting in a payback period of 12-13 years. Tseng and Pilcher (2015) estimated total external costs savings of $2.8 million (only NO_x and CO_2) for 60 container ships berthing in the Kaohsiung port using SSE, alongside an increase in private costs per ship of $6,920. Innes and Monios (2018) estimated total private "port-side" costs of €7.4 million for SSE installation in a medium-sized port (Aberdeen) and assessed that total external costs savings could be up to €1.4 million annually, resulting in

Net Present Values (NPVs) of €1.2 million (10 year period) and €8.7 million (25 year period). Dai et al. (2019) reported negative NPVs in range of −1.3 billion to −2.9 billion Chinese Yuan (CNY) for SSE usage by containerships in Shanghai port, for three adoption rates, incorporating CO_2 emission trading only. Yu et al. (2019) estimated an average payback period of less than 4 years for the use of SSE by containerships visiting Dalian port, with the total external cost savings being $128 million annually. Winkel et al. (2016) estimated the total external cost savings with the prospective use of SSE across several European (including Irish) ports to be €2.94 billion, while for a similar scenario, Stolz et al. (2021) indicated significant achievable reductions in shipping emissions (3 million tonnes CO_2, 86,431 tonnes NO_x, 4,130 tonnes SO_x and 1,596 tonnes $PM_{2.5}$).

Despite the extant literature on costs and benefits of using SSE, gaps still remain to be addressed. Firstly, except for Innes and Monios (2018), studies have not analysed the impact of the future energy mix for grid supply, an important aspect when assessing the profitability of long term investments such as SSE. Within the EU, significant changes are expected in the future energy mix, with an estimated increase in the uptake of renewable energy sources from 34% (year 2019) to 65% (year 2030), as a part of newly proposed European green deal (European Commission, 2020a, EEA, 2022). Although Innes and Monios (2018) outlined the socio-environmental benefits arising from the considered baseline (year 2015) and future (year 2020) Scottish energy mix, there was no discussion on the subsequent changes in the supplied electricity price, as this will also impact the overall cost-effectiveness of using SSE. Secondly, it was observed that researchers have rarely examined the costs and benefits of SSE based on the variance in its levels of adoption. While it has been suggested in the past that switching high visiting frequency ships to SSE could be advantageous (Innes and Monios, 2018), it is important to provide a detailed cost-benefit analysis under a range of different scenarios to assist with the identification of most profitable pathway for implementing SSE. Thirdly, previous studies have rarely assimilated both the port-side and the ship-side installation costs with that of achieved socio-environmental benefits through reduced external costs alongside the economic benefits from saved fuel costs while conducting SSE feasibility studies. Fourthly, it was seen that despite having one of the highest death rates in the world due to shipping emissions (Rutherford and Miller, 2019), Ireland was never subject to an SSE cost-benefit case study. To address these gaps, this research conducts a cost-benefit analysis of SSE investment at six different levels of its implementation, considering the current (year 2019) and future (year 2030) Irish energy mix, using the NPV approach, assimilating the port-side and ship-side installation costs and the incurred benefits through reduced external costs and saved fuel costs.

Based on Spengler and Tovar (2021), enabling all the national ports and visiting ships to use SSE will be practically impossible due to high capital costs, and hence, the initial focus should be on the ports situated in highly populated cities, and for those ships which present the highest energy demand at berth and often visit same port multiple times (Zis, 2019). For these reasons, this case study will focus on Dublin and Belfast, the two most populated cities in Ireland (NISRA, 2019, CSO, 2022b), and on passenger (i.e. Roll/on-Roll/off (Ro-Ro) ferries and cruise) ships, which are known to make frequent port calls and have, globally, displayed higher energy demand at berth when compared to that of cargo ships (Winkel et al., 2016, Spengler and Tovar, 2021).

3.4 Materials and methods

3.4.1 Geographical scope

Being an island nation, maritime transportation is the backbone of the Irish economy, with its ports acting as the important gateways for trade and tourism. Irish merchandise export volume in 2019 stood at 18.5 million tonnes, with 90% of the exported tonnage being moved through Irish ports (Irish Maritime Development Office [IMDO], 2020). Ireland is separated into two jurisdictions, the Republic of Ireland and Northern Ireland. Dublin, the capital of the Republic of Ireland and the most populated city in the nation (CSO, 2022b), accounts for almost 50% of the national maritime trade (IMDO, 2021). Belfast, the capital of Northern Ireland handles 70% of the Northern Irish seaborne trade and hosts the majority of the Northern Irish population (NISRA, 2019, McDonnell, 2020). Within Europe, the share of Ro-Ro ferries in the total seaborne freight was the highest for Ireland (31.6%) (Eurostat, 2021), indicating the significance of such ship type in the Irish maritime economy. Several popular ferry companies such as Stena Line, P&O ferries, Seatruck ferries and Irish ferries offer connectivity to British and mainland European ports. More than 4 million ferry passengers transited through Irish ports in 2019, with Dublin and Belfast ports combined representing 75% of the total volume (IMDO, 2020). Along with ferries, cruise ships have also played a significant role in boosting Ireland's tourism economy. More than 700,000 passengers arrived in Ireland in 2019 through cruise ships, with Dublin and Belfast remaining the most dominant cruise ports, accounting for 70% of the total passengers (IMDO, 2020).

3.4.2 Shipping emissions

3.4.2.1 Onboard operation

For all passenger ships which berthed in Dublin and Belfast ports during 2019, the total AE emissions from the onboard use of MGO were determined by Eq. (1), as derived from Tzannatos (2010a):

$$E_{MGO} = \sum_i (T_B \times [P_{AE} \times LF_{AE} \times EF_{AE}^i] \times 10^{-6}) \qquad (1)$$

Where E_{MGO} is the total emissions from MGO usage (tonnes), i refers to the pollutants: SO_2, NO_x, $PM_{2.5}$ and CO_2, T_B is the time spent at berth (hours), P_{AE} is AE power (kW), LF_{AE} is the load factor of the AE at berth (in %) and EF_{AE}^{i} is the emission factor of the AE for each emitted pollutant (g/kWh).

For this study, our dataset was built from statistics on ship movements and specifications obtained from the Refinitiv Eikon (2022a) AIS database. From the AIS dataset, it was observed that 34 and 59 passenger ships berthed in Dublin and Belfast during 2019 registering 3,618 and 1,046 port calls, respectively. As the 2005/33/EU directive does not apply to calls at berth made for less than 2 hours, such movements were excluded from the study, representing only 21 of the total 4,664 port calls being made across Dublin and Belfast ports. Information on P_{AE} and T_B for the ships under investigation was retrieved from the AIS dataset. LF_{AE} for each ship was assigned based on the study of De Meyer et al. (2008). The allocation of EF_{AE}^{i} depends upon the considered fuel type (in this instance, MGO) and on the ship engine type (Tzannatos, 2010a). Based on the study of Spengler and Tovar (2021), we assumed that auxiliary engines are of the "medium speed diesel" type for the selected ships. EF_{AE}^{i} was assumed as 0.42 g/kWh for SO_2, 13.9 g/kWh for NO_x, 0.17 g/kWh for $PM_{2.5}$ and 690.71 g/kWh for CO_2 (Inner City Fund, 2009).

3.4.2.2 SSE operation

The use of SSE by ships at berth will generate additional electricity requirements from the local power grid (Tzannatos, 2010a). Within the SSE operation, ships while at berth will be required to use their AEs for one hour to connect and disconnect from the external power supply in port (Zis, 2019). Associated emissions from the SSE operation can be calculated by Eq. (2):

$$E_{SSE} = \sum_i ((T_B - T_{CHANGEOVER}) \times [P_{AE} \times LF_{AE} \times EF_{SSE}^i] \times 10^{-6}) + (T_{CHANGEOVER} \times [P_{AE} \times LF_{AE} \times EF_{AE}^i] \times 10^{-6}) \quad (2)$$

Where E_{SSE} is the total emissions from the SSE operation (tonnes), i refers to the pollutants: SO_2, NO_x, $PM_{2.5}$ and CO_2, T_B is the time spent at berth (hours), $T_{CHANGEOVER}$ is the total changeover time for shore-side power connecting and disconnecting (estimated at one hour), P_{AE} is AE power (kW), LF_{AE} is the load factor of the AE at berth (in %), EF_{SSE}^i is the grid emission factor for each emitted pollutant (g/kWh) and EF_{AE}^i is the emission factor of AE for each emitted pollutant (g/kWh).

In 2019, a total of 31.3 TWh of electricity was produced in Ireland, with the share of renewable energy sources being 37.57% (SEAI, 2020). Recently, Ireland has committed to reduce its dependence on non-renewable sources in electricity production, by increasing the uptake of renewable energy sources to 80% by 2030, 15% higher than the EU target (European Commission, 2020a, Grid Beyond, 2021). Within the renewables sector, wind and solar energy have been receiving the topmost priority from the Irish government to meet the set 2030 targets (Department of Environment, Climate and Communications, 2022). Based on the projected capacity of renewable energy production in 2030, it is estimated that wind will fulfil 61% of the total Irish energy demand, with solar fulfilling 19% (Turner and Zhang, 2018). While for the non-renewable sector, the use of coal, peat and oil is expected to be phased out before the end of 2030 (Environmental Protection Agency, 2020), with gas remaining the only major contributor (Grid Beyond, 2021), to meet the remaining 20% of the Irish energy demand. Figure 3.1 indicates the structure of the Irish energy mix in present year 2019 and the prospective mix in year 2030.

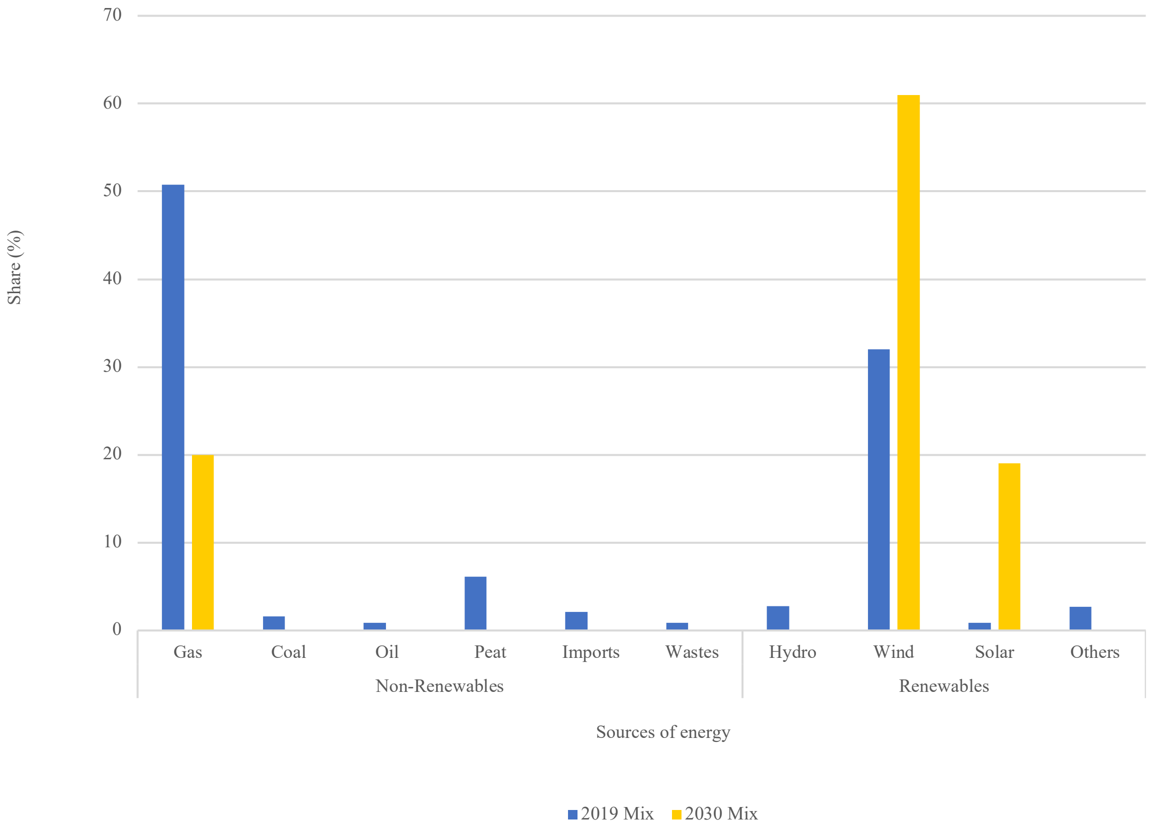


Figure 3.1. Irish energy mix in 2019 and prospective 2030 mix

Source: Turner and Zhang (2018), SEAI (2020), Grid Beyond (2021)

Such changes in the overall structure of the energy mix are also expected to impact the cost-effectiveness of using SSE against MGO as the grid emission factors will be changing accordingly, affecting the derived socio-environmental benefits. Table 3.1 provides the grid emission factors for year 2019 and 2030 energy mix, which were simulated based on the information in SEAI (2020), EPA (2021) and SEAI (2021).

Table 3.1. Grid emission factor for year 2019 and year 2030 energy mix

Energy mix	Grid Emission factor (g/kWh)			
	SO_2	NO_x	CO_2	$PM_{2.5}$
Year 2019	0.071	0.191	324.5	0.008
Year 2030	0.041	0.110	186.91	0.004

Source: Data based on SEAI (2020), EPA (2021), SEAI (2021)

3.4.3 External costs

Following established research on external cost assessment using the top-down approach (Tichavska and Tovar, 2015b, Nunes et al., 2019, Spengler and Tovar, 2021), a similar methodology was also adopted in this research. The top-down approach involves the estimation of external costs using cost factors from reference bottom-up studies (e.g., Benefits Table database (BeTa) and Clean Air For Europe (CAFE) and New Energy Externalities Development for Sustainability (NEEDS)) (Nunes et al., 2019).

BeTa provides external cost factors for NO_x, SO_2 and $PM_{2.5}$ depending on the zone (urban (short-range externality) or rural (long-range externality)) and population density for 14 EU member states (including Ireland) (Holland and Watkiss, 2002). In 2005, the external cost factors (rural) for BeTa were updated by the CAFE project, covering 25 EU member states and forecasted for a 2010 baseline scenario (Holland et al., 2005, Nunes et al., 2019). The size of the port city is used as a guide to calculate the external costs of emitted pollutants, with an additional rural externality for the country the port is situated within (Holland and Watkiss, 2002). Studies have frequently used the combination of BeTa (urban) and CAFE (rural) cost factors to enhance the estimation of external costs (Castells Sanabra et al., 2014, Tichavska and Tovar, 2015b, Nunes et al., 2019) and therefore a similar approach was adopted in this study. For urban cost estimation, external cost factors for SO_2 and $PM_{2.5}$ suggested in BeTa for a city of 100,000 people must be multiplied by a scale factor, which is linear up to 500,000 inhabitants, to adjust the provided cost factors in line with the respective population of Dublin and Belfast. In this study, linearity of the scale was assumed. Data on the population of Dublin (554,600 in 2016) and Belfast (333,871 in 2011) was obtained from NISRA (2019) and CSO (2022b), and adjusted by 4% and 7%, respectively, based on the increase in the total Irish population from the two reference years until 2019 (Eurostat, 2023b). The derived year 2019 numbers were further incremented by 7.4% (for Dublin) and 2% (for Belfast) to adjust as per the projected increase in 2030 population figures (CSO, 2022c, Office for National Statistics, 2022). CAFE provides rural cost factors for four different settings which vary due to ways to value mortality rates, the size of the effects on health and the differential impact of cut-off points for ozone impact (Nunes et al., 2019). To homogenise all these scenarios, average results for the four sensitivity scenarios were considered when allocating the rural cost factors.

Along with BeTa and CAFE, the NEEDS project has been used as a suitable methodology for assessing the external costs of maritime transport (within sea regions) (Maragkogianni and Papaefthimiou, 2015, Tichavska and Tovar, 2015, Nunes et al., 2019). However, it should be noted that the NEEDS approach does not include both urban and rural cost factors, which would underestimate the total external costs from shipping emissions (Nunes et al., 2019). Also, BeTa makes explicit mention of air pollution damage in port areas caused by shipping, which is not the case in NEEDS (Nunes et al., 2019). Given the importance of this specific damage, it can be said that using a combination of BeTa and CAFE cost factors seems to be a more reliable approach to estimating external costs when investigating the achieved socio-environmental benefits of a port-based emission reduction technology like SSE. For CO_2, the external cost factor was derived from the CE Delft report, where the "average" cost factor of €86/ton was assumed (Van Essen et al., 2011).

Cost factors provided in the BeTa and CE Delft report refer to the year 2000 and 2008 prices, respectively, while CAFE reflects the year 2010 prices. The Consumer Price Index (CPI) for Ireland as available in the Organisation of Economic Co-operation and Development (OECD) statistical profiles was used to update these prices to 2019 levels (OECD, 2022). According to OECD (2022), the Irish CPI in 2019 was 101.8, while the CPI was 74.8, 100.9 and 95.3 in the year 2000, 2008 and 2010, respectively. To adjust for the year 2030 prices, Irish CPI projections as in PwC (2022) were utilised. The long term CPI rate (to end of the 2020s) is forecasted to be 2% (PwC, 2022), hence, there will be an increment of 22% in the considered year 2019 prices to reflect the prospective year 2030 prices. Table 3.2 presents calculated external cost factors for NO_x, SO_2, $PM_{2.5}$ and CO_2, considering the port cities of Dublin and Belfast.

Table 3.2. Updated Dublin and Belfast External Cost Factors

Ports	Dublin			Belfast		
Pollutant	BeTa Urban	CAFE Rural	Total	BeTa Urban	CAFE Rural	Total
			Year 2019 (€/ton)			
NO_x	3,556	7,414	10,970	3,556	7,414	10,970
SO_2	43,951	9,514	53,465	27,222	9,514	36,736
$PM_{2.5}$	241,730	28,701	270,431	149,720	28,701	178,421
CO_2	–	–	86	–	–	86
			Year 2030 (€/ton)			
NO_x	4,338	9,045	13,383	4,338	9,045	13,383
SO_2	57,588	11,607	69,195	33,875	11,607	45,482
$PM_{2.5}$	316,734	35,015	351,749	186,312	35,015	221,327
CO_2	–	–	105	–	–	105

Source: Calculated based on Holland and Watkiss (2002), Holland et al. (2005), Van Essen et al. (2011)

3.4.4 Private costs

3.4.4.1 Onboard operation

Following Tzannatos (2010a), no extra costs are required for installation of AEs as they will be available onboard the ships no matter the level of SSE adoption. Ship-side private costs for onboard operation are the fuel and maintenance costs of using AEs at berth (Tzannatos, 2010a). The total fuel costs incurred can be estimated as a function of total fuel consumed by AEs while at berth, which can be calculated using the following Eq. (3):

$$FC_{MGO} = T_B \times [P_{AE} \times LF_{AE} \times SFC] \times 10^{-6} \tag{3}$$

Where FC_{MGO} is the total fuel (MGO) consumed (tonnes), T_B is the time spent at berth (hours), P_{AE} is AE power (kW), LF_{AE} is the load factor of the AE at berth (in %) and SFC is specific fuel consumption (g/kWh). For medium speed engines and the onboard use of MGO, SFC was assumed to be 217 g/kWh (Inner City Fund, 2009). Further, total fuel costs depend upon fuel prices (Tzannatos, 2010a). The "Rotterdam" bunker fuel price (on 31 December 2019) of €536.8/ton was assumed for MGO (Shipandbunker, 2022). The price listed in \$/ton was converted to €/ton using conversion rates as of "31 December 2019" from European Central Bank (2022). The maintenance cost for the operation of AEs was taken at €0.014/kWh (Perčić et al., 2020). As the average brent crude price in 2030 is expected to be at \$73/barrel, around 12.33% higher than the average brent crude price in 2019 (\$64/barrel) (United States Energy Information Administration, 2020, Wong, 2022a), hence, the MGO price estimate for the year 2030 was considered to be €603/ton. Further, the AE maintenance costs were incremented by 22%, based on the projected Irish CPI rate.

3.4.4.2 SSE operation

3.4.4.2.1 Ship-side SSE costs

The ship-side private costs of SSE will include the fuel costs for running the AE for one hour (changeover time) which are estimated as a function of fuel consumed during the required process, as noted in Eq. (4):

$$FC_{CHANGEOVER} = T_{CHANGEOVER} \times [P_{AE} \times LF_{AE} \times SFC] \times 10^{-6} \tag{4}$$

Where $FC_{CHANGEOVER}$ is the total fuel consumed during the changeover process (tonnes), $T_{CHANGEOVER}$ is the time for power connecting and disconnecting (one hour), P_{AE} is AE power (kW), LF_{AE} is the load factor of the AE at berth (in %) and SFC is specific fuel consumption (g/kWh). We have assumed, as per Whall et al. (2010) that passenger ships used either Marine Distillate Oil (MDO) (1.5% sulphur) or MGO, during changeover time. For ships using MDO, SFC was assumed 217 g/kWh (Whall et al., 2010), with the "Rotterdam" bunker fuel price (on 31 December 2019) being €539.9/ton (Shipandbunker, 2022), where the price in \$/ton was converted to €/ton based on currency conversion rates (European Central Bank, 2022). Further, the considered MDO price was incremented by 12.33%, to adjust for the year 2030 estimate. While for ships using MGO, SFC and fuel prices (year 2019 and 2030) as assumed in section 3.2.4.1 were considered, along with the maintenance cost of AEs.

To allow for SSE operation, it was assumed that any required installation must be retrofitted on the considered passenger ship, the data for which was obtained from an EU-based study by De Jonge et al. (2005). As the baseline year for this study was 2005, the given prices were updated to the 2019 levels based on the changes in EU-27 and Irish CPI (OECD, 2022). The year 2019 retrofit costs were incremented by 22% to obtain an estimate of the year 2030 costs. Table 3.3 shows the updated retrofit costs and lifespan of the ship-based SSE equipment's.

Table 3.3. Updated ship-based SSE retrofit costs (per ship)

	Year 2019		Year 2030	
Equipment	Cost (€)	Lifespan (years)	Cost (€)	Lifespan (years)
Ship transformer cost	337,873	10	412,205	10
Cable cost	4,524	12.5	5,519	12.5

Source: Calculated based on De Jonge et al. (2005)

The final costs for SSE utilisation will also include electricity as well as system maintenance costs. In this study, we have assumed the perspective of port authority towards the use of SSE to be "neutral", where the port sells the power to the ships at exactly the cost of purchasing it from the power station (Zis, 2019). In such an instance, all the electricity costs will be passed on to the shipowners. In 2019, the cost of electricity in Ireland for non-household consumers was €0.1294/kWh (Eurostat, 2022c). To obtain an estimate of the "year 2030 electricity price", an assumption would have to be made based on the prospective energy mix. By compiling the average "year 2030" Irish wind (onshore and offshore) and solar electricity costs (Turner and Zhang, 2018), and the projected gas prices in 2030 (Wong, 2022b), based on their share in the total energy mix, the final electricity price in 2030 was estimated to be €0.0848/kWh. Along with electricity, the maintenance cost of using SSE was also assumed to be passed onto the ships (De Jonge et al., 2005). For the years 2019 and 2030, an SSE maintenance cost of €0.00754/kWh and

€0.0092/kWh was assumed, respectively, based on the update of prices in De Jonge et al. (2005) to 2019 and 2030 levels.

3.4.4.2.2 Port-side SSE costs

The port-side private costs will primarily be the retrofit costs of the required SSE-related equipment for the existing berths in Dublin and Belfast ports. The costs for retrofitting berths with SSE technology were obtained from an EU-based study by De Jonge et al. (2005), where the given costs were updated to 2019 levels based on the changes in EU-27 and Irish CPI (OECD, 2022). Due to the considerably longer lifespan of SSE port-side equipment, there will be no re-installation costs over the period under investigation in this study. Table 3.4 shows the updated retrofit costs and lifespan of the port-based SSE equipment's.

Table 3.4. Updated port-based SSE retrofit costs (per berth)

Equipment	Cost (€)	Lifespan (years)
High Voltage Electricity Connection	617,120	30
High Voltage Cable Installation	211,120	40
Fixed Cable Reel System	176,320	30
Electricity Converter	507,500	20

Source: Calculation based on De Jonge et al. (2005)

Currently, there are 11 passenger berths in Dublin port, while in Belfast, there are 9 passenger berths (4AllPorts, 2015, Dublin Port, 2019, Dublin Port, 2022), which will be considered for SSE-retrofit within this study.

3.4.5 Scenario development: berth allocation

To make a comparison between the existing system of using MGO and the possible use of SSE as its replacement, we developed six scenarios representing different levels of implementation, separately for passenger ships calling in Dublin and Belfast ports, identified as follows:

(A) Top 5 frequent ship callers switch from MGO to SSE

(B) Top 10 frequent ship callers switch from MGO to SSE

(C) Top 15 frequent ship callers switch from MGO to SSE

(D) Top 20 frequent ship callers switch from MGO to SSE

(E) Top 25 frequent ship callers switch from MGO to SSE

(F) All ship callers switch from MGO to SSE

To estimate the number of berth(s) to be retrofitted under each scenario, assumptions have to be made. From Table 2.5, the combined "average berthing time" for top 5 callers in Dublin was 24.21 hours, i.e., on average each ship spent 4.84 hours at berth in a single day. Since it will not be feasible to accommodate all these ships on a single SSE-retrofitted berth in one day, hence, we assumed that 3 berths will be allocated to allow for smoother operation. Similar assumptions were also made for other scenarios.

Table 3.5. Average Berthing Time and SSE berths retrofitted, for six SSE scenarios

Scenario	Dublin		Belfast	
	Berthing time (hours/day)	SSE berths	Berthing time (hours/day)	SSE berths
Top 5 Callers	24.21	3	13.93	2
Top 10 Callers	41.04	6	14.95	3
Top 15 Callers	41.59	7	15.64	4
Top 20 Callers	41.86	8	16.17	5
Top 25 Callers	42.09	9	16.45	6
All Callers	42.72	11	18.46	9

Source: Own elaboration based on AIS data

3.4.6 Cost-benefit analysis for SSE installation

To evaluate the financial and socio-environmental attractiveness of implementing SSE, we calculated the NPV for the investment, using Eq. (5):

$$NPV = -CAPEX_{SSE} + \sum_{t=1}^{n} ((B^{EC} + B^{Fuel}) - OPEX_{SSE})/(1+r)^t \quad (5)$$

Where NPV is the net present value (€), $CAPEX_{SSE}$ is the capital (investment) costs of SSE port and ship retrofit (€), n is the duration of the installation (years), B^{EC} is the total socio-environmental benefits achieved (i.e. saved external costs) with the use of SSE against MGO (€), B^{Fuel} is the total benefits achieved from the avoided MGO fuel and AE maintenance costs while using SSE (€), $OPEX_{SSE}$ is the annual operation and maintenance costs (fuel and AE maintenance costs during changeover process, as well as electricity and maintenance of installed SSE technology) (€), r is the discount rate and t represents time periods. Because ships will be required to replace their onboard transformer after every 10 years to be able to use SSE, we assumed the maximum duration of this installation as 10 years. We took the Irish social discount rate of 4% (Department of Public Expenditure and Reform, 2019).

3.5. Results and Discussion

3.5.1 Results

In the present scenario of consuming MGO for onboard AE operation, the total emissions during 2019 for all passenger ships berthing in Dublin and Belfast ports stood at 35,005 tonnes and 16,247 tonnes, respectively. From the compiled ship emissions in Dublin and Belfast, CO_2 was found to be the most dominant pollutant in both cases (97.95%), followed by NO_x (1.97%), SO_2 (0.06%) and $PM_{2.5}$ (0.02%). Figure 3.2 shows the total emissions from the use of MGO for the six scenarios developed based on the frequency of ship callers in Dublin and Belfast. Overall, it was observed that ships with the most frequent calls in the respective ports also contributed the most to the total emission levels.

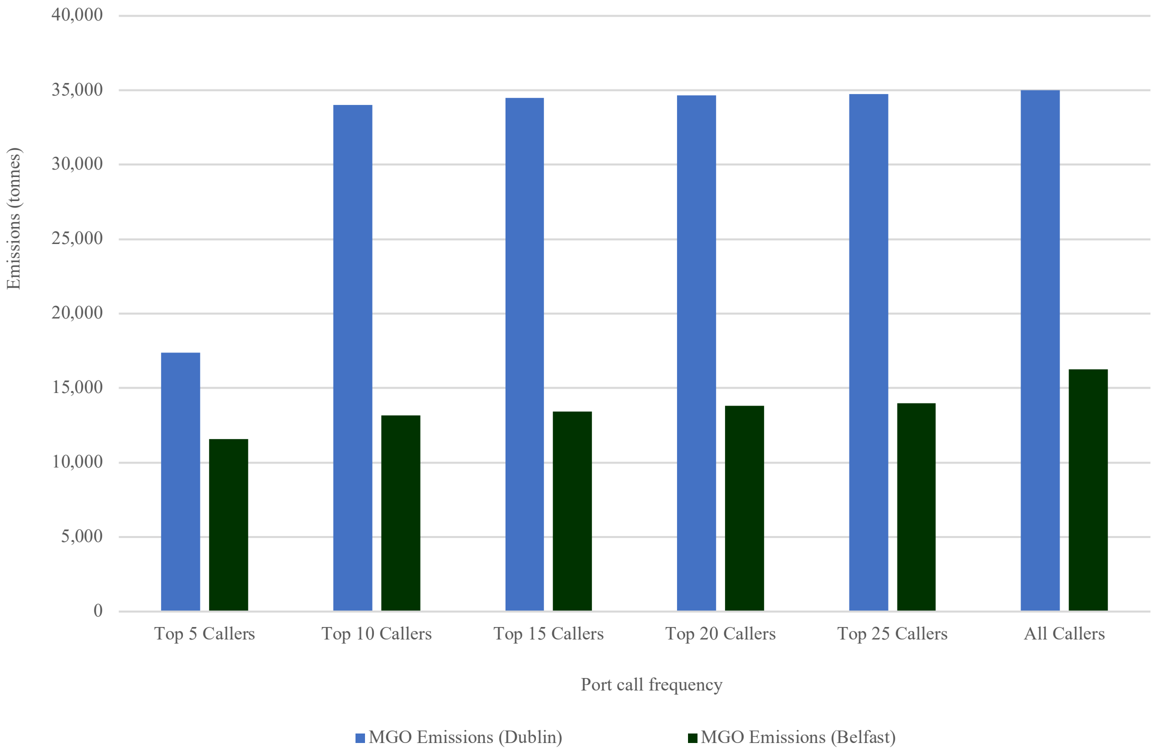
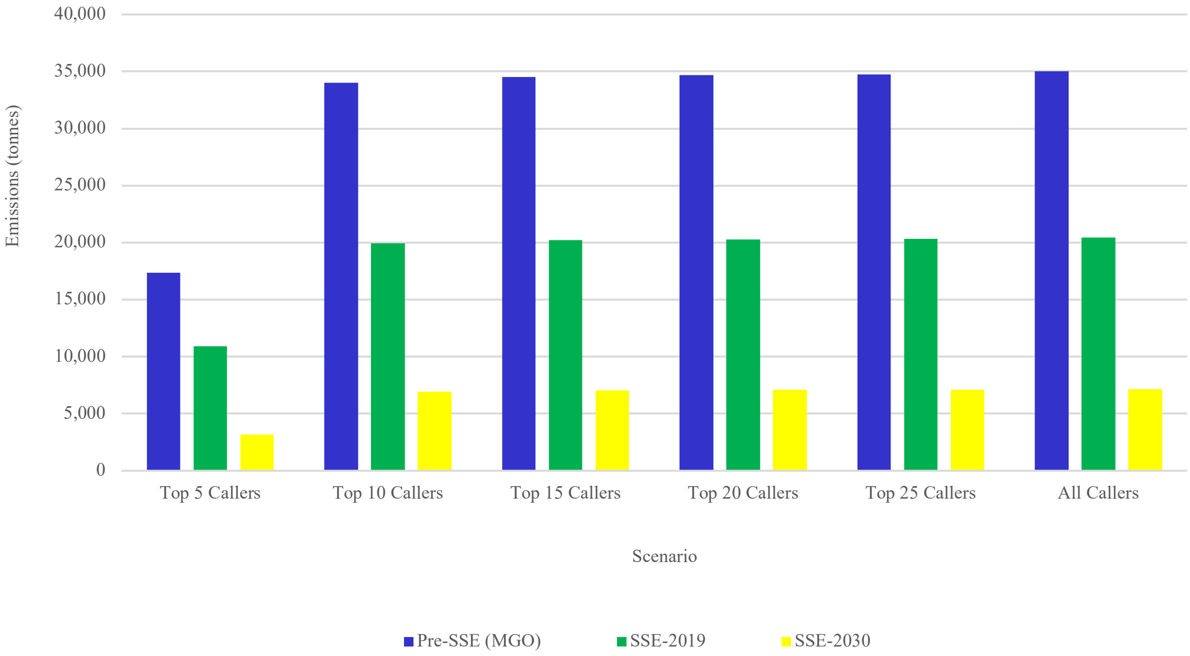
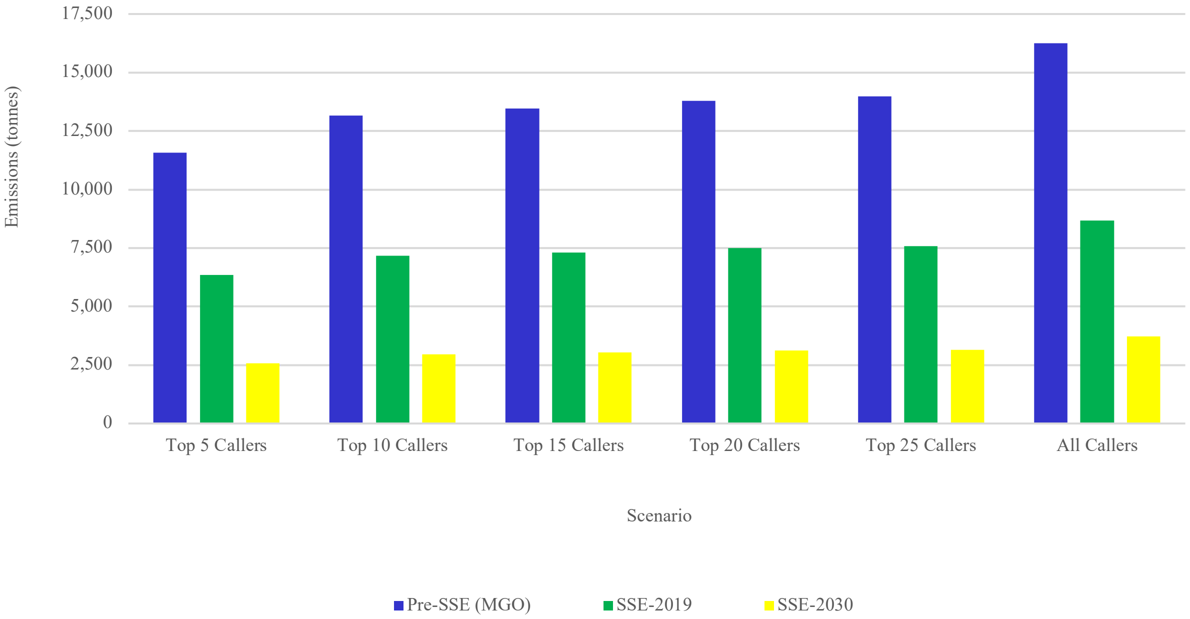


Figure 3.2. Contribution of frequent callers to MGO emissions in Dublin and Belfast

The outcomes of a comparison of MGO versus SSE emissions across the six scenarios in Dublin and Belfast ports is shown in Figure 3.3. In all scenarios, emission levels improved significantly in comparison to the current option of MGO. The reductions in overall emissions were higher when supplying ships with SSE from a comparatively "cleaner" year 2030 grid than the one being used in 2019, due to higher projected uptake of renewable energy sources in the former.



(a) Emissions in Dublin

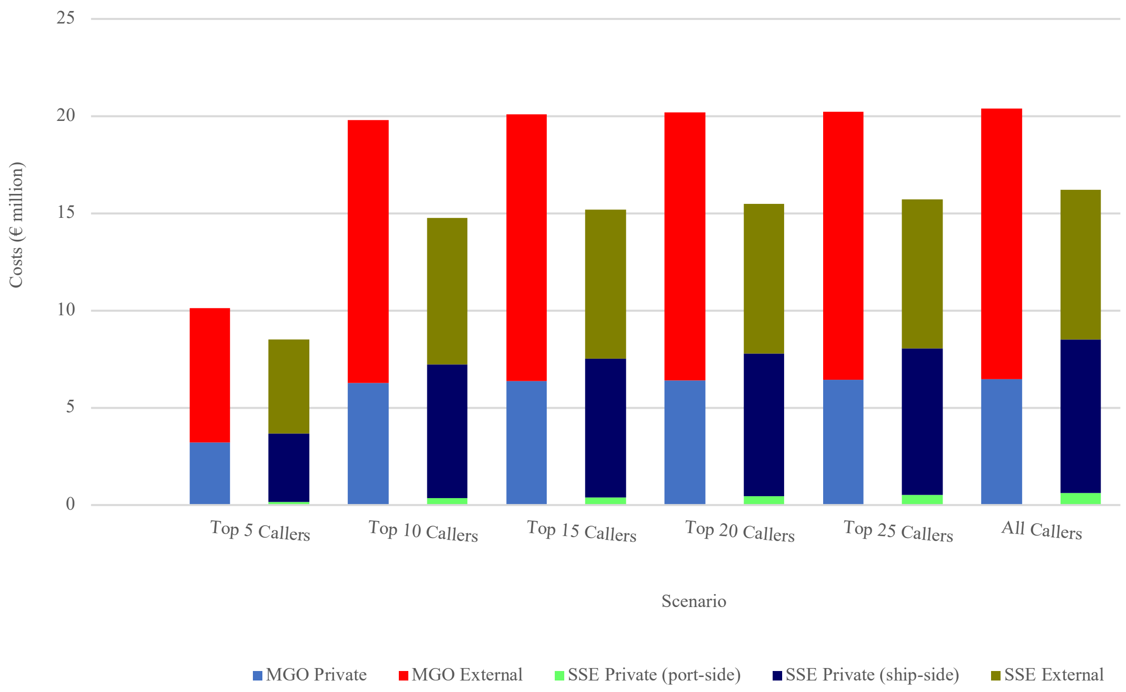


(b) Emissions in Belfast

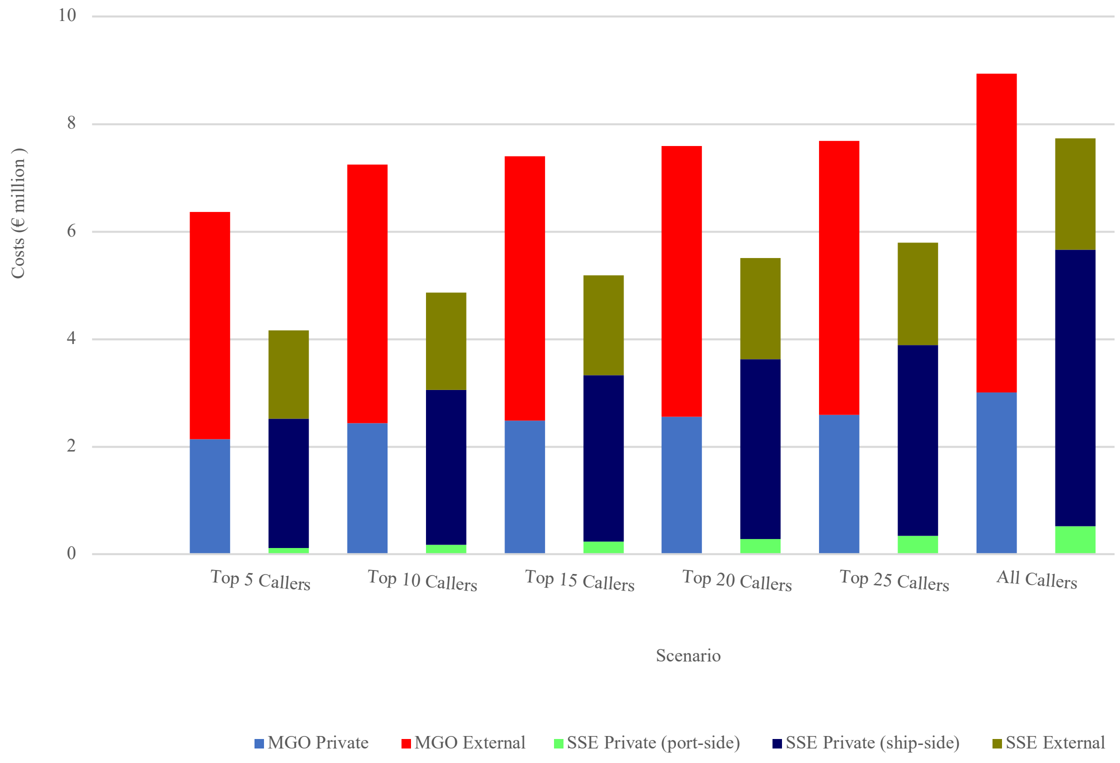
Figure 3.3. Emission levels for MGO and SSE in six scenarios, for Dublin and Belfast

For the exclusive use of SSE (year 2019 grid) by all the ships in Dublin and Belfast ports, a reduction of 41.5% and 46.5% in the overall emissions from the use of MGO was observed, respectively, with similar reductions (in %) visible for other scenarios as well.

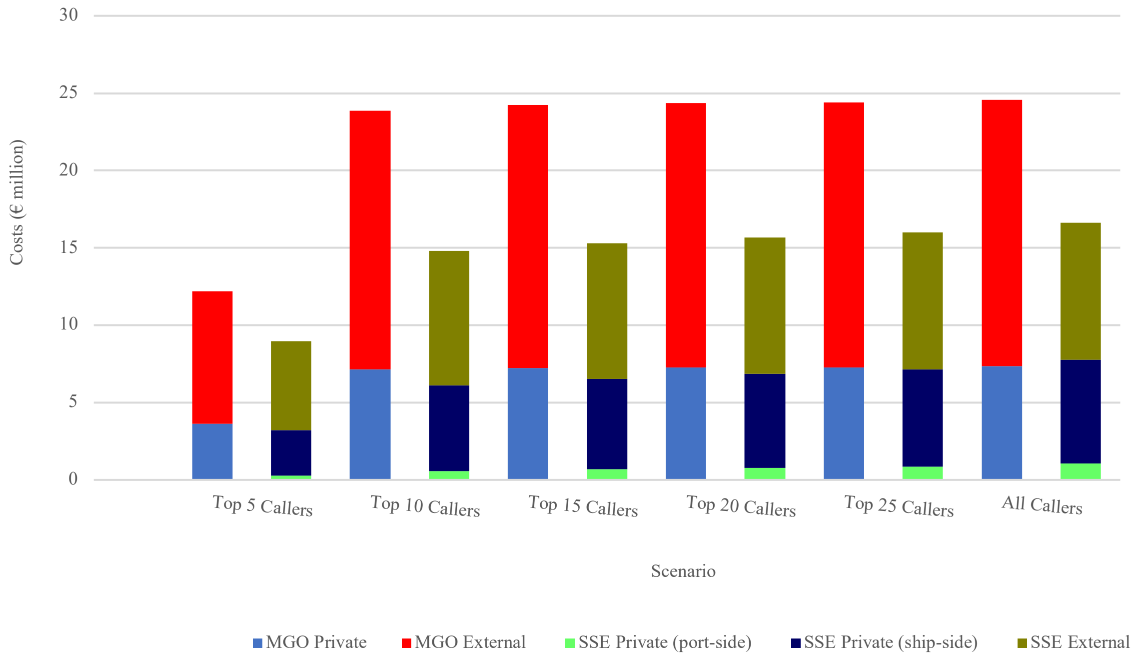
When using SSE from the prospective year 2030 grid, the reductions from the use of MGO in Dublin and Belfast ports were nearly twofold. While implementing SSE certainly enables a significant reduction in emissions, however, it leads to a substantial increase in private costs. The increase in private costs can be attributed to capital costs arising from ship-side and port-side retrofits of SSE-related equipment, hourly usage of fuel during the changeover period and most importantly, the electricity costs. Based on the allocated berths, port-side installation costs were calculated alongside the respective ship-side costs for each of the considered scenarios. The derived private costs for SSE usage were later summed up with the respective external costs generated under each scenario and compared against the costs of using MGO under similar scenarios. Figure 3.4 shows the annualised private and external "year 2019" and "year 2030" costs from the usage of MGO and SSE for six scenarios, in Dublin and Belfast ports.



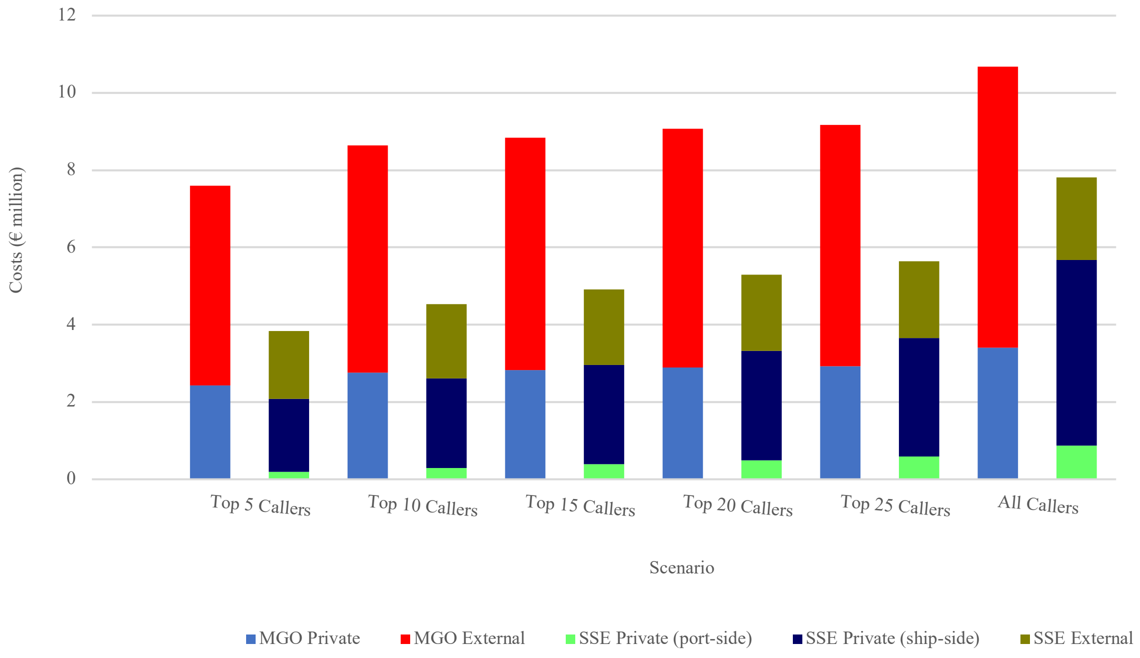
(a) Annualised (Year 2019) costs in Dublin



(b) Annualised (year 2019) costs in Belfast



(c) Annualised (year 2030) costs in Dublin



(d) Annualised (year 2030) costs in Belfast

Figure 3.4. Annualised (2019 and 2030) private and external costs for six scenarios

From Figure 3.4, it was observed that in each of the considered scenarios, under current (2019) and future (2030) grid supply, the total annualised costs of using SSE were lower than that of MGO, mainly due to lesser external costs being generated through the use of SSE technology. The total external costs from the exclusive use of SSE (year 2019 grid) by all ships berthed in Dublin and Belfast stood at €7.70 million and €2.07 million, respectively. These figures were lower by 44.6% (for Dublin) and 65.1% (for Belfast) than that from MGO (year 2019) external costs, with similar reductions (in %) visible for other scenarios as well. The total external costs of €8.85 million and €2.15 million were generated for the use of SSE (year 2030 grid) by all ships in Dublin and Belfast, respectively. This indicates a reduction of 47.93% (for Dublin) and 69.91% (for Belfast) than that from MGO (year 2030) external costs.

To determine the overall feasibility of using SSE i.e., if the total benefits achieved in the form of saved external and fuel costs outweigh the total private costs over the considered time period, NPV analysis was conducted for different scenarios of SSE implementation. In general, a positive NPV will indicate that the use of SSE over MGO is profitable, with the scenarios reflecting higher positive NPVs being deemed more attractive to implement. Figure 3.5 indicates the estimated NPVs using a 10-year time horizon for six scenarios of SSE implementation in Dublin and Belfast ports, considering an estimate of "year 2019" and "year 2030" costs.

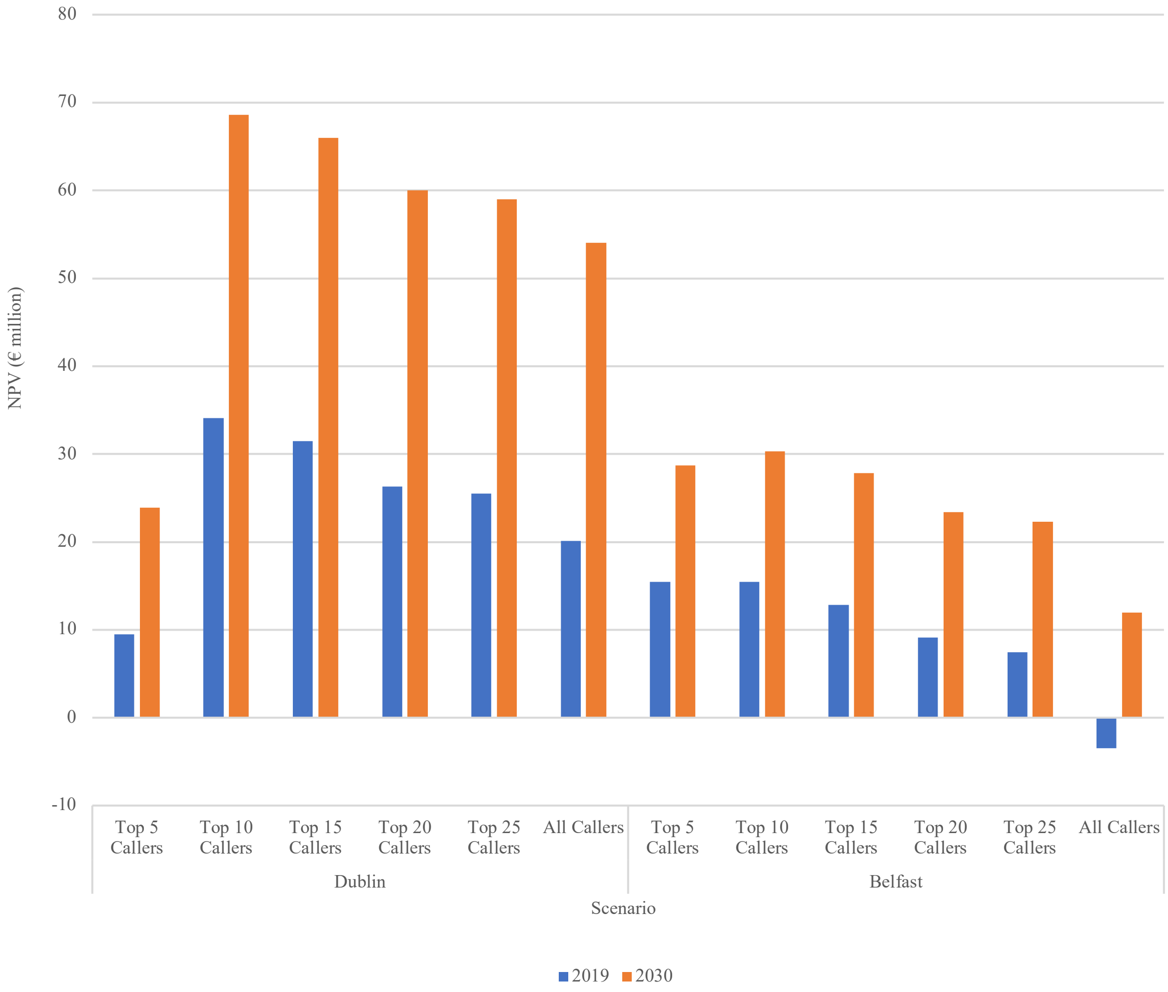
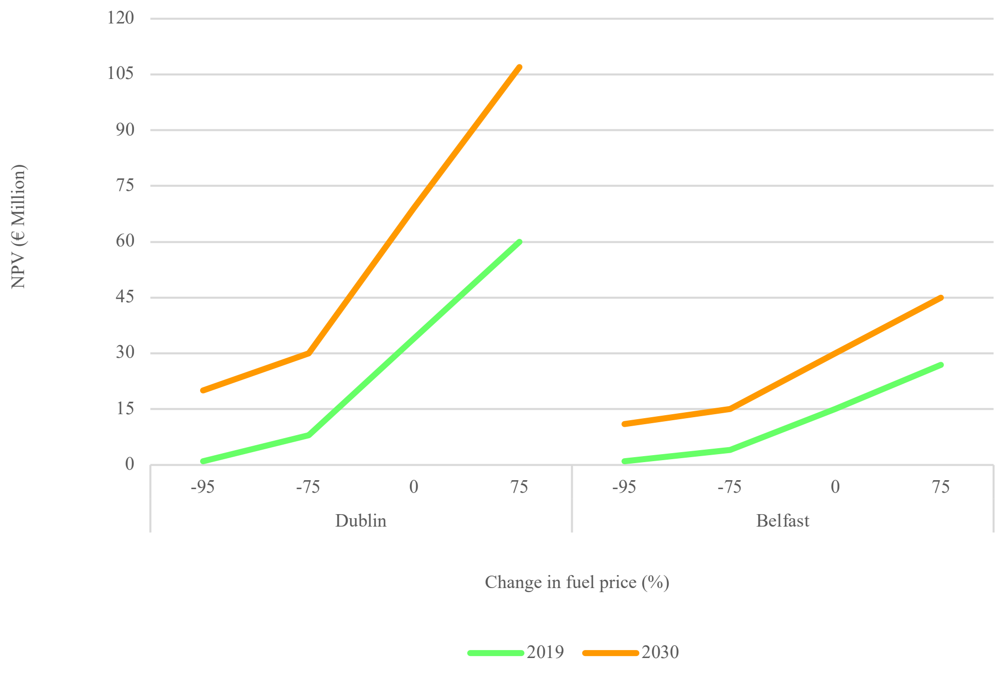


Figure 3.5. 10-year NPV for six SSE scenarios, for 2019 and 2030 cost estimates

Findings from Figure 3.5 reveal that owing to positive NPVs, introducing SSE seems feasible for all scenarios in Dublin port. Due to a negative NPV of −€3.50 million, switching all passenger ships to SSE in Belfast will remain inviable as per year 2019 costs.

A significant boost in NPVs (by 50%) for all scenarios is expected when considering the year 2030 costs, which is mainly due to higher benefits incurred in the form of saved external costs alongside the lower electricity costs, resulting from increased use of renewable energy sources in year 2030 grid. For the most viable scenario (by NPV) observed in Figure 3.5 (SSE for top 10 callers), we conducted a sensitivity analysis to investigate the subsequent changes in year 2019 and year 2030 NPVs, with changes in electricity and fuel price in either direction, as shown in Figure 3.6.

(a) NPV sensitivity of top 10 callers to electricity price variation



(b) NPV sensitivity of top 10 callers to fuel price variation

Figure 3.6. NPV sensitivity of top 10 callers to electricity and fuel price variation

From Figure 3.6, it is observed that an increment in the year 2019 electricity price by 90% and 100% will result in negative NPV for SSE utilisation by top 10 callers in Dublin and Belfast, respectively. Furthermore, in spite of a detrimental increase of 150% in the projected year 2030 electricity price, both the NPVs remained positive. Also, even a drop of 95% in the considered year 2019 and year 2030 fuel price will not generate negative NPV.

3.5.2 Discussion

From section 3.3.1, it was observed that switching all passenger ships to SSE in Dublin with 2019 energy mix will reflect a positive NPV, although the same could not be said for Belfast. This result was due to higher applied private costs in Belfast, primarily from ship-side retrofits, as around 59 passenger ships visited Belfast, compared to 34 in Dublin. Overall, the adoption of SSE for the top 10 frequent passenger callers seems the most attractive option, as it presented the highest positive NPV amongst the studied scenarios.

When comparing with previous studies, the estimated NPVs in Dai et al. (2019) were found to be effectively negative, probably due to the exclusion of external cost savings from the analysis, with more ships being considered for retrofit (12,000). Innes and Monios (2018) considered external costs savings, and their estimated NPV for Aberdeen was comparatively lower than that for Dublin, as shown in this study, possibly due to higher population level of Dublin, which garnered significant external cost savings. For studies such as Ballini and Bozzo (2015) and Yu et al. (2019), the use of SSE also seemed viable with lower payback periods, albeit only at port-side and ship-side levels, respectively. Also, similarly to this study, Tzannatos (2010a) showed lower total (private + external) annualised costs for SSE against MGO. Overall, the studies which considered external cost savings showed either lower payback periods (or costs) or positive NPVs, reflecting its significance while evaluating the cost-effectiveness of SSE.

The main challenge with SSE deployment is that the ports and shipowners that will have to invest in the necessary infrastructure are not the ones who benefit from the reduced emission levels (Winkel et al., 2016). To help ports recover the invested retrofit costs, subsidies would be required. According to the ESPO (2021), so far, every SSE facility established in European ports has been supported by up to 50% of public financing. The total port-side retrofit costs in Dublin and Belfast stood at €9.07 million and €4.54 million, respectively, for the optimal scenario (SSE for top 10 frequent callers). In the best possible case, it is expected that public financing will cover at least €4.54 million and €2.27 millions of invested costs, respectively. Further, Dublin and Belfast ports may decide to put a markup of €0.0122/kWh (i.e., increment electricity price by 8.62%) and €0.0144/kWh (i.e., increment electricity price by 10.01%), respectively, as this will help recover the remaining 50% of retrofit costs in 10 years. For shipowners, the tactics could be to increase the passenger ticket price to recover the paid costs. For example, from the AIS dataset, the top

10 frequently calling ships in Dublin and Belfast have a combined passenger capacity of 10,292 and 15,234, respectively. By compiling this information with the number of annual calls being made alongside the total ship-side costs, we observed that the top 10 callers to Dublin and Belfast can increment their ticket prices by €0.03 and €0.04 (per passenger seat) every year, respectively, to recover the total costs over the course of the next 10 years.

3.6. Uncertainties and limitations

Despite the methodological contributions of this study, there remains some uncertainties and limitations. It should be noted that the supplied electricity and fuel prices tend to fluctuate quite frequently, which will affect the overall costs and benefits of SSE implementation. With the ever-changing global geo-political situation, these conditions have now become even more relevant, since it was observed that the electricity and fuel prices (as of early 2022) have reached an all-time high, especially within the EU (Batlle et al., 2022, Shipandbunker, 2022). Currently, the major source of electricity production within Ireland and the EU is imported natural gas, which has shown a high volatility in terms of available spot price and subsequently, has been the main driver behind high electricity prices (Batlle et al., 2022). To reduce their dependence on such highly priced, volatile, and non-renewable commodity, Ireland and the EU have prioritised the use of wind and solar energy sources for the majority of their electricity production by 2030, thus improving their energy sovereignty (European Commission, 2020a, Grid Beyond, 2021). Although electricity production costs from renewable sources might be decorrelated from geo-political situations, prices do fluctuate as well, depending on weather conditions (Energia, 2022). Hence, the viability of using SSE (in current or future years) will depend on the evolution in electricity and fuel prices. Considering such uncertainties, a sensitivity analysis was provided to determine any changes in the NPV for the optimal scenario (SSE for top 10 callers).

With regards to the reliability of the calculated emissions, significant efforts were made to obtain precise data on ship activities while at berth using the AIS database. Information on issues such as engine and fuel type profiles, load factors, specific fuel consumption and emission factors are based on numerous assumptions which, while were obtained from high quality sources, may have some inherent variation. In the case of external cost estimation, the cost factors used have been widely applied in the literature and an attempt was made to localise the cost factors as much as possible.

3.7. Conclusion

The present study contributes to the existing literature by examining the costs and benefits of adopting SSE at varying levels of implementation, when considering the present (year 2019) and future (year 2030) Irish energy mix. To achieve this, we performed a cost-benefit analysis of introducing SSE, assimilating the port-side and ship-side private costs with the benefits achieved through reduced socio-environmental external costs and saved fuel costs, across six scenarios in Dublin and Belfast ports, using the NPV methodology. This is also the first study which investigated the potential use of SSE in Ireland.

The selection of Dublin and Belfast was primarily due to their higher population levels, while the impetus for selecting passenger ships was based on their proven energy demands while berthing and their significance to the Irish maritime economy. As of 2019, the composition of the Irish energy mix in electricity production is 62.43% non-renewable and 37.57% renewable, but it is expected to change to 20% non-renewable and 80% renewable, by 2030. For the 2019 grid supply, the use of SSE seemed viable for the top 5, 10, 15, 20 and 25 most frequently calling passenger ships, for both Dublin and Belfast ports. While switching all passenger ships to SSE in Dublin was feasible, the same was not the case for Belfast, due to higher private (mainly ship-side retrofit) costs. Switching to the year 2030 grid supply is expected to boost the obtained NPVs by 50%. Overall, the most profitable scenario by NPV was the implementation of SSE for the top 10 callers in Dublin and Belfast. From the sensitivity analysis carried out for this scenario, it was shown that unless there is an increase in the year 2019 electricity price by 90% (for Dublin) and 100% (for Belfast), the NPVs will remain positive. Furthermore, significant changes in the fuel prices, and 2030 electricity price, are not expected to impact the respective NPVs negatively.

The methodological framework proposed in this research is applicable for other port cities that wish to explore the potential of SSE, particularly in Europe, where there are similar profiles in terms of visiting ship types and a prevalence of urban ports. Future studies can also expand the proposed framework to other ship types (e.g., bulkers, containers, general cargo) to determine the viability of using SSE with current and future energy mix, on a wider scale.

CHAPTER FOUR

Reducing emissions externalities from ships: The role of biofuels

4.1 Abstract

This study investigates the cost-effectiveness of three blended biofuels (Fatty Acid Methyl Ester (FAME), Hydrotreated Vegetable Oil (HVO) and Fischer-Tropsch (FT) Diesel), when compared against the conventional emission abatement options of scrubbers and Marine Gasoline Oil (MGO), for the case of ferry ships operating from Irish ports in 2019, assimilating the private, external and carbon tax costs. Our results show that, to comply with the International Maritime Organisation (IMO) 2020 regulation, the use of blended FAME within MGO will be the most cost-effective choice using the Net Present Value (NPV) methodology (€998,429,573), while it also offers 11.4% reduction in CO_2 emissions, the highest level across the five studied measures, and this aspect has been overlooked in the literature. Although, there needs to be an increment (by 85%) in the current Irish FAME production levels to accommodate for ferry usage, this can be met using the local biomass reserves available.

4.2 Keywords

Cost-benefit analysis; Scrubber; Marine gasoline oil; Biofuels; Ireland

4.3 Introduction

Shipping has often been recognised as a significant source of global sulphur oxides (SO_x), nitrogen oxides (NO_x), particulate matter (PM) and carbon dioxide (CO_2) emission levels (Zhu et al., 2020, Zhao et al., 2021), imposing negative societal (i.e., human health) and environmental externalities (Antturi et al., 2016). Nearly 70% of ship emissions occur within 400 km of coastlines, and such emissions tend to travel across long distances in the atmosphere from sea to land (Eyring et al., 2010, Alver et al., 2018). Recognising the strong need to control the negative externalities associated with shipping activities, the International Maritime Organisation (IMO) has set down a global fuel sulphur limit of 0.5% to be used onboard, known as "IMO 2020", which indicates a significant reduction from the previous limit of 3.5% (IMO, 2019). The IMO has suggested three practical approaches to help shipowners comply with the outlined limits. The first option is to use fuel oil which is inherently low enough in sulphur, (e.g., Marine Gasoline Oil (MGO)) (IMO, 2019, Zhu et al., 2020). The second option is to install an exhaust gas cleaning system, also known as "scrubber" which absorb most of the sulphur content in the exhaust, and therefore enables the shipowners to keep using cheaper Heavy Fuel Oil (HFO) (also known as Residual Oil (RO)) (Gu and Wallace, 2017, IMO, 2019). The last option is to consider alternative fuel types containing low or zero sulphur, such as Liquified Natural Gas or biofuels (IMO, 2019).

To assist shipowners and decision-makers with the selection of most suitable sulphur limit compliance measure, there have been significant discussions among academic researchers in recent years. Jiang et al. (2014) investigated the costs and benefits of reduction measures such as scrubbers and MGO, while integrating the private costs with socio-environmental benefits from emission reduction. For the selected case study of a container ship operating between Rotterdam and Gothenburg, it was found that the use of MGO will be more viable using Net Present Value (NPV) as the appraisal technique, although an increase in the price spread between MGO and HFO will improve the NPV of scrubbers over MGO. Panasiuk and Turkina (2015) evaluated the relative investment efficiency of scrubbers and MGO, when employed on a test ship (cargo ferry vessel), using a five-year time horizon. The results showed that although there will be a large cash outflow in the initial year of scrubber instalment, the invested costs could be recouped within a single year of its usage, with its use more profitable than that of MGO in the later years, due to the use of cheaper RO fuel. Zhu et al. (2020) compared the cost-effectiveness of using sulphur scrubbers against that of MGO using the NPV methodology, when applied to a 19,000 twenty-foot equivalent unit container ship sailing between Far East and Europe. Here, scrubber was shown as the most economically profitable option due to its higher NPV, although, its attractiveness would be highly dependent upon the changes in fuel price spread between HFO and MGO. Zhao et al. (2021) compared the economic lifespan costs for the varied combinations of namely five technological choices (scrubbers (open-loop, closed-loop, and hybrid), Selective Catalytic Reduction and Exhaust Gas Recirculation, complying with both the sulphur and Tier III NO_x limits, considering a “test” feeder containership. The use of sulphur scrubbers (open-loop mode) in combination with Exhaust Gas Recirculation technology was found to be the most economically viable choice, although, the viability of installing scrubbers will further depend on the fuel price spreads between heavy-sulphur and low-sulphur fuel oils and the remaining lifespans of the ships. Tan et al. (2022) investigated the strategic choice of selecting scrubber or low-sulphur fuel for an inland container ship, while considering the impact of river streamflow velocity. Their analysis showed that a ship with scrubber will operate on a higher engine speed than the one using low-sulphur fuel, resulting in higher fuel consumption for the latter than the former. With the increase in streamflow velocity, in conjunction with the engine speed, the cost incentives for installing a scrubber increases significantly over the usage of low-sulphur fuels. Perčić et al. (2021) conducted the life-cycle assessment of varied emission abatement technologies such as electricity, methanol, hydrogen, LNG, dimethyl ether and blended biodiesel, for different ship types of passenger, cargo and dredger, operating with Croatian inland waterway sector. Electricity (i.e., battery) powered ships were found to have lowest life-cycle GHG emissions and in this analysis for all considered ship types, with methanol being mentioned as the most "cost-effective" option, as it offered lower life-cycle economic (investment, maintenance, carbon credit) costs, while considerably reducing GHG emissions, in line with environmental regulations. Also, several studies in the academic literature compared the sulphur emission abatement measures in condition of compliance with Emission Control Areas (ECAs), which requires ships to operate on marine fuel oil with sulphur limit of 0.1%. Lindstad et al. (2015) showed that the use of MGO will be more economically profitable over retrofit options (i.e., scrubbers) within ECA waters, if the annual fuel consumption is less than 1,000 and 1,500 tonnes, for ships with small (4,000 kW) and large (12,000 kW) engine sizes, respectively. Also, in the condition of low oil prices, the use of MGO will be more attractive than that for scrubbers, irrespective of fuel consumption. Abadie et al. (2017) compared the economic costs of using scrubbers with that of switching to low-sulphur fuels, where it was shown that the use of scrubber is more attractive when a ship has longer remaining lifetime and spends most of its time at sea while sailing in ECAs. However, it was also noted that when scrubbers are used, overall fuel consumption values are higher, resulting in higher CO_2 emissions. Gu and Wallace (2017) evaluated the economic impact of different sailing patterns on the use of MGO and scrubbers. They also studied the impact of port call density inside ECAs on the shipowner's choice of emission abatement measure. Here, the results indicated that the use of scrubbers will be more profitable for ships that have a higher density of port calls within ECAs. Fan et al. (2020) investigated the cost-effectiveness of using scrubbers against switching to low-sulphur fuel. The results show that for ships sailing on transcontinental routes, the use of low-sulphur fuels will be the better choice owing to lesser time being spent in established ECAs.

Despite the presence of extensive literature surrounding the cost assessment of sulphur emission abatement measures, we found that except for Perčić et al. (2021), there has been limited investigation of the cost-effectiveness of biofuels, which have been designated by the IMO as a sulphur limit compliance measure, with much of the academic literature focussing on the use of scrubbers and low-sulphur fuel oils. Although, Perčić et al. (2021) did not consider the benefits from saved external costs, while only measuring the drop in CO_2 emissions, excluding other major pollutants like SO_2, NO_x and $PM_{2.5}$. External costs are the monetary damages imposed on the local population and built environment due to shipping emissions (Tichavska and Tovar, 2017, Nunes et al*.,* 2019). To provide an impetus for investing in any abatement technology from a policy-making perspective, the benefits attained through saved external costs must outweigh the total private costs, where the benefits are estimated as a differential of the external costs of ship emissions with and without the use of reduction technologies (Jiang et al*.,* 2014). Within the European Union (EU), increased attention is being paid on improving energy sovereignty through reducing dependence on fossil fuels (European Council, 2022), due to the concerns about the global depletion of fossil fuel reserves (Ammar, 2019), and the ever-changing global geo-political situation. To support the recently launched "RePower package" which aims to boost the EU's energy security while continuing with its drive to a circular economy, biofuels, which are produced from crops, wastes, and residues (Vackeová and Noyon, 2022*),* have been classified as renewable alternatives to existing fossil fuels, especially within the transport industry (European Commission, 2022a). In the most recent session (78th) of Marine

Environment Protection Committee (MEPC), there were increased discussions on the use of blended biofuels within the maritime industry, specifically, on their potential role as "transitional fuels" to steer the industry towards the long-term decarbonization targets set by the IMO (IMO, 2022b). Considering the most recent decision by IMO to introduce carbon tax for maritime emissions (Muchira, 2022), and also the fact that abatement measures such as scrubbers and MGO tend to increase CO_2 emission levels in parallel to limiting SO_x emissions (Lindstad and Eskeland, 2016, Zis et al., 2022), the use of biofuels as an alternative solution could be of utmost importance within the maritime industry. Also, it was concluded in the 78th MEPC session that the use of biofuels (when blended up to 30% in the conventional marine fuels) will not increase overall NO_x emissions, compared to that of using conventional fuels, hence avoiding any additional technical and regulatory hurdle in terms of compliance with the set NO_x emission limits (ABS 2022, IMO, 2022b).

To assist decision-makers with the identification of most economically, socially, and environmentally cost-effective strategy to implement, it is important to compare the use of different sulphur emission abatement measures while incorporating private costs alongside the benefits achieved through saved external costs. Further, in extension to the study of Jiang et al. (2014), in the current global scenario, it is also important to consider carbon tax costs, which has been viewed regionally (EU) and globally (IMO) as a potential pathway to help alleviate maritime carbon emissions.

This research aims to conduct a cost-benefit analysis of three blended biofuels: Fatty Acid Methyl Ester (FAME), Hydrotreated Vegetable Oil (HVO) and Fischer-Tropsch (FT) diesel and comparing them with two traditionally available sulphur abatement measures such as scrubbers and MGO, while incorporating their respective economic costs alongside the benefits from saved external costs and the difference in paid carbon tax costs, using the

NPV approach. The discussed abatement measures were applied to passenger (i.e., Roll/on-Roll/off (Ro-Ro) ferry) ships operating from Irish ports, with the baseline year being 2019.

Here, Ireland has been selected as the case subject as we found that it is primarily an energy importing economy, relying on gas and oil imports to meet its energy needs (Department of the Environment, Climate and Communications, 2020). In 2020, Ireland's net energy imports per capita stood at 84 Gigajoules, which was higher by 15% when compared to the EU average (71 Gigajoules) (Eurostat, 2022d). Acknowledging this fact, the Irish government in recent years have prioritised a reduction in its reliance on fossil fuels and further alleviation of greenhouse gas emissions in all sectors of the economy, including transport (Department of the Environment, Climate and Communications, 2020), where, as part of the "National Climate Action Plan", significant attention has been given to increase the use of biofuels in this sector (Department of the Environment, Climate and Communications, 2021). Currently, through the Irish "biofuel obligation scheme," road transport fuel suppliers must include a percentage (10%) of environmentally sustainable biofuels across their general fuel mix (Government of Ireland, 2019). Although there is no mention of the maritime transport industry within this obligation scheme, the potential use of biofuels for this industry could be of utmost importance for the transitioning of Ireland away from the use of fossil fuels and towards the use of "cleaner" sources of energy, especially considering that Ireland as a nation has been at the receiving end of significant negative externalities imposed from shipping emissions, as it occupied 6th position globally (in 2015) in terms of premature deaths due to shipping emissions (Rutherford and Miller, 2019).

The paper is organised as follows: after the introduction in section 1, section 2 describes in detail the methodology to evaluate emissions from ships while at-sea and the associated external costs and paid carbon tax costs. Further, it discusses the potential private costs of emission reduction measures as well as the methodology employed to conduct the cost-benefit analysis. Section 3 provides the obtained results alongside the surrounding discussion, while section 4 offers the main conclusions on this topic.

4.4. Materials and methods

4.4.1 Study area

Situated in north-western Europe, Ireland is an island nation with its maritime transport industry closely intertwined with its national economic prosperity, as it plays an indispensable role in facilitating international trade and maintaining connectivity with the European and global markets (Department of Transport, 2021). In 2019, the total Irish merchandise trade volume stood at 60.8 million tonnes, with nearly 90% of the traded goods being moved through Irish ports (Irish Maritime Development Office [IMDO], 2020). Along with trade, Irish ports also act as important gateways for its local tourism industry, as it welcomed around 4.25 million ferry and 700,000 cruise passengers in 2019, respectively (IMDO, 2020). In general, the Irish maritime sector has an annual turnover of €2.3 billion, providing employment to over 5,000 individuals (Marine Institute, 2020). There are 24 ports in Ireland, with locations in the highly populated cities of Dublin, Belfast, Cork, Limerick and Galway, alongside those in other medium and small-sized coastal towns. In 2019, total 1,594 ships visited Irish ports, recording 20,720 calls (Refinitiv Eikon, 2022a). From which, it was observed that Ro-Ro ferry ships registered the highest number of calls (10,220), representing around 50% of the total calls by ship types, despite the fact that there were only 27 Ro-Ro ferries by arrivals, which is the lowest figure among the ship types. This information indicates the significance of Ro-Ro ferry ships within the Irish maritime economy. Nearly 90% of the Ro-Ro traffic is concentrated on the Irish-British route, with the remaining 10% traffic happening between the Irish and other EU ports (IMDO, 2020). Further, according to IMDO (2020), the Irish Ro-Ro ferry traffic has been increasing steadily since 2009, with Ro-Ro volumes becoming more concentrated in larger ports over the course of the Irish economic recovery post the 2008 financial crisis. It is noted that Dublin and Belfast, the two of the largest Irish ports, combined represent around 80% of the national Ro-Ro traffic market share, with the remaining 20% being made up by small-sized ports (IMDO, 2020). Coincidentally, Dublin and Belfast also happened to be the largest Irish cities by population, combined representing 25% of the total scale (NISRA, 2021, CSO, 2022b). Further, it is noted that around 40% of the national Irish population resides within 5 km of the coast (CSO, 2022a). Based on such facts, it can be said that local Irish population and the built environment is highly vulnerable to the negative externalities imposed from shipping emissions, especially arising from the highly concentrated Ro-Ro ferry movements, which primarily happen near the Irish coastline, even considering that all ships spending more than two hours at berth in Irish ports are already required to use MGO due to the existing EU sulphur directive (Castells Sanabra et al., 2014). To alleviate such negative externalities from ship exhaust emissions near the Irish coastline, it is important to assist the involved stakeholders with the identification of most cost-effective strategy to implement, from the social, environmental, and economic perspective.

4.4.2 Shipping emissions

For estimating shipping at-sea emissions from Ro-Ro ferry movements, the activity-based methodology has been utilised. This methodology has been adopted due to its proven accuracy over the fuel-based method (Song and Shon, 2014, Tichavska and Tovar, 2015a), and also, is a relatively popular approach (Whall et al., 2010, López-Aparicio et al., 2017, Alver et al., 2018; Gore et al., 2022). For the baseline scenario, SO_2, CO_2 and $PM_{2.5}$ emissions have been examined using the following Eq. (1), as given in Whall et al. (2010):

$$E^{Base} = \sum_i T \times \left[\left(ME \times LF_{ME} \times EF_{i(ME)}^{Base}\right) + \left(AE \times LF_{AE} \times EF_{i(AE)}^{Base}\right)\right] \times 10^{-6} \qquad (1)$$

Where E^{Base} represents baseline emissions while at-sea (tonnes), i refers to the pollutants: SO_2, $PM_{2.5}$ and CO_2, T indicates total time spent at-sea for ferry journey, ME and AE are main engine power and auxiliary engine power (kW), respectively, LF_{ME} and LF_{AE} are the load factors of main and auxiliary engines (%), respectively, while $EF_{i(ME)}^{Base}$ and $EF_{i(AE)}^{Base}$ are the emission factors assigned to main and auxiliary engines for the emitted pollutant i (g/kWh), respectively, in the baseline scenario. The statistics in relation to total recorded movements, time spent at-sea for journey, main and auxiliary engine powers for all the Ro-Ro ferry ships that visited Irish port during 2019 was obtained through the Refinitiv Eikon (2022a) Automatic Identification System (AIS) database.

The regulation on SO_x emissions requires shipowners to retrofit their ships with suitable compliance technologies (e.g., scrubbers), or switch to cleaner fuels with a sulphur content of less than 0.1% (MGO or blended biofuels) (IMO, 2019). For this paper, different scenarios have been developed through the combination of such emission abatement alternatives to fulfil the sulphur emission limits, compared against the baseline (year 2019) scenario, which are as follows:

Scenario A: Use of RO combined with scrubber

Scenario B: Use of MGO

Scenario C: Blend of FAME (20%) within MGO (80%)

Scenario D: Blend of HVO (20%) within MGO (80%)

Scenario E: Blend of FT Diesel (20%) within MGO (80%)

For this study, we have tested three blended biofuels: FAME, HVO and FT Diesel. FAME is the generic chemical term for biodiesel derived from renewable sources (Zhou et al., 2020). Biodiesel can replace MGO in its entirety in low to medium speed diesel engines (for e.g., in cargo ships), although this will require significant adjustments in diesel engines alongside an approval from the engine manufacturers, hence it is more commonly used as a fuel additive and can be poured directly (known as "drop-in") into fuel tanks, with blends up to 20% (Hsieh and Felby, 2017). Also, it should be noted that existing volume of biofuel production is not high enough to effectively displace the use of conventional fuels, and hence they are more commonly offered as blends in combination with that of diesel fuels like MGO (Kass et al., 2018). HVO is produced by hydro processing Fats, Oils and Greases (FOGs) that come from the same feedstocks as FAME biodiesel. In parallel to FAME, HVO has also shown compatibility with incumbent combustion engines and can be used as a drop-in fuel in combination with MGO (Zhou et al., 2020). While blends up to 50% have been tested for HVO (Khan et al., 2012), in this study, to maintain the linearity of the results, we have assumed a blend of 20% for HVO. FT diesel is usually produced from the synthesis of either fossil fuels, such as coal and natural gas, or from lignocellulosic biomass such as forest residue and willow (Zhou et al., 2020). This pathway consists of two main steps, gasification and then the Fischer-Tropsch synthesis process. Depending on the feedstocks used for FT synthesis, the final products are derived from coal-to-liquid, gas-to-liquid, or biomass-to-liquid (Zhou et al., 2020). Like FAME and HVO, FT Diesel can be used as a drop-in marine fuel in diesel marine engines with no engine modification (Balcombe et al., 2019). While the information on blend ratio of FT Diesel is limited in the literature, we assumed a similar blend ratio (20%) to that of FAME and HVO.

The ship exhaust emission levels under each considered scenario will change due to the change in emission factors. The total emissions from the application of varied abatement measures in each scenario (A, B, C, D, E) can be calculated using the following Eq. (2), as adapted from Whall et al. (2010):

$$E^{A,B,C,D,E} = \sum_i T \times \left[\left(ME \times LF_{ME} \times EF_{i(ME)}^{A,B,C,D,E}\right) + (AE \times LF_{AE} \times \; EF_{i(AE)}^{A,B,C,D,E} \;\right] \times 10^{-6}$$

(2)

Where $E^{A,B,C,D,E}$ represents emissions while at-sea (tonnes) for each of the defined scenarios, i refers to the pollutants: SO_2, $PM_{2.5}$ and CO_2, T indicates total time spent at-sea for ferry journey, ME and AE are main engine power and auxiliary engine power (kW), respectively, LF_{ME} and LF_{AE} are the load factors of main and auxiliary engines (%), respectively, while $EF_{i(ME)}^{A,B,C,D,E}$ and $EF_{i(AE)}^{A,B,C,D,E}$ are the emission factors for the main engine and auxiliary engine for the defined abatement scenarios, respectively, for the emitted pollutant i (g/kWh), .

4.4.3 Ship Engine Power and Emission Factors

Information on Main Engine (ME) and Auxiliary Engine (AE) powers for the concerned ships was retrieved mainly from the Refinitiv AIS dataset. For 14 Ro-Ro ferry ships, there was no information on AE power in the dataset. Hence, the required data was filled based on the available AE power information for the remaining 13 ships, by developing a fraction of installed AE to ME power (%). Load factors for ME and AE while at-sea were assumed to be 80% and 30%, respectively, as obtained from Whall et al. (2010). Emission factors are largely dependent on engine/fuel type profiles, fuel sulphur content as well as any employed emission abatement measure (Whall et al., 2010). For this study, the main engine type profile for Ro-Ro ferry ships was considered to Medium Speed Diesel (MSD), based on given information in Whall et al. (2010). While for auxiliary engine type, all ferry ships were assumed to have MSD or HSD engines without distinction (M/H SD) (Whall et al., 2010). For the baseline scenario, ships were assumed to use two fuel types: i) Marine Distillate Oil (MDO) (1.5% sulphur m/m) and ii) MGO (0.1% sulphur m/m). Here, fuel types used by each ship (for ME and AE) were assigned based on the given configuration in Whall et al. (2010). While for scenario A and B, ships will mainly use RO or MGO (for both ME and AE), respectively, and in scenario C, D and E, respective biofuels of FAME, HVO and FT diesel will be employed, blended within 80% MGO. Baseline emission factors for SO_2, $PM_{2.5}$ and CO_2 were taken from Inner City Fund (2009) and Whall et al. (2010). The obtained baseline emission factors were later adjusted based on the percentage reduction in emission offered by technologies such as scrubbers (De Jonge et al., 2005), as well as the considered biofuels (Ushakov et al., 2013, Hsieh and Felby, 2017, Gilbert et al., 2018, Zhou et al., 2020). Emission factors were assigned according to respective engine and fuel type, alongside any installed emission abatement technology (e.g., scrubbers), for the discussed scenarios, as indicated in Table 4.1.

Table 4.1. Emission factors for pollutants under the discussed scenarios

	Emission factors (g/kWh)		
Engine, Engine type, Fuel	SO_2	CO_2	$PM_{2.5}$
Scenario A			
ME, MSD, RO	0.23	691	0.15
AE, M/HSD, RO	0.25	736	0.15
Scenario B			
ME, MSD, MGO	0.40	645	0.17
AE, M/HSD, MGO	0.42	690	0.17
Scenario C			
ME, MSD, (FAME + MGO)	0.321	571.5	0.157
AE, M/HSD, (FAME + MGO)	0.337	607.5	0.157
Scenario D			
ME, MSD, (HVO + MGO)	0.320	571.5	0.180
AE, M/HSD, (HVO + MGO)	0.336	607.5	0.180
Scenario E			
ME, MSD, (FTD + MGO)	0.320	639.8	0.176
AE, M/HSD, (FTD + MGO)	0.336	684.4	0.176

Sources: Inner City Fund (2009), Whall et al. (2010), Ushakov et al. (2013), Hsieh and Felby (2017), Gilbert et al. (2018), Zhou et al. (2020).

4.4.4 External Costs and Carbon Tax

For this study, the top-down methodology for the estimation of external costs was utilised, due to its relative popularity within the literature (Maragkogianni and Papaefthimiou, 2015, Tichavska and Tovar, 2015b, Nunes et al., 2019; Gore et al., 2022). The external costs of the shipping emissions for the baseline scenario were estimated using the following Eq. (3), as adapted from Nunes et al. (2019):

$$EC^{Base} = \sum_i E_i^{Base} \times ECF_i \tag{3}$$

Where EC^{Base} indicates the total external costs for the baseline scenario (€), i refers to the pollutants: SO_2, $PM_{2.5}$ and CO_2, E_i^{Base} represents the baseline emissions for each pollutant (tonnes) and ECF_i is the external cost factor for each pollutant (€/ton).

With specific reference to Ireland, external cost factors for SO_2 and $PM_{2.5}$ as given in the New Energy Externalities Development for Sustainability (NEEDS) report have been utilised, which has been recognised as the most suitable approach for the evaluation of external costs from shipping emissions at-sea, especially within the EU (Tichavska and Tovar, 2015b, Nunes et al., 2019). The cost factors as given in the NEEDS study (Preiss et al., 2008) were later updated by Korzhenevych et al. (2014) to 2010 prices, using gross domestic product per capita figures, for each EU member state. For CO_2, an external cost factor was obtained from Van Essen et al. (2011), considering an average of low-estimate and high-estimate damage costs in Europe. It should be noted that cost factors provided in Van Essen et al. (2011) and Korzhenevych et al. (2014) refer to the year 2008 and 2010 prices, respectively, and hence, we utilised the Consumer Price Index (CPI) for Ireland as available in the Organisation of Economic Co-operation and Development (OECD) statistical profiles (OECD, 2022) to update them to the year under consideration (2019). According to OECD (2022), the Irish CPI in 2019 was 101.8, while the CPI was 95.5 and

100.9 in the year 2010 and 2008, respectively. Table 4.2 indicates the updated (year 2019) Irish external cost factors used in this study.

Table 4.2. Updated External Cost Factors for Ireland (€/ton)

Pollutants	SO_2	CO_2	$PM_{2.5}$
External cost factor	7,397	86	17,552[a]

[a] - "Rural" $PM_{2.5}$ cost factor was considered

Source: Van Essen et al. (2011), Korzhenevych et al. (2014)

Based on the estimated baseline external costs, the annual benefits (i.e., saved external costs) for each of the emission abatement scenarios can be calculated by the following Eq. (4):

$$\Delta\, EC^{A,B,C,D,E} = EC^{Base} - EC^{A,B,C,D,E} \tag{4}$$

Where $\Delta\, EC^{A,B,C,D,E}$ represents the saved external costs for each scenario (€), EC^{Base} indicates the total external costs for the baseline scenario (€) while $EC^{A,B,C,D,E}$ represents the total external costs for each of the defined abatement scenario (€).

External costs for the application of different abatement measures under the defined scenarios are calculated using the following Eq. (5), as adapted from Nunes et al. (2019):

$$EC^{A,B,C,D,E} = \sum_i E_i^{A,B,C,D,E} \times ECF_i \tag{5}$$

Where $EC^{A,B,C,D,E}$ represents the external costs for each scenario (€), i refers to the pollutants: SO_2, $PM_{2.5}$ and CO_2, $E_i^{A,B,C,D,E}$ indicates the total shipping emissions for each pollutant, under each scenario of using abatement measure (tonnes) while ECF_i is the external cost factor for each emitted pollutant (€/ton).

The total carbon tax costs applicable for the baseline scenario will be estimated using the following Eq. (6):

$$CT^{Base} = E_i^{Base} \times CTR \tag{6}$$

Where CT^{Base} indicates the total carbon taxes paid for the use of baseline fuels (€), E_i^{Base} represents the baseline emissions for the pollutant i, which is CO_2 (tonnes) and CTR is the tax rate for each ton of CO_2 emitted (€/ton).

The saved carbon tax costs for each of the considered emission abatement scenarios can be calculated by following Eq. (7):

$$\Delta\, CT^{A,B,C,D,E} = CT^{Base} - CT^{A,B,C,D,E} \tag{7}$$

Where $\Delta\, CT^{A,B,C,D,E}$ represents the change in carbon tax costs with the employment of each abatement scenario (€), CT^{Base} indicates the total carbon tax costs applicable for the baseline scenario (€) while $CT^{A,B,C,D,E}$ represents the total carbon taxes applicable for the considered abatement scenarios (€). Carbon taxes for the different scenarios of using emission abatement measures can be calculated using the following Eq. (8):

$$CT^{A,B,C,D,E} = E_i^{A,B,C,D,E} \times CTR \tag{8}$$

Where $CT^{A,B,C,D,E}$ represents the paid carbon taxes under each of the defined abatement scenarios (€), i refers to the pollutant: CO_2, $E_i^{A,B,C,D,E}$ indicates the total CO_2 emissions, under each abatement scenario (tonnes) while CTR is the considered tax rate for emitted CO_2 (€/ton).

Currently, there has not been any agreement yet on the amount of carbon tax to be paid out, with significantly different rates being proposed by the various stakeholders involved (Muchira, 2022). Maersk, the world's biggest container shipping company, has proposed a carbon tax rate of \$150/ton, while the "getting to Zero" coalition group, which is an association of the leading maritime companies and environmental non-governmental organisations, has suggested a tax rate of \$200/ton (Muchira, 2022). Considering both the perspectives, for this study, we have considered the "median" carbon tax rate of \$175/ton, which translates to €157.5/ton, based on the given currency conversion rates as in European Central Bank (2022).

4.4.5 Private costs

4.4.5.1 Fuel costs

In the baseline scenario, the total fuel consumed by ships while at-sea can be calculated using the following Eq. (9), as adapted from Kim et al. (2020):

$$FT^{Base} = \sum_{lf} T \times \left[\left(ME \times LF_{ME} \times SFC_{ME}^{lf}\right) + \left(AE \times LF_{AE} \times SFC_{AE}^{lf}\right)\right] \times 10^{-6} \qquad (9)$$

Where FT^{Base} is the total fuel consumed by ships while at-sea for the baseline scenario, annually (tonnes), lf refers to the baseline fuels (MDO/MGO), T indicates total time spent at-sea for ferry journey, ME and AE are main engine power and auxiliary engine power (kW), respectively, LF_{ME} and LF_{AE} are the load factors of main and auxiliary engines (%), respectively, while SFC_{ME}^{lf} and SFC_{AE}^{lf} represent the specific fuel consumption for the main engine and auxiliary engine, respectively, based on the considered baseline fuels (g/kWh), whose values depend on engine and fuel type for the considered ship (Inner City Fund, 2009).

For the estimated fuel consumption, the annual fuel costs for the baseline scenario will be estimated using the following Eq. (10):

$$FC^{Base} = FT_{lf}^{Base} \times FP_{lf} \tag{10}$$

Where FC^{Base} indicates the annual fuel costs for the baseline scenario (€), lf refers to the considered baseline fuels, FT_{lf}^{Base} represents the total fuel consumed by ships in the baseline scenario, for each of the considered baseline fuel lf, annually (tonnes) and FP_{lf} is the fuel price for each baseline fuel (€/ton).

To estimate the total fuel consumption in scenarios A (RO with scrubber) and B (MGO), the following Eq. (11) has been utilised, as adapted from Kim et al. (2020):

$$FT^{A,B} = \sum_f T \times \left[\left(ME \times LF_{ME} \times SFC_{f(ME)}^{A,B}\right) + \left(AE \times LF_{AE} \times SFC_{f(AE)}^{A,B}\right)\right] \times 10^{-6} \tag{11}$$

Where $FT^{A,B}$ is the total fuel consumed by ships while at-sea for the defined scenarios A and B, annually (tonnes), f refers to the fuels utilised by ships in scenario A (RO) and scenario B (MGO), T indicates total time spent at-sea for ferry journey, ME and AE are main engine power and auxiliary engine power (kW), respectively, LF_{ME} and LF_{AE} are the load factors of main and auxiliary engines (%), respectively, while $SFC_{f(ME)}^{A,B}$ and $SFC_{f(AE)}^{A,B}$ represent the specific fuel consumption for the main engine and auxiliary engine, respectively, for the considered fuels (g/kWh), in scenarios A and B. Here, it has to be noted that in scenario A, the use of scrubbers by ferry ships will increase their RO fuel consumption by 2% (Campling et al., 2013), due to additional energy required for scrubbers to operate (Abadie et al., 2017).

For the estimated fuel consumption in scenarios A and B, the annual fuel costs will be calculated using the following Eq. (12):

$$FC^{A,B} = FT_f^{A,B} \times FP_f \tag{12}$$

Where $FC^{A,B}$ indicates the annual fuel costs for the defined scenarios A and B (€), f refers to the considered fuels in scenario A (RO) and B (MGO), $FT_f^{A,B}$ represents the total fuel f consumed by ships in scenario A and B, annually (tonnes) and FP_f is the fuel price for the considered fuels of RO or MGO (€/ton).

For this study, biofuels such as FAME, HVO and FT diesel will be used as ‘drop-in’ fuels in combination with MGO, hence the total fuel consumption in such scenarios will be equal to the sum of consumed biofuel and MGO, as indicated in the following Eq. (13):

$$FT^{C,D,E} = \sum_f \left(x_f \times (T \times \left[\left(ME \times LF_{ME} \times SFC_{f(ME)}^{C,D,E} \right) + \left(AE \times LF_{AE} \times SFC_{f(AE)}^{C,D,E} \right) \right] \times 10^{-6}) \right) + \sum_{bf} \left(x_{bf} \times (T \times \left[\left(ME \times LF_{ME} \times SFC_{bf(ME)}^{C,D,E} \right) + \left(AE \times LF_{AE} \times SFC_{bf(AE)}^{C,D,E} \right) \right] \times 10^{-6}) \right) \tag{13}$$

Where $FT^{C,D,E}$ is the total fuel consumed in scenarios C, D and E (tonnes), x_f and x_{bf} represents the proportion of MGO (f) and biofuels (bf) consumed, which is 80% and 20%, respectively, T indicates total time spent at-sea for ferry journey, ME and AE are main engine power and auxiliary engine power (kW), respectively, LF_{ME} and LF_{AE} are the load factors of main and auxiliary engines (%), respectively, $SFC_{f(ME)}^{C,D,E}$ and $SFC_{f(AE)}^{C,D,E}$ represent the main engine and auxiliary engine specific fuel consumption values for the fuel (f) (MGO) utilised in the respective scenarios of C, D and E (g/kWh), while $SFC_{bf(ME)}^{C,D,E}$ and $SFC_{bf(AE)}^{C,D,E}$ represent the main engine and auxiliary engine specific fuel consumption values for the biofuel (bf) (FAME/HVO/FT Diesel) utilised in the respective scenarios of C, D and E (g/kWh).

For the estimated fuel consumption in scenarios C, D and E, the annual fuel costs will be calculated using the following Eq. (14):

$$FC^{C,D,E} = \left(FT_f^{C,D,E} \times FP_f\right) + \left(FT_{bf}^{C,D,E} \times FP_{bf}\right) \tag{14}$$

Where $FC^{C,D,E}$ indicates the annual fuel costs for the defined scenarios C, D and E (€), f refers to the considered fuel (MGO) in scenario C, D and E, bf refers to the considered biofuels (FAME/HVO/FT Diesel) in the respective scenarios C, D and E, $FT_f^{C,D,E}$ represents the total fuel f consumed by ships in scenario C, D and E, annually (tonnes), $FT_{bf}^{C,D,E}$ represents the total biofuel bf consumed by ships in scenario C, D and E, annually (tonnes), FP_f is the fuel price for the considered fuel f (€/ton) and FP_{bf} is the fuel price for the considered biofuels bf (€/ton)

Table 4.3 indicates specific fuel consumption values for different engine and fuel type profiles under the defined baseline and emission abatement scenarios, alongside the respective fuel prices. Here, the specific fuel consumption values for biofuels (FAME, HVO, FT Diesel) were simulated based on the observed changes in MGO consumption, as discussed in Ushakov et al. (2013), Gilbert et al. (2018) and Ushakov and Lefebvre (2019). A similar adjustment was also made when determining the respective “year 2019” biofuel prices (International Energy Agency [IEA], 2020). Also, the obtained specific fuel consumption of MGO (Whall et al., 2010) was proportional by 80% in scenarios C, D and E, with the values for biofuels being proportional by 20%. The specific fuel consumption values for other fuels such as RO (scenario A) and MDO (baseline) were also obtained from Whall et al. (2010), where the obtained value was incremented by 2% for the use of scrubber in scenario A (Campling et al., 2013). Fuel prices for RO (classified as Intermediate Fuel Oil (IFO380)), MDO (classified as MGO (1.5%)) and MGO (classified as Low-sulphur Marine Gasoline Oil (LSMGO)) (0.1% sulphur) as in Shipandbunker

(2022) were obtained, considering an average price over the period of "26 April 2019 – 1 January 2020". The prices listed in \$/ton were converted to €/ton using 2019 USD to EURO average conversion rates by European Central Bank (2022).

Table 4.3. Specific Fuel Consumption Values and Fuel Prices

Engine (Fuel type)	Specific fuel consumption (g/kWh)	Fuel price (€/ton)
Baseline		
ME (MDO)	203.0	536.4
AE (MDO)	217.0	
ME (MGO)	203.0	533.6
AE (MGO)	217.0	
Scenario A		
ME (RO)	217.3	310.1
AE (RO)	231.5	
Scenario B		
ME (MGO)	203.0	533.6
AE (MGO)	217.0	
Scenario C		
ME, (FAME)	162.4, 40.0	789.7[a]

AE (FAME)	173.6, 42.5	
Scenario D		
ME (MGO, HVO)	162.4, 43.0	827.9[a]
AE (MGO, HVO)	173.6, 46	
Scenario E		
ME (MGO, FT Diesel)	162.4, 43.6	835.6[a]
AE (MGO, FT Diesel)	173.6, 46.7	

[a] – Biofuel prices only, MGO prices considered the same as in scenario B

Sources: Whall et al. (2010), Ushakov et al. (2013), Gilbert et al. (2018), Ushakov and Lefebvre (2019), IEA (2020), Shipandbunker (2022)

4.4.5.2 Scrubbers

An alternative to using low sulphur fuels is the use of sulphur scrubbers to reduce SO_x emissions (Campling et al., 2013). Three types of systems are used: open-loop (seawater) scrubbers, closed-loop (freshwater) scrubbers and hybrid scrubbers (Zhao et al., 2021). Open-loop scrubbers utilise untreated seawater, using the natural alkalinity of the seawater to neutralise the sulphur from exhaust gases, while in a close-loop scrubber, exhaust gases are neutralised with caustic soda (Sodium Hydroxide (NaOH)), which is added to fresh water in a closed system (Den Boer and Hon, 2015). Hybrid scrubbers can operate both in open-loop mode (when on high seas) and on a close-loop mode (when in port waters) (Sethi, 2021). Most recently, the use of open-loop scrubbers has been banned from being used within port waters by namely three Irish ports, Dublin, Cork and Waterford (Safety4Sea, 2020a). This is mainly due to damages caused from the discharged exhaust water from such scrubbers, which can potentially pollute the local marine environment. Considering this fact, we have assumed that all Ro-Ro ferry ships within scenario A will be retrofitted with hybrid scrubbers. Table 4.4 summarises the investment and operational costs of retrofitting scrubbers on existing ships.

Table 4.4. Private costs for Hybrid Scrubber

Parameter	Unit	Hybrid
Capital		
Installation	€/kW	438
Lifespan	Years	15
Operational		
Sludge produced	L/MWh	1.3
Sludge disposal cost	€/L	0.12
NaOH consumption	L/MWh	15
NaOH costs	€/ton	610
Maintenance cost	€/MWh	0.25

Sources: Campling et al. (2013), Den Boer and Hon (2015), Barker (2020), Zhao et al. (2021)

4.4.6 Cost-Benefit analysis

To perform a cost-benefit evaluation of the considered emission abatement scenarios, a NPV analysis was conducted. For evaluating the cost-effectiveness of scrubber usage in scenario A, the following Eq. (15) has been utilised, as adapted from Jiang et al. (2014), where alongside the saved external costs, we have also added the benefits from saved carbon tax costs and avoided baseline fuel costs:

$$NPV^{A} = -\,CAPEX^{A} + \textstyle\sum_{t=1}^{n} ((\Delta\, EC^{A} + FC^{Base} + \Delta\, CT^{A}) - (OPEX^{A}))/(1+r)^{t} \quad (15)$$

Where NPV^{A} indicates the net present value for the use of scrubbers in considered scenario A (€), $CAPEX^{A}$ is the capital (installation) costs of scrubbers in scenario A (€), n indicates the lifespan of scrubber retrofit based on the remaining lifespan of the considered fleet (years), $\Delta\, EC^{A}$ is the total external cost savings achieved for use of scrubbers in scenario A (€), FC^{Base} indicates the total baseline fuel costs, i.e. fuel benefits achieved (€), $\Delta\, CT^{A}$ represents the change in paid carbon tax costs with the employment of scrubbers in scenario A (€), $OPEX^{A}$ is the annual operational costs (for RO fuel usage) and maintenance costs, for scrubbers in scenario A (€), r is the discount rate (%), and t represents the number of periods. The average age for the considered fleet of Ro-Ro ferry ships was found to be 18 years from the AIS dataset. Taking the maximum lifespan of a ship as 30 years, we assumed n as 12 years (Safety4Sea, 2020b).

For the use of MGO in scenario B, alongside the blend of MGO and biofuels (FAME/HVO/FT Diesel) in the respective scenarios of C, D and E, the NPV was calculated using the following Eq. (16), as adapted from Jiang et al. (2014), where alongside the saved external costs, we have also added the benefits from saved carbon tax costs and avoided baseline fuel costs:

$$NPV^{B,C,D,E} = ((\Delta\, EC^{B,C,D,E} + FC^{Base} + \Delta\, CT^{B,C,D,E}) - (OPEX^{B,C,D,E}))/r \quad (16)$$

Where $NPV^{B,C,D,E}$ indicates the net present value for the use of different abatement measures in the defined scenarios B, C, D and E (€), $\Delta\, EC^{B,C,D,E}$ is the total external cost savings achieved in the defined scenarios (€), FC^{Base} indicates the total baseline fuel costs

(€), $\Delta\, CT^{B,C,D,E}$ represents the change in paid carbon tax costs in the defined scenarios (€), $OPEX^{B,C,D,E}$ is the annual operational costs (for MGO and biofuel usage) in the defined scenarios (€) and r is the discount rate (%). For this study, the Irish social discount rate of 4% has been assumed (Department of Public Expenditure and Reform, 2019).

4.5 Results and discussion

4.5.1 Results

The total at-sea emissions for the considered abatement scenarios, for year 2019 is depicted in Figure 4.1, where they are compared against the obtained baseline emissions (1,413,129 tonnes).

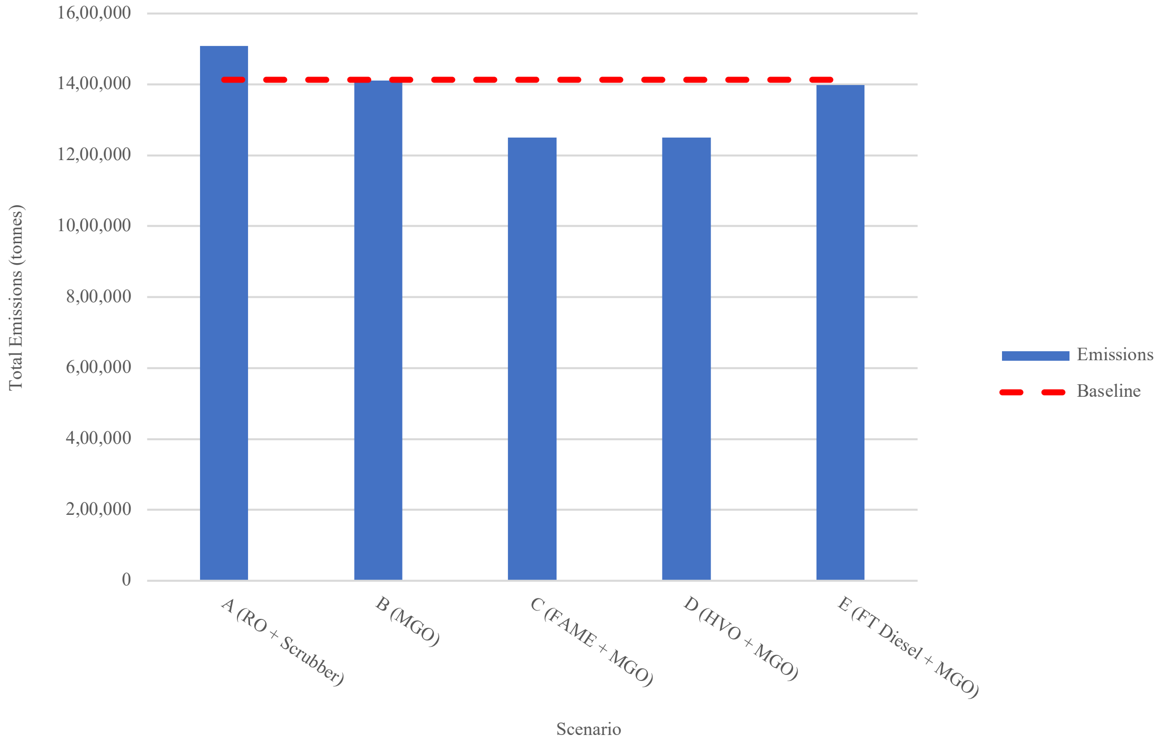


Figure 4.1. Estimated shipping emissions for baseline and abatement scenarios

Overall, it was observed from Figure 4.1 that among all the scenarios, scenario C (FAME blended within MGO) offered the highest emission reduction potential, as a drop of 13.11%

was observed from the total baseline emissions, with scenario D (HVO blended within MGO) showing a nearly equivalent drop in emissions by 13.09%. Scenarios E (FT Diesel blended within MGO) and B (MGO) offered a very minimal reduction of 1.01% and 0.18%, respectively, while the overall emissions increased by 6.38% with the use of scrubbers (with RO) in scenario A. Table 4.5 shows the breakdown of total baseline and abatement scenario emissions, for the considered pollutants in this paper (SO_2, CO_2, $PM_{2.5}$).

Table 4.5. Scenario-related shipping emissions (tonnes)

Scenario	SO_2	CO_2	$PM_{2.5}$
Baseline	3,436	1,409,238	454
A (RO + Scrubber)	503	1,508,532	329
B (MGO)	873	1,409,238	370
C (FAME + MGO)	700	1,248,389	342
D (HVO + MGO)	699	1,248,389	392
E (FT Diesel + MGO)	699	1,397,874	383

Source: Authors

From the estimated breakdown of total emissions by pollutants in Table 5, it is shown that although the use of scrubbers (with RO) in scenario A offered the highest SO_2 and $PM_{2.5}$ reduction potential against the baseline, by 85.4% and 27.5%, respectively, the overall CO_2 emissions in this scenario increased by 7.1%. This result can mainly be attributed to the fact that installation of scrubbers demands additional energy for operational purposes and subsequently, increase the total CO_2 emissions (Abadie et al., 2017, Zis et al., 2022). All the considered biofuels (FAME, HVO and FT Diesel) depicted nearly equivalent drop in SO_2 emissions (79.6%), while the use of blended FAME (scenario C) offered a drop of 24.6% in $PM_{2.5}$ emissions, which was comparatively higher than that of other discussed biofuel scenarios D and E. In relation to CO_2, the use of blended FAME (scenario C) and HVO (scenario D) will lessen the considered emissions by 11.4%, highest among all the considered scenarios. The use of MGO (scenario B) reflected a drop in SO_2 and $PM_{2.5}$ emissions by 74.6% and 18.45%, respectively, with no change in overall CO_2 emissions against the baseline.

Based on the derived shipping emissions, external costs were analysed, alongside the carbon tax costs, as shown in Figure 4.2. The total change in external and carbon tax costs with the use of emission abatement measures in scenarios A, B, C, D and E against the baseline will be seen as benefits while conducting the cost-benefit analysis.

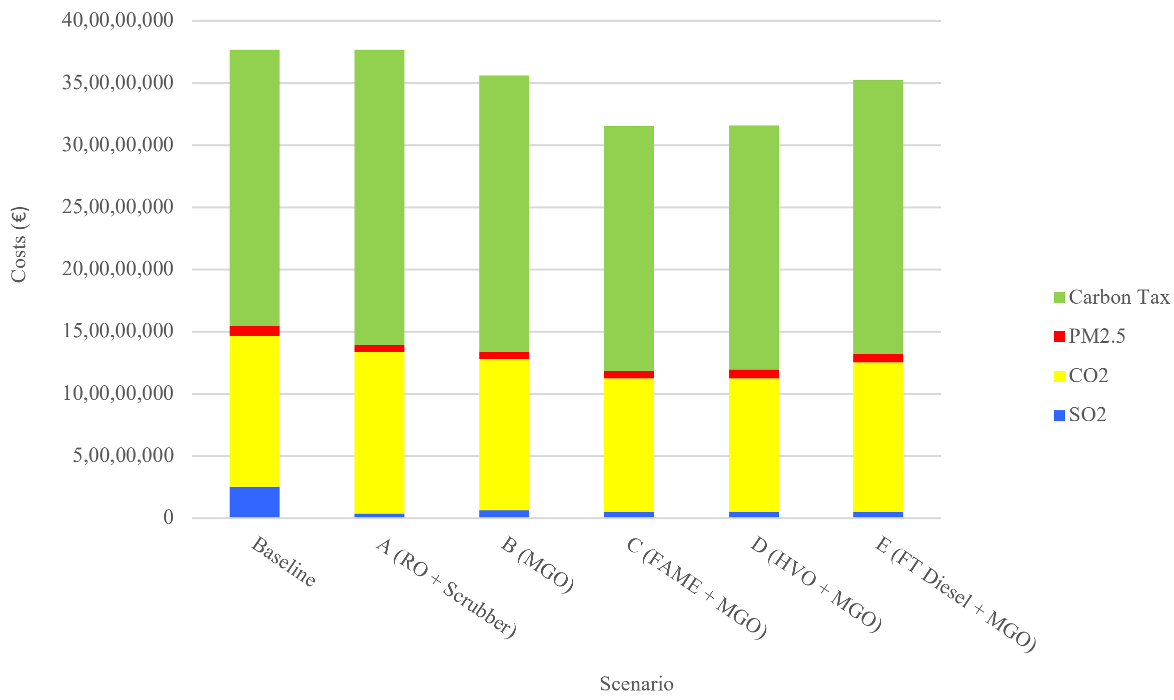


Figure 4.2. External and carbon tax costs for the baseline and abatement scenarios

From Figure 4.2, it is shown that the utilisation of varied emission abatement scenarios will alleviate the overall baseline external costs (€154,583,541) to a certain extent, with the lowest external costs being generated with the blend of FAME and MGO in scenario C (€118,548,327), hence, offering a benefit of €36,035,213. This was followed by scenario D (blend HVO and MGO), which offered a benefit of €35,171,707, scenario E (blend FT Diesel and MGO) (€22,468,983), scenario B (MGO) (€20,429,192) with the lowest benefits being from scenario A (scrubber with RO) (€15,351,029). Overall, the externalities imposed from CO_2 emissions remained most prominent among the considered pollutants, as they made up nearly 90% of the total external costs for all scenarios. Further, it was noticed that €221,955,042 of carbon tax costs were applicable to be paid in baseline and scenario B, annually. If ships were to switch to scenario C or D, they will be paying €196,621,282 as carbon tax, hence saving €25,333,760. While in scenario E, total benefits from carbon tax savings were found to be €1,789,933. Due to scrubber usage in scenario

A, an additional carbon tax of €15,638,751 will have to be paid over baseline i.e., this will be added as loss when evaluating the cost-effectiveness of this scenario.

While all the abatement scenarios indeed reflected noteworthy changes in the external and carbon tax costs, it is expected that there will also be significant adjustments in the associated private costs against the baseline, mainly due to installation of suitable technology (scrubber) and from the utilisation of fuels such as RO, MGO, FAME, HVO or FT Diesel. Figure 4.3 indicates the total private costs associated with the varied scenarios.

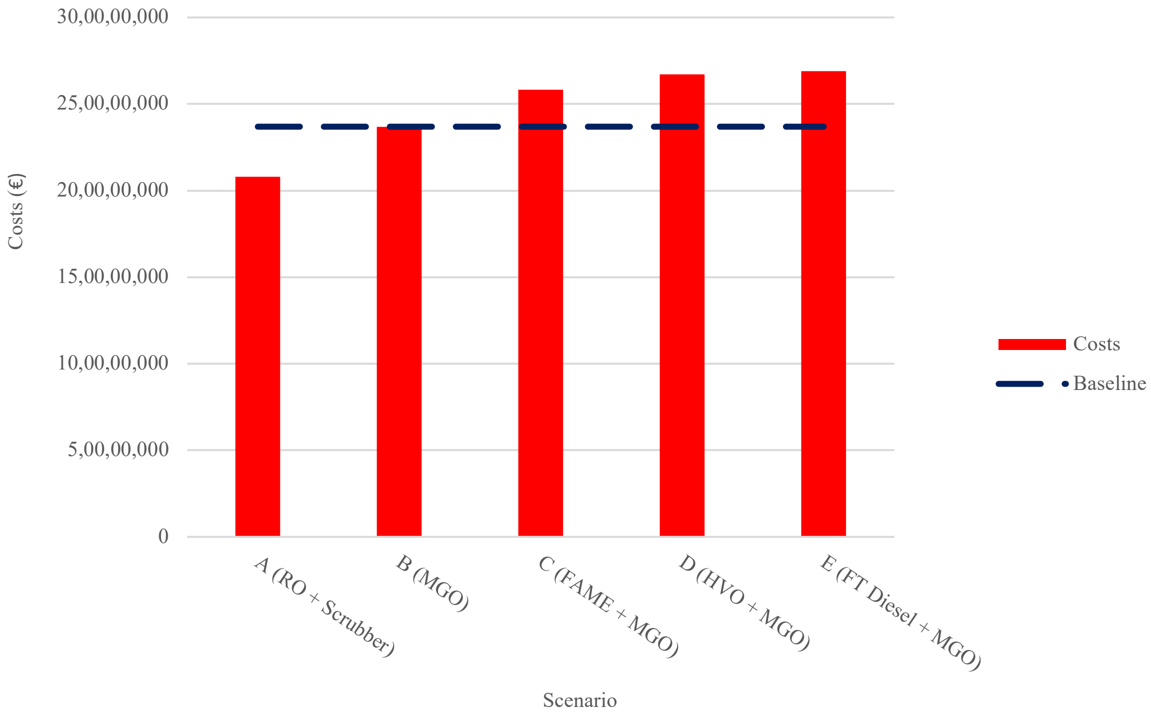


Figure 4.3. Annualised private costs for the baseline and selected abatement scenarios

From the indicated results in Figure 4.3, an orderly increase in the annualised private costs was observed for the considered abatement scenarios, with the lowest total costs being showed in scenario A (€208,005,944), a reduction of 13.9% against the baseline costs, and the highest total costs in scenario E (€269,050,949), an increment by 11.95% against the baseline. The impetus behind lower annualised private costs in scenario A against other abatement scenarios is due to RO consumption for scrubber operation, which is available on a comparatively lower bunker price than the other discussed fuels. Among the biofuel options, the use of FAME (scenario C) offered the lowest annualised private costs, mainly due to its lower specific fuel consumption value, alongside its comparatively lower price over other biofuels such as HVO and FT Diesel.

Based on the estimated private, external and carbon tax costs, we conducted a cost-benefit analysis, using the NPV approach, for the considered scenarios, as shown in Figure 4.4.

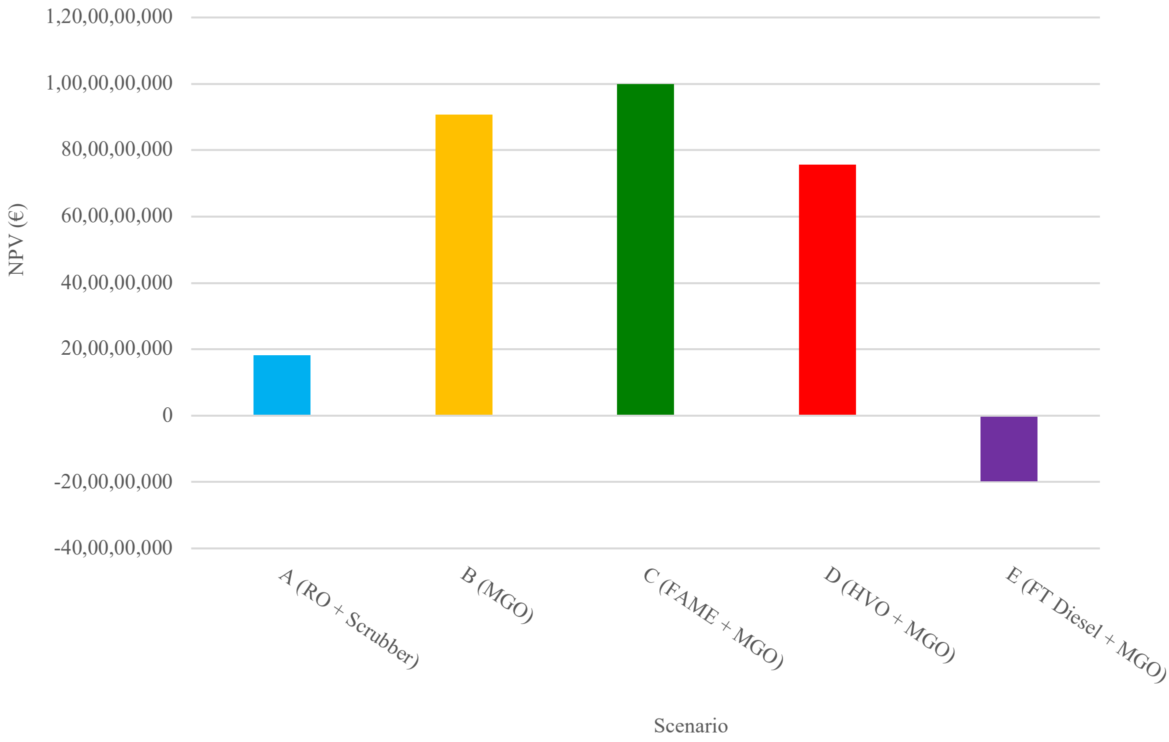


Figure 4.4. Estimated NPVs for the selected abatement scenarios

From Figure 4.4, it is shown that scenario C (FAME blend within MGO) has the highest total NPV (€998,429,573), while in scenario E, we observed that the use of FT Diesel (blended within MGO) will be inviable, due to a negative NPV (−€197,071,994). There were two main reasons for this outcome: 1) High price of FT Diesel biofuel and 2) FT Diesel generated comparatively lower benefits in terms of external and carbon tax costs, in relation to other biofuels such as FAME and HVO. Also, even though scenario A had the lowest annualised private costs among the abatement scenarios, due to the use of cheaper RO fuel, its NPV (€182,227,852) was even lower than that of scenarios B (€907,144,824) and D (€755,643,137). This outcome was largely due to the annualised scrubber installation costs when accumulated over the considered retrofit period (12 years) could not be offset by the saved external and baseline fuel costs, alongside the reasoning that the use of scrubber increased overall CO_2 emissions, resulting in annual losses from higher carbon taxes being paid out (€15,638,751). Hence, based on the estimated results, the most cost-effective strategy complying with IMO 2020 sulphur regulation, from an NPV perspective, will be the use of FAME (blended within MGO) by the considered Ro-Ro ferry ships visiting Ireland.

4.5.2 Discussion

From the obtained results in section 4.3.1, it was shown that nearly every abatement scenario reflected a positive NPV, except for the use of FT Diesel (blended within MGO) by Ro-Ro ferry ships. The most cost-effective strategy from an Irish perspective will be blended FAME (within MGO), due to its highest NPV (€998,429,573). Although, it must be noted that due to increased volatility of bunker fuel prices, the considered NPVs are subject to fluctuation. For example, the price spreads between heavy-sulphur fuel oils (i.e., RO) and low-sulphur fuel oils (i.e., MGO) dwindled significantly ($60/ton – Rotterdam bunker) under the impacts of Coronavirus disease 2019 (COVID-19), which would have made the use of scrubbers even less economically worthwhile in comparison to the use of low-sulphur oil such as MGO (Zhao et al., 2021, Shipandbunker, 2022). Although, with the return to normal operations globally post the two years of the COVID-19 pandemic, it was seen that the price spread between RO and MGO in early 2022 has widened significantly, even at higher levels than that in 2019 (Lloyd's List, 2022). For instance, the average RO-MGO price spread was estimated at $319/ton (in December 2019), which dipped to $125/ton (in December 2020) and increased sharply to $725/ton (in June 2022) (Shipandbunker, 2022). This variance in the RO-MGO price spread will consecutively impact the cost-competitiveness of all the respective scenarios, due to the usage of MGO (in scenarios B, C, D and E) and of RO (in scenario A). Based on this reasoning, we conducted a sensitivity check for the change in NPVs of abatement scenarios A, B, C, D and E, with subsequent changes in RO-MGO price spread considered in this study (€223.5/ton), as shown in Figure 4.5.

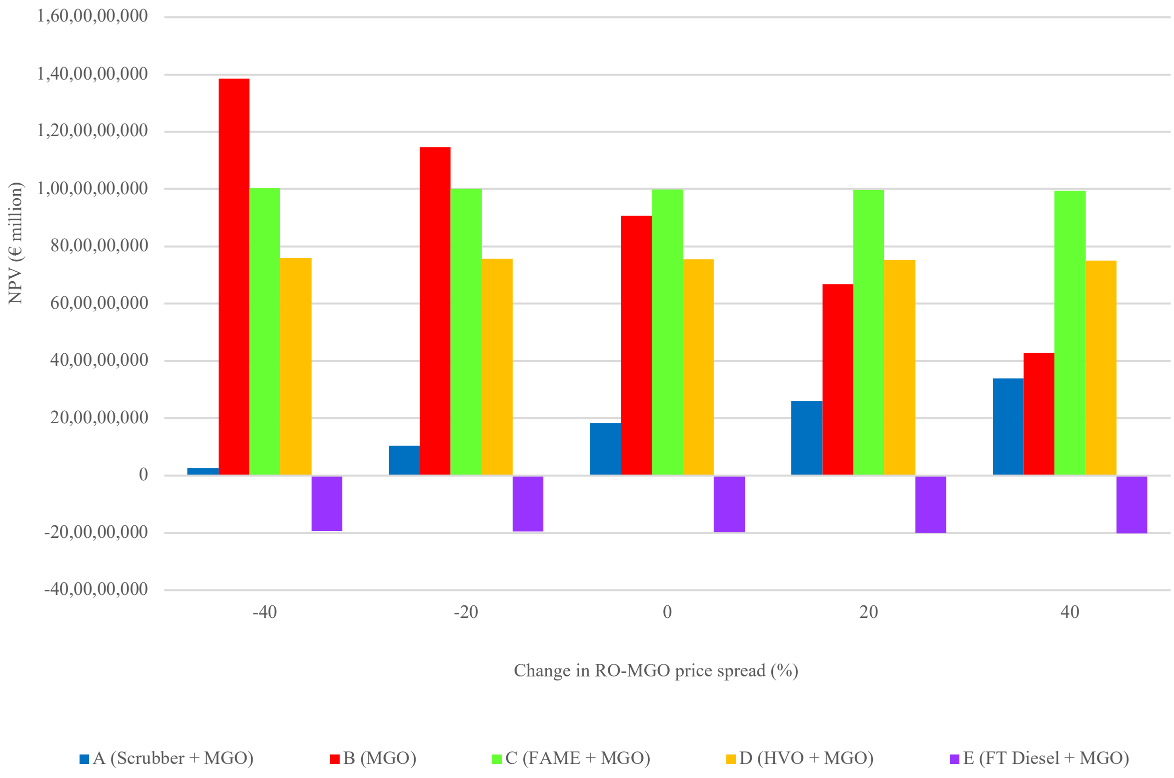


Figure 4.5. NPV sensitivity to changes in RO-MGO price spread

In Figure 4.5, it is shown that NPVs for the considered abatement scenarios B, C, D and E will increase with a decrease in the considered RO-MGO price spread, while the NPV for scenario A will decrease, and vice-versa. Here, with a decrease of 20% in the considered price spread, the use of MGO (scenario B) will achieve a higher NPV over scenario C

(FAME and MGO blend). While an increment in the considered price spread by 20% will further lower the viability of MGO utilisation than that of scenario D (HVO and MGO blend). Recently, the RO-MGO price spread (in December 2022) reached \$436/ton (i.e., €414/ton) (European Central Bank, 2022, Shipandbunker, 2022), indicating an increment of 85% to that of considered price spread for this study. Hence, it can be said that there will certainly be a drop in the estimated NPVs of scenarios B, C, D and E under current circumstance, although, based on the sensitivity pattern in Figure 4.5, scenario C is expected to remain the most viable solution to implement, with scenario A possibly achieving a higher NPV than scenario B.

Overall, the conducted analysis and obtained results point out that the use of FAME (in blend with MGO) will be the most cost-effective pathway to follow in order to fulfil the IMO 2020 requirements successfully. Although, it is also important to estimate the availability of suitable biomass feedstock and the maintained production capacity, from an Irish perspective, to further understand the applicability of such fuel on a larger scale. Based on the feedstock utilised for production, a distinction can be made between "conventional" (i.e., 1st generation) and "advanced" (i.e., 2nd/3rd generation) FAME biodiesel. Most commonly, FAME biodiesel is produced using the "conventional" biomass feedstocks such as oil crops, which may also be used for food and animal feed production (Sustainable Shipping Initiative, 2021). Although, it has been noted that producing FAME using such feedstocks presents significant sustainability concerns such as direct deforestation and peatland dewatering (Sustainable Shipping Initiative, 2021), with increased evidence of high greenhouse gas impact (Zhou et al., 2020). Parallelly, FAME can also be produced using "advanced" biomass feedstocks such as waste cooking oil, animal fats (tallow) and energy crops that are grown on marginal and underutilised lands (Sustainable Shipping Initiative, 2021). Such "advanced" feedstocks do not compete directly with food production (agricultural land) or compromise biodiversity and are capable of delivering improved life-cycle greenhouse gas emission savings compared with “conventional” feedstocks (Zhou et al., 2020, Sustainable Shipping Initiative, 2021). Through the Renewable Energy Directive 2018/2021 (RED II), the EU has been increasingly proactive on the development and utilisation of “advanced” biofuels over “conventional” alternatives, with the set minimum target of 3.5% (by 2030) for the use of advanced biofuels in the transport sector (European Commission, 2023). As of 2020, the FAME biodiesel production capacity in Ireland stood at 115 million litres (i.e., 102,700 tonnes), with the entirety of biofuel being produced from the advanced feedstocks such as used cooking oil and tallow, with production capacity and available feedstock being expected to increase in the next 5-10 years in line with the forecasted demand (Ó Cléirigh, 2022, SEAI, 2022). The following Table 4.6 indicates the availability of such advanced feedstocks, expected FAME biodiesel production and maritime requirements (for the considered Ro-Ro ferry ships), for the years 2020, 2025 and 2030, from an Irish perspective.

Table 4.6. Irish FAME Feedstock, Production and Ferry demand (tonnes).

Year	Irish Feedstock Availability	Irish FAME Production	FAME required as marine fuel
2020	3,750,000	102,700	87,368
2025	4,050,000	261,000	87,368
2030	4,470,000	404,000	87,368

Source: Own elaboration based on Ó Cléirigh (2022), SEAI (2022)

From Table 4.6, it is shown that the current FAME biodiesel production in Ireland, as of 2020 (102,700 tonnes) will need to be increased by 85% to accommodate for the requirement (87,368 tonnes) arisen by its use in Ro-Ro ferry ships operating from Irish ports. For years 2025 and 2030, the production levels are expected to increase by nearly 60% and 75%, respectively, while we assumed that maritime requirements would remain same, mainly due to the fact that we have only considered Ro-Ro ferry ships in this study which tend to operate on a fixed route on a regular basis and hence, a significant variance is not expected in terms of their movements. When looking at the availability of biomass feedstock, the total reserves in year 2020 stood at 3,750,000 tonnes. Considering the biodiesel yield of 900 litres for 1 ton of used cooking oil or tallow (Rice, 2009, Ó Cléirigh, 2022), this would result in the total yield of 3,375,000 tonnes of FAME biodiesel, with the total yield being 3,645,000 tonnes and 4,023,000 tonnes, respectively, for year 2025 and year 2030. When comparing the possible biofuel yield from the available feedstock with that of maritime requirements, the required share of its use by Ro-Ro ferry ships comprises less than 3% of the total biodiesel yield for all the given years (2020, 2025, 2030). Overall, it can be said that the advanced biomass feedstocks (for FAME) in Ireland are available in abundance when compared to that of its requirements by Ro-Ro ferry ships, although, the current (year 2020) FAME production levels in Ireland will need to be improved significantly (by 85%) to be able to incorporate the maritime requirements, which could be met with improved production levels in the next 5-10 years.

4.6. Conclusion

This paper evaluated the cost-effectiveness of varied abatement measures complying with IMO 2020 sulphur regulation (scrubbers, MGO and blended biofuels (FAME, HVO and FT Diesel)), using the NPV methodology, assimilating their respective private costs with that of benefits through saved external and carbon tax costs, for the baseline year 2019. To the best of our knowledge, this is one of the first studies till date which evaluated the cost-effectiveness of biofuels, which have been designated by the IMO as measures which comply with existing fuel sulphur limits and are also being seen as interim solutions for compensating greenhouse gas emissions. Ireland was selected as the case study, as it is primarily an "energy importer" state, and as the use of biofuels could be of utmost importance for the nation to reduce its dependence on importing fossil fuels and further, to mitigate harmful emissions along its coastline, especially considering that Ireland has one of the highest death rates in the world due to shipping emissions (Rutherford and Miller, 2019).

From the estimated results, the scenario involving the use of blended FAME within MGO presented the highest NPV of €998,429,573, mainly due to their high saving potential in terms of external and carbon tax costs. This was followed by only MGO utilisation (€907,144,824), blended HVO within MGO (€755,643,137), use of scrubber with RO

(€182,227,852), with a negative NPV being shown by blended FT Diesel within MGO (−€197,071,994). Here, although the scenario involving scrubber utilisation depicted the lowest annualised private costs, its NPV was comparatively lower than that majority of other abatement scenarios, with the impetus being the accumulated installation costs which could not be offset by the saved external and avoided baseline fuel costs over the considered retrofit period (12 years), along with additional losses suffered from higher carbon tax being paid due to increased CO_2 emissions levels with scrubber usage. While the unviability of blended FT Diesel usage was mainly due to its high price and lower benefits offered from saved external and carbon tax costs. From the sensitivity analysis, we observed that a reduction of 20% in the considered RO-MGO price spread will be required to improve the NPV of only using MGO for sulphur compliance, over the application of blended FAME, while any increment in RO-MGO price spread will further boost the viability of blended FAME over other measures. Overall, not only the use of blended FAME will be the most cost-effective pathway (by NPV) to follow for IMO 2020 compliance, but it will also present a 11.4% reduction in CO_2 emissions, which was found to be the highest among all the available sulphur compliance measures, establishing itself as the best interim solution to steer the maritime industry for long term commitments of its decarbonization. Further, our analysis showed that there will need to be an increment of nearly 85% in the current (year 2020) FAME biodiesel production (102,700 tonnes) in Ireland, to be able to meet the necessary biofuel required for its operation by Ro-Ro ferry ships operating from Irish ports (87,368 tonnes). It is expected that the production levels for FAME biodiesel in Ireland will improve significantly in the coming 5-10 years, alongside the biomass reserves, which were found to be remarkably high enough to accommodate the required capacity for maritime usage comfortably.

In relation to the reliability of the obtained data, a significant effort was made to obtain precise information on ship activities using the AIS database. Although data with regards to load factors, specific fuel consumption, emission factors, external cost factors and carbon tax rate, fuel prices was collected from high quality sources, there is a possibility of some inherent variation. Despite the limitations, this study provides a comprehensive analysis of the varied emission abatement measures to assist with the selection of most cost-effective strategy to implement for IMO 2020 compliance. Also, the current study was limited to comparing the cost-effectiveness of abatement measures which have been outlined for sulphur emission reduction. In the recent years, an increased attention has been given by the IMO on limiting NO_x emissions from shipping by establishing Nitrogen Emission Control Areas, where ships will be required to install Selective Catalytic Reduction or Exhaust Gas Recirculation to comply with the emission limits. It is expected that future studies will also explore the cost-effectiveness of such measures when used on ships, especially in combination with biofuels. Further, future studies should also investigate the use of blended biofuels on long distance cargo and passenger (cruise) ships, to investigate if the biofuels maintain their relative cost-effectiveness when employed on such ship types and movements

CHAPTER FIVE

Cost assessment of alternative fuels for maritime transportation in Ireland

5.1 Abstract

In this study, we investigated the cost-effectiveness of four alternatives: Liquified Natural Gas (LNG), methanol, green hydrogen, and green ammonia, for the case of top 20 most frequently calling ships to Irish ports in 2019, through the Net Present Value (NPV) methodology, incorporating the benefits incurred through saved external, carbon tax and conventional fuel costs. LNG had the highest NPV (€6,166 million), followed by methanol (€1,705 million) and green hydrogen (€319 million). Green ammonia utilisation (as a hydrogen carrier) looks inviable due to higher operational costs, resulting from its excessive consumption (i.e., losses) during the cracking and purifying processes and its lower net calorific value. Green hydrogen remains the best option to meet future decarbonization targets, although, a further reduction in its current fuel price (by 60%) or a significant increment in the proposed carbon tax rate (by 275%) will be required to improve its cost-competitiveness over LNG and methanol.

5.2 Keywords

Shipping emissions; alternative fuels; cost-benefit analysis; emission targets

5.3. Introduction

Maritime transport has long been considered the most attractive option for transferring commodities, based on its high capacity and economical freight rates (Li et al., 2020). Although shipping is understood to be the most energy-efficient means of transport, it remains an important contributor to global anthropogenic emissions, based on its sheer scale (Balcombe et al., 2019). Shipping emissions can detrimentally impact the atmospheric concentration levels of several pollutants, mainly carbon dioxide (CO_2), nitrogen oxides (NO_x), sulphur dioxide (SO_2) and particulate matter (PM) (Alver et al., 2018, Monteiro et al., 2018). There has been an increased interest in the adverse societal and environmental effect of atmospheric emissions resulting from the use of fossil fuels by ship engines (Hua et al., 2017, Li et al., 2020, Ampah et al., 2021). This is all in the context of an expected boost in the development and prosperity of marine shipping, with consequent implications for the level of emissions (Al-Enazi et al., 2021).

To address such concerns, the International Maritime Organisation (IMO) has proposed stringent measures to reduce emissions (Abadie et al., 2017, Balcombe et al., 2019). To mitigate sulphur emissions, from 1 January 2020, the sulphur content of maritime fuel was limited to 0.5% in global seas, with the limit of 0.1% being already in operation within the IMO-enforced Emissions Control Areas (ECAs), alongside the imposition of Tier III NO_x limits in several ECAs (Zhao et al., 2021). In terms of decarbonization, the IMO has previously outlined a long-term target to reduce the Green House Gas (GHG) emissions by at least 50% by 2050, relative to emissions in 2008 (Ampah et al., 2021). While there are no existing binding agreements on decarbonization from the IMO, the European Union (EU) has been pushing to introduce more stringent legislation on reducing GHG emissions within its jurisdiction (DNV, 2022a). For instance, the “Fit for 55” package launched in 2021 aims to move the EU maritime sector towards decarbonization, by reducing its GHG emissions by at least 55% until 2030, compared to 1990 levels (Marketa, 2022). In 2020, the EU parliament adopted a resolution to include shipping in Europe's emission trading scheme from 2023, with a target to achieve a 40% reduction in CO_2 emissions by 2030 (DNV, 2022a). Non-compliance with such a scheme is expected to lead to heavy fines, and a possible ban on the ship(s) from EU waters (DNV, 2021a). To meet these long-term goals and agreements, different alternative fuels have been discussed as substitutes for conventional fossil fuels, including Liquified Natural Gas (LNG) (Thomson et al., 2015, Iannaccone et al., 2020), methanol (Ammar, 2019, Helgason et al., 2020), hydrogen (Bicer and Dincer, 2018, McKinlay et al., 2021) and ammonia (Hansson et al., 2020, Kim et al., 2020). To comply with the current IMO sulphur directive, the majority of ships have switched to either low-sulphur fuels (Law et al., 2021), or have installed scrubbers so as to continue using Heavy Fuel Oil (HFO) (Zis et al., 2022). This may be an optimal solution to comply with the existing regulations, although, in the longer-term, with growing concerns about the availability of such fuels and to fulfil the ambitious targets set by the IMO and the EU, there is an expected growth in the use of alternative fuels for ship propulsion (DNV, 2018, Gilbert et al., 2018, Ammar, 2019, Al-Enazi et al., 2021).

In this research, we investigate the cost-effectiveness of the following four alternative marine fuels: LNG, methanol, hydrogen and ammonia. For this study, we assume a "tank-to-wake" scope to examine the economic, as well as the environmental, potential of the considered fuels. For the case of hydrogen and ammonia, it was observed that the emissions during well-to-tank phase are significantly higher than that in tank-to-wake phase (Lindstad et al., 2021). While in the instance of LNG, methanol as well as diesel fuels, the emissions during the well-to-tank phase are comparatively lower than that for tank-to-wake phase (Lindstad et al., 2021). Hence, considering a "low-emission" framework, we assumed that hydrogen and ammonia will be produced from "greener", i.e., renewable, sources, while the sources for LNG and methanol will remain non-renewable. There are three main objectives to be fulfilled to achieve the outlined research aim:

1) To estimate shipping exhaust emissions for the time spent “at-sea” (i.e., cruising) for a particular baseline (year 2019) scenario. To calculate this, we looked at the top 20 most frequently calling ships that visit Irish ports.

2) Given these ships, to analyse and compare the CO_2 reduction potential of LNG, methanol, green hydrogen and green ammonia and their impact on alleviating SO_2, NO_x and $PM_{2.5}$ emissions, as well as the associated external costs and carbon taxes.

3) Based on the estimated capital and operational costs of using alternative fuel technologies alongside the attached external and carbon tax costs, conduct a cost-benefit analysis of the alternative fuels through Net Present Value (NPV) analysis.

The paper is organised as follows: after the introduction in section 5.1, section 5.2 reviews the relevant literature. Section 5.3 describes in detail the methodology to evaluate fuel consumption and emission levels from ships while at-sea, the associated fuel and external costs alongside the paid carbon tax costs. Further, it discusses the methodology employed to conduct the cost-benefit analysis. Section 5.4 indicates the scope of the conducted research, alongside the input data to estimate the required quantities. Section 5.5 contains the obtained results as well as the surrounding discussion, while section 5.6 offers our conclusions on this topic.

5.4. Literature Review

We reviewed studies concerning the four fuels analysed, namely LNG, methanol, hydrogen, and ammonia. For LNG, it was observed that there is an increased interest for its use as a maritime fuel (Brynolf et al., 2014, Schinas and Butler, 2016, Hua et al., 2017).

LNG is composed almost exclusively of methane and has shown particular promise as an alternative fuel, as it offers lower SO_x, NO_x, PM and CO_2 emissions in comparison to distillate fuels (Gilbert et al., 2018, Xu and Yang, 2020). Alongside its emission reduction potential, other advantages of LNG include its higher calorific value than conventional fuels, which significantly reduces operating costs (Li et al., 2020), and also its economic advantage in terms of lower bunker prices (Thomson et al., 2015). LNG is a mature technology, with 121 ships already in operation worldwide and 126 ships on order (Lacey et al., 2019). One of the major disadvantages of using LNG is “methane slip”, which occurs when unburnt methane is released in conjunction with the exhaust gas (Perčić et al., 2020), and this can have a detrimental impact in terms of global warming (Brynolf et al., 2014), while significantly reducing the environmental benefits of using LNG. There has been an increased attention from engine manufacturers to reduce methane leakage, and this issue is expected to be resolved in the near future (Wärtsilä, 2020).

Methanol is another potential alternative fuel for maritime transport (Brynolf et al., 2014, Lagemann et al., 2022). Methanol is obtained from the synthesis of natural gas or biomass, in a methanol synthesis reactor (Brynolf et al., 2014). *Stena Germanica,* which is “world's first methanol-powered ship”, is suggested to have meaningfully reduced its atmospheric SO_x, NO_x, PM and CO_2 emissions (Balcombe et al., 2019). There are currently 12 methanol-fuelled ships operating internationally, with Maersk further announcing 8 container ships which will be running on methanol in the near future (Sahu, 2021). Owing to its lower energy density than conventional fuels, methanol requires more storage space onboard than current fuels (Ellis and Tanneberger, 2015). Also, methanol is a toxic and highly flammable fuel, which may require more extensive monitoring (McKinlay et al., 2021).

Hydrogen is one of the most abundant and lightest elements in the universe (Wang et al., 2021). It is an energy carrier that exists in a gaseous state and is naturally in a carbon-free structure, and this has been one of the main drivers of increased attention from policymakers, researchers, and shipping companies to further explore its potential as an alternative fuel for future marine transport (Inal et al., 2022). Hydrogen can be produced either from a fossil-based (non-renewable) process through natural gas or gasification of coal, or from a green (renewable) approach through electrolysis in combination with renewable electricity (European Commission, 2020b). There have been some developments in relation to hydrogen-powered ships, although at a very smaller scale in terms of energy demand, such as the "Zemship" (small passenger ferry based in Hamburg) or the "Energy Observer" (McKinlay et al., 2021). Low energy density, high flammability range (4%-77% in air) and complex storage requirements are some of the disadvantages associated with the use of hydrogen (McKinlay et al., 2021).

Ammonia is a compound of hydrogen and nitrogen with zero carbon content and has been offered as an alternative for ships (Bilgili, 2021, McKinlay et al., 2021). Like hydrogen, ammonia can also be produced either from a fossil-based source such as natural gas (Haskell, 2021) or using a renewable approach, which involves feeding green hydrogen into the Haber-Bosch process, powered by renewable electricity (The Royal Society, 2020). The advantage of using ammonia over hydrogen is its simple storage requirements, as it can be stored as a liquid at ambient temperature or at ambient pressure with minimal special arrangements (McKinlay et al., 2021). Catalytic converters will need to be retrofitted to alleviate NO_x emissions arising from the combustion of ammonia in an internal combustion engine, although ammonia can be an "emission-free" alternative when used as a carrier of hydrogen in combination with a fuel cell (McKinlay et al., 2021).

Several studies have examined the economic and environmental potential of these alternative fuels within the maritime sector. Ammar (2019) assessed methanol as a fuel for a container ship and found that the use of dual-fuel engines reduced NO_x, SO_x, CO_2 and PM emissions significantly when compared to diesel engines. Despite the environmental benefits of methanol, the economic cost of a similar diesel engine was lower. Ammar (2019) suggested a reduction in ship speed (by 28%) to make the use of methanol more cost-effective and found that the combined benefits from slow steaming and the saved costs from no additional technology usage (i.e., catalytic converters) will help pay back the dual-fuel investment costs within 12 years. Deniz and Zincir (2016) compared the economic and environmental performances of methanol, ethanol, LNG, and hydrogen using the analytic hierarchy process, based on the opinions of five experts within the sector. LNG was found to be the most preferred alternative fuel among all options, though it was acknowledged that hydrogen had significant potential to be the superior alternative. Iannaccone et al. (2020) carried out a sustainability assessment using multi-criteria analysis to compare fuel systems based on LNG with Marine Gasoline Oil (MGO). To support this analysis, key performance indicators were evaluated, for the three domains of economy, environment, and safety of the fuel system. The results found that LNG-based fuel systems had higher performance on the sustainability indicator than MGO, with the scenario of using a low-pressure dual-fuel system offering the most sustainable alternative. Helgason et al. (2020) compared the cost-competitiveness of conventional and renewable methanol with HFO in Iceland. The economic cost of production (fuel costs) and environmental externalities (external costs) were compared for the three fuel types over the period of 2018-2050, according to low, medium, and high scenarios for fuel prices and externalities. Considering the high “external” cost scenario, conventional (natural gas) methanol was found to be the most cost-competitive option. Cariou et al. (2021) analysed the impacts of carbon tax, regulated through EU emission trading scheme, when implemented on 2,513 oil tankers which made around 38,701 voyages within Europe between 2017-2019. This study also estimated the required payback period to offset the invested costs on switching the ships from diesel fuels to low-carbon fuel like LNG, with the benefits attained through saved carbon taxes. It was found that ships operating on intra-European trade routes and having a higher number of voyages are expected to have lower payback periods for switching to new-built LNG systems, as more carbon tax savings could be attained in such an instance. Similar studies focusing on the economic and environmental performances of alternative fuels were conducted by Ellis and Tanneberger (2015), Ammar and Seddiek (2017), Yoo (2017), DNV (2018), Hansson et al. (2020), Kim et al. (2020) and Inal et al. (2022).

Some studies have also conducted a Life-Cycle Assessment (LCA) to analyse the economic and environmental impact of alternative fuels. Brynolf et al. (2014) examined the life-cycle environmental performance of LNG, methanol, liquified biogas and bio-methanol, when applied for the use by a Roll-on/Roll-off (Ro-Ro) cargo ship. According to results, the use of LNG or methanol will considerably improve the overall well-to-tank and tank-to-wake environmental performance when compared to conventional marine fuels. Hwang et al. (2020) compared the life-cycle environmental performances of MGO, LNG and hydrogen (produced from natural gas/nuclear energy/renewable electricity/current South Korean electricity mix), for the case of coastal ferry operating in the Korean region. Hydrogen produced from nuclear and renewable energy had the lowest life-cycle emissions. Also, when comparing the tank-to-wake phase, the use of MGO and LNG was deemed “unfit” to meet the IMO-2050 targets. Perčić et al. (2020) conducted a LCA of electricity, methanol, hydrogen, LNG, dimethyl ether and biofuel, using the case of different Croatian passenger and Ro-Ro cargo ships. Electricity (i.e., battery) powered ships were found to have lowest life-cycle emissions in this analysis. This study also conducted a Life-Cycle Cost

Assessment (LCCA), where battery-powered ships remained the most economical solution to implement, owing to lower life-cycle costs (by 56%) than that of diesel-powered ships. Perčić et al. (2021) also conducted LCA and LCCA for similar fuels as in Perčić et al. (2020), although applied it to different ship types namely passenger, container and dredger. While battery remained the most environmentally friendly option, the most cost-effective option varied for each ship type. Alongside the investment and operational costs, the studies of Perčić et al. (2020) and Perčić et al. (2021) also included the carbon emission costs in their LCCA analysis. Lagemann et al. (2022) also conducted LCA and LCCA analysis for alternative fuels, while including the carbon tax costs. For a lower-bound fuel price and carbon tax scenario, bio-fuels were found to be more cost-effective than electro-fuels. Perčić et al. (2022) conducted LCA and LCCA analysis for the use of hydrogen and ammonia fuels (produced from varied sources) in combination with fuel cells, using the case of three passenger ships. The results showed that green hydrogen had the lowest life-cycle CO_2 emissions, although, it was also the least cost-effective option. Lindstad et al. (2021) performed LCA and LCCA analysis, comparing the conventional diesel fuels with that of alternative fuels. Fossil-based (i.e. grey) hydrogen had the highest life-cycle CO_2 output, with green hydrogen having the lowest. Switching to green hydrogen or green ammonia is shown to be cheaper to use than the other hydrocarbon-based renewable fuels such as E-LNG or E-methanol. Similar studies on LCA (and/or LCCA) were conducted by Thomson et al. (2015), Hua et al. (2017), Bicer and Dincer (2018), Gilbert et al. (2018), Balcombe et al. (2021) and Law et al. (2021).

Although there has been increased attention from the researchers on the topic of alternative fuels, it was observed that except for Helgason et al. (2020), there have not been many studies to date which evaluated the environmental potential alongside the cost-effectiveness of different solutions while also including the associated external costs. External costs indicate the monetary damages inflicted by ship exhaust emissions on the population residing near the port and the surrounding environment (Tichavska and Tovar, 2017). “If emissions from maritime applications are not seen as costs within feasibility studies and their accounting is omitted from regulatory frameworks, there is little incentive for maritime firms to mitigate environmental externalities by investing in alternative energy systems” (Helgason et al., 2020, p.1). While Helgason et al. (2020) compared the economic fuel costs for methanol and HFO, little information was provided on the possible investment costs for implementing such an alternative. To address this gap in the literature and to assist the policymakers with the identification of suitable alternative fuel(s) from the investment perspective, this research conducts a cost-benefit analysis of using LNG, methanol, green hydrogen, and green ammonia fuels, considering a “tank-to-wake” scope, incorporating the attached external costs as well as the applied carbon tax costs. Further, we also compare the decarbonization impacts of the outlined alternative fuels, to help understand their potential in meeting the IMO-2050 and EU-2030 targets.

5.5. Methodology – Analytical Equations

5.5.1. Fuel Consumption and Boil Off Gas

To evaluate and compare the performances of alternative fuels against a baseline (year 2019) scenario, four different scenarios were developed, where the ships switched to LNG (scenario A), Methanol (scenario B), Green hydrogen (scenario C) and Green ammonia (scenario D). Of the considered alternative fuels, methanol has the highest boiling point of 65°C, which means its storage in liquid form at ambient temperatures is simpler when compared to other fuels (McKinlay et al., 2021). LNG is a natural gas which is cooled down to a cryogenic temperature of –153°C at atmospheric pressure, to be stored in a liquified form in the onboard storage tanks (Nerheim et al., 2021). Hydrogen and ammonia fuels can be stored either in liquified form at the temperatures of –253°C and −33°C, respectively, or in a compressed form by applying a pressure of 700 bar and 10 bar, respectively (Lindstad et al., 2021, McKinlay et al., 2021). Although it has been found that storing compressed hydrogen and ammonia in highly pressurised storage tanks has lesser energy requirements, the potential capital costs of installing such system exceeds the requirements for using a liquid storage system (ABS, 2020, Lindstad et al., 2021). Also, it was found that storage space required for installing pressurised tanks is comparatively higher than that for using liquid tanks (McKinlay et al., 2021). Based on these factors, in this paper we assume hydrogen and ammonia fuels are stored in liquified form.

In a baseline scenario with all ships using marine fuels, the total fuel consumed by ships while at sea can be calculated through the following Eq. (1), as given in Kim et al. (2020):

$$FT^{Base} = \sum_{bf} T \times \left[\left(ME \times LF_{ME} \times SFC_{ME}^{bf}\right) + \left(AE \times LF_{AE} \times SFC_{AE}^{bf}\right)\right] \times 10^{-6} \tag{1}$$

Where FT^{Base} is the total fuel consumed by ships while at-sea for the baseline scenario, annually (tonnes), bf refers to the baseline fuels, T indicates the total time spent by each ship while at-sea in 2019 (hours), ME and AE are main engine power and auxiliary engine power (kW), respectively, LF_{ME} and LF_{AE} are the load factors of main and auxiliary engines (%), respectively, while SFC_{ME}^{bf} and SFC_{AE}^{bf} represent the specific fuel consumption for the main engine and auxiliary engine, respectively, based on the considered baseline fuels (g/kWh).

For scenario A (LNG) and scenario B (methanol), it was assumed that dual-fuel diesel engines will replace the existing marine engines. These systems require a small amount of pilot, i.e. diesel fuel, to initiate the combustion of the main fuel (Perčić et al., 2021). Here, we have assumed the pilot fuel to be MGO, with the main fuel being LNG (scenario A) and methanol (scenario B), respectively. For green hydrogen (scenario C) and green ammonia (scenario D), in this paper, the use of Proton Exchange Membrane (PEM) fuel-cell technology was considered for ship propulsion (Perčić et al., 2021). PEM fuel-cell has been referred to as an efficient method for extracting energy from hydrogen, since it allows direct conversion of the fuel's chemical energy into electric energy via electrochemical reactions, with its only by-product being water (McKinlay et al., 2021, Perčić et al., 2021). Ammonia, owing to its relatively simple storage and large hydrogen content, has been viewed instead as a carrier of hydrogen (McKinlay et al., 2021). The advantage of using ammonia with fuel-cell technology is that it will mitigate the release of NO_x, as otherwise it would have required additional installation of post-combustion devices such as catalytic converters in the conventional engine system, further increasing costs (McKinlay et al., 2021).

For scenarios A and B, the fuel consumption for the employed dual-fuel system has to be calculated in two parts: for main fuel (LNG and methanol) and the pilot fuel (MGO). The total fuel consumption for LNG and methanol powered ships can be calculated using the following Eq. (2) and Eq. (3), as given in Perčić et al. (2021):

$$FT_{mf}^{A,B} = \sum x_{mf}^{A,B} \times T \times \left[P_{DF} \times LF_{DF} \times SFC_{mf}^{A,B} \right] \times 10^{-6} \tag{2}$$

$$FT_{pf}^{A,B} = \sum x_{pf}^{A,B} \times T \times \left[P_{DF} \times LF_{DF} \times SFC_{pf}^{A,B} \right] \times 10^{-6} \tag{3}$$

Where $FT_{mf}^{A,B}$ and $FT_{pf}^{A,B}$ refers to the total main fuel and pilot fuel consumed, for the respective scenarios of A and B, annually (tonnes), mf and pf indicate the considered main fuels (LNG and methanol) and pilot fuel (MGO), respectively, $x_{mf}^{A,B}$ and $x_{pf}^{A,B}$ represent the proportions of the main fuel and pilot fuel in the dual-fuel engine, respectively, for the considered scenarios of A and B (in %), T indicates the total time spent by each ship while at-sea in 2019 (hours), P_{DF} represents the power output of the dual-fuel engine (kW), LF_{DF}

is the load factor for the dual-fuel engine (%) while $SFC_{mf}^{A,B}$ and $SFC_{pf}^{A,B}$ indicates the specific fuel consumption for main fuel and pilot fuel in the dual-fuel engine, respectively, for the considered scenarios of A and B (g/kWh).

To estimate the green hydrogen consumption by the employed PEM fuel cells in scenario C, the following Eq. (4) has been utilised, as given in Perčić et al. (2021):

$$FT_{hf}^{C} = \sum[(T \times P_{CL} \times L_{CL})/(\eta_{CL} \times NCV_{hf}^{C})] \times 10^{-3} \tag{4}$$

Where FT_{hf}^{C} refers to the total green hydrogen fuel hf consumed in scenario C, annually (tonnes), T indicates the total time spent by each ship while at-sea in 2019 (hours), P_{CL} represents the power output of fuel cell (kW), L_{CL} is the load factor of the fuel cell (%), η_{CL} is the efficiency of the fuel cell (%) and NCV_{hf}^{C} is the net calorific value for the consumed green hydrogen fuel (kWh/kg).

For this study, we have considered ammonia as a carrier of hydrogen. Here, ammonia is processed through a "cracker", which decomposes it into hydrogen and nitrogen, and then it is passed through a "purifier" so that only purified hydrogen enters the fuel cell (Perčić et al., 2021). To examine the total green ammonia consumption in scenario D, the following Eq. (5) has been used, as given in Perčić et al. (2021):

$$FT_{af}^{D} = \sum[(T \times P_{CL} \times L_{CL})/(\eta_{CL} \times \eta_{CR} \times \eta_{PR} \times NCV_{af}^{D})] \times 10^{-3} \tag{5}$$

Where FT_{af}^{D} refers to the total green ammonia fuel af consumed in scenario D, annually (tonnes), T indicates the total time spent by each ship while at-sea in 2019 (hours), P_{CL} represents the power output of fuel cell (kW), L_{CL} is the load factor of the fuel cell (%), η_{CL} is the efficiency of the fuel cell (%), η_{CR} is the efficiency of cracker (%), η_{PR} is the efficiency of purifier (%) and NCV_{af}^{D} is the net calorific value for the consumed green ammonia fuel (kWh/kg).

Also, it has to be considered that when storing such liquified alternative fuels onboard, especially at lower temperatures, a small amount of heat-in-leak is inevitable (McKinlay et al., 2021, Smith et al., 2022). After a prolonged period of time, a small portion of the stored liquid will unavoidably heat up and reach its boiling point, leading to the formation of a gas, known as Boil Off Gas (BOG) (Al-Breiki and Bicer, 2020, McKinlay et al., 2021). It is possible to re-liquify the BOG and use it for ship propulsion, although, this process will demand additional storage space and the installation costs of suitable re-liquification system (McKinlay et al., 2021). The easiest method to avoid such re-liquification costs is to dispose of BOG directly into the atmosphere, as the release of BOG tends to be unharmful for the environment (DEMACO, 2022). Hence, in this paper, no additional re-liquification system costs have been considered, assuming that BOG will disposed into atmosphere. However, when considering the total fuel demand for a ship, we also have to include the fuel lost from naturally generated BOG from the storage of liquid alternative fuels, alongside the actual fuel consumption, as displayed in Eq. (6):

$$FD^{A,B,C,D} = ((FT_{mf}^{A,B} + FBOG_{mf}^{A,B}) + FT_{pf}^{A,B}) + (FT_{hf}^{C} + FBOG_{hf}^{C}) + (FT_{af}^{D} + FBOG_{af}^{D})$$

(6)

Where $FD^{A,B,C,D}$ refers to the total fuel demand arising from shipping activities, for the discussed alternative fuel scenarios, annually (tonnes), $FT_{mf}^{A,B}$ and $FT_{pf}^{A,B}$ indicate the total main fuel and pilot fuel consumed, for the respective scenarios of A and B, annually (tonnes), $FBOG_{mf}^{A,B}$ is the total main fuel lost as BOG for the respective scenarios of A and B, annually (tonnes), FT_{hf}^{C} and FT_{af}^{D} indicate the annual green hydrogen fuel and green ammonia fuel consumption in scenario C and D, respectively (tonnes) while $FBOG_{hf}^{C}$ and $FBOG_{af}^{D}$ represent the annual green hydrogen fuel and green ammonia fuel lost as BOG in scenario C and D, respectively (tonnes).

The total fuel lost in the form of BOG for scenarios A and B can be calculated using the following Eq. (7), as given in Kim et al. (2020):

$$FBOG_{mf}^{A,B} = (b_{mf}^{A,B} \times 365/100) \times FT_{mf}^{A,B} \tag{7}$$

Where $FBOG_{mf}^{A,B}$ indicates the stored main fuel mf which evaporated as BOG (annually) in scenarios A and B (tonnes), $b_{mf}^{A,B}$ is the boil off rate of the main fuel in scenarios A and B (%/day) and $FT_{mf}^{A,B}$ refers to the total main fuel consumed, for the respective scenarios of A and B, annually (tonnes).

The total fuel lost in the form of BOG for scenarios C and D can be calculated using the following Eq. (8) and Eq. (9), as given in Kim et al. (2020):

$$FBOG_{hf}^{C} = (b_{hf}^{C} \times 365/100) \times FT_{hf}^{C} \tag{8}$$

$$FBOG_{af}^{D} = (b_{af}^{D} \times 365/100) \times FT_{af}^{D} \tag{9}$$

Where $FBOG_{hf}^{C}$ and $FBOG_{af}^{D}$ indicate the stored green hydrogen fuel hf and green ammonia fuel af which evaporated as BOG (annually) in scenarios C and D, respectively (tonnes), b_{hf}^{C} and b_{af}^{D} is the boil off rate for green hydrogen fuel and green ammonia fuel, in scenarios C and D, respectively (%/day) while FT_{hf}^{C} and FT_{af}^{D} refer to the total green hydrogen fuel and green ammonia fuel consumed, for the respective scenarios of C and D, annually (tonnes).

5.5.2 Shipping Emissions

For estimating shipping emissions, the activity-based methodology has been utilised. The activity-based methodology has been adopted due to its accuracy when compared to the fuel-based method, as it is built on more detailed data (Song, 2014, Song and Shon, 2014), and also, is a relatively popular approach (Goldsworthy and Goldsworthy, 2015, Nunes et al., 2017a, Dragović et al., 2018). For the baseline scenario, CO_2, SO_2, NO_x and $PM_{2.5}$ emissions from ships have been examined using the following Eq. (10), as given in Whall et al. (2010):

$$E^{Base} = \sum_i T \times \left[\left(ME \times LF_{ME} \times EF_{ME}^{i}\right) + \left(AE \times LF_{AE} \times EF_{AE}^{i}\right)\right] \times 10^{-6} \qquad (10)$$

Where E^{Base} represents annual baseline emissions (tonnes), i refers to the pollutants: CO_2, SO_2, NO_x and $PM_{2.5}$, T indicates the total time spent by each ship while at-sea in 2019 (hours), ME and AE are main engine power and auxiliary engine power (kW), respectively, LF_{ME} and LF_{AE} are the load factors of the main and auxiliary engines (%), respectively, EF_{ME}^{i} and EF_{AE}^{i} are the emission factors assigned to main and auxiliary engines for each of the emitted pollutants (g/kWh), respectively.

Emissions from the use of dual-fuel engines for LNG and methanol can be calculated using the following Eq. (11), as given in Ammar (2019):

$$E^{A,B} = \sum_i T \times \left[\, P_{DF} \times LF_{DF} \times \; EF_{i}^{A,B} \,\right] \times 10^{-6} \qquad (11)$$

Where E^{A} and E^{B} represents emissions from the use of LNG and methanol in scenarios A and B, respectively (tonnes), i refers to the pollutants: CO_2, SO_2, NO_x and $PM_{2.5}$, T indicates the total time spent by each ship while at-sea in 2019 (hours), P_{DF} represents the power output of the dual-fuel engine (kW), LF_{DF} is the load factor for the dual-fuel engine (%) and $EF_i^{A,B}$ indicates the emission factors for the considered pollutants, based on the application of dual-fuel engine for each specific scenario (g/kWh).

Emissions from the application of PEM fuel cells, for the use of green hydrogen, were calculated using the following Eq. (12). This method was developed using the appropriate information as given in Perčić et al. (2021), where we have replaced net calorific value (NCV_{hf}^{C}) with that of emission factor (EF_i^{C}):

$$E^C = \sum_i [(T \times P_{CL} \times L_{CL})/\eta_{CL}] \times EF_i^C \times 10^{-6} \tag{12}$$

Where E^C represents emissions from the use of green hydrogen in scenario C (tonnes), i refers to the pollutants: CO_2, SO_2, NO_x and $PM_{2.5}$, T indicates the total time spent by each ship while at-sea in 2019 (hours), P_{CL} represents the power output of fuel cell (kW), L_{CL} is the load factor of the fuel cell (%), η_{CL} is the efficiency of the fuel cell (%) and EF_i^C indicates the emission factors for the considered pollutants, based on the application of green hydrogen to the fuel cell system in scenario C (g/kWh).

For this study, we have considered ammonia as a carrier of hydrogen. Emissions from the application of PEM fuel cells, for the use of green ammonia, will be calculated using the following Eq. (13). This method was developed using the appropriate information as given in Perčić et al. (2021), where we have replaced net calorific value (NCV_{af}^{D}) with that of emission factor (EF_i^{D}):

$$E^D = \sum_i [(T \times P_{CL} \times L_{CL})/(\eta_{CL} \times \eta_{CR} \times \eta_{PR})] \times EF_i^D \times 10^{-6} \tag{13}$$

Where E^D represents emissions from the use of green ammonia in scenario D (tonnes), i refers to the pollutants: CO_2, SO_2, NO_x and $PM_{2.5}$, T indicates the total time spent by each ship while at-sea in 2019 (hours), P_{CL} represents the power output of the fuel cell (kW), L_{CL}

is the load factor of the fuel cell (%), η_{CL} is the efficiency of the fuel cell (%), η_{CR} is the efficiency of cracker (%), η_{PR} is the efficiency of purifier (%) and EF_i^D indicates the emission factors for the application of green ammonia as the ship fuel in scenario D (g/kWh).

5.5.3 Fuel Costs

On the basis of estimated fuel consumption, the annual fuel costs for the baseline scenario can be estimated using the following Eq. (14):

$$FC^{Base} = FT_{bf}^{Base} \times FP_{bf} \tag{14}$$

Where FC^{Base} indicates the annual fuel costs for the baseline scenario (€), bf refers to the considered baseline fuels, FT_{bf}^{Base} represents the total fuel consumed by ships in the baseline scenario, for each of the considered baseline fuel bf, annually (tonnes) and FP_{bf} is the fuel price for each baseline fuel (€/ton).

For the considered scenarios of A (LNG) and B (methanol) which employ dual-fuel system, the annual fuel costs can be calculated using the following Eq. (15):

$$FC^{A,B} = (FT_{mf}^{A,B} + FBOG_{mf}^{A,B}) \times FP_{mf} + FT_{pf}^{A,B} \times FP_{pf} \tag{15}$$

Where $FC^{A,B}$ represents the annual fuel costs for the respective scenarios of A and B (€), $FT_{mf}^{A,B}$ and $FT_{pf}^{A,B}$ refers to the main fuel mf and pilot fuel pf consumed for the respective scenarios of A and B, annually (tonnes), $FBOG_{mf}^{A,B}$ refers to the stored main fuel which evaporated in the form of BOG, for scenarios A and B, annually (tonnes) while FP_{mf} and FP_{pf} is the fuel price for the main fuel and pilot fuel (€/ton), respectively.

For the scenarios C (green hydrogen) and D (green ammonia), the annual fuel costs can be calculated using the following Eq. (16) and Eq. (17):

$$FC^{C} = (FT_{hf}^{C} + FBOG_{hf}^{C}) \times FP_{hf} \tag{16}$$

$$FC^{D} = (FT_{af}^{D} + FBOG_{af}^{D}) \times FP_{af} \tag{17}$$

Where FC^{C} and FC^{D} indicate the annual fuel costs for the scenarios C and D (€), FT_{hf}^{C} and FT_{af}^{D} represent the total green hydrogen fuel and green ammonia fuel consumed by ships (annually) in the scenarios C and D (tonnes), respectively, $FBOG_{hf}^{C}$ and $FBOG_{af}^{D}$ refers to the stored green hydrogen fuel and green ammonia fuel which evaporated in the form of BOG, for the respective scenarios C and D, annually (tonnes) and FP_{hf} and FP_{af} is the price for the green hydrogen fuel and green ammonia fuel (€/ton), respectively.

5.5.4 External Costs and Carbon Tax

Following established research on external cost assessment using the top-down approach (Song, 2014, Dragović et al., 2018, Nunes et al., 2019), a similar methodology was also adopted in this research.

The external costs of the shipping emissions for the baseline scenario were estimated using the following Eq. (18), as given in Nunes et al. (2019):

$$EC^{Base} = \sum_{i} E_{i}^{Base} \times ECF_{i} \tag{18}$$

Where EC^{Base} indicates the total external costs for the baseline scenario (€), i refers to the pollutants: CO_2, SO_2, NO_x and $PM_{2.5}$, E_{i}^{Base} represents the baseline emissions for each pollutant (tonnes) and ECF_{i} is the external cost factor for each pollutant (€/ton).

The annual saved external costs with different scenarios of utilising alternative fuels can be calculated by following Eq. (19):

$$\Delta\, EC^{A,B,C,D} = EC^{Base} - EC^{A,B,C,D} \tag{19}$$

Where $\Delta\, EC^{A,B,C,D}$ represents the saved external costs for each scenario (€), EC^{Base} indicates the total external costs for the baseline scenario (€) while $EC^{A,B,C,D}$ represents the total external costs for the use of different alternative fuels under the considered scenarios (€). External costs for the different scenarios of alternative fuel usage are calculated using the following Eq. (20), as given in Nunes et al. (2019):

$$EC^{A,B,C,D} = \sum_i E_i^{A,B,C,D} \times ECF_i \tag{20}$$

Where $EC^{A,B,C,D}$ represents the external costs for each scenario (€), i refers to the pollutants: CO_2, SO_2, NO_x and $PM_{2.5}$, $E_i^{A,B,C,D}$ indicates the total shipping emissions for each pollutant, under each scenario of alternative fuel usage (tonnes) while ECF_i is the external cost factor for each pollutant (€/ton).

The total carbon tax to be paid by shipowners while using baseline fuels can be estimated using the following Eq. (21):

$$CT^{Base} = E_i^{Base} \times CTR \tag{21}$$

Where CT^{Base} indicates the total carbon taxes applicable for the baseline scenario (€), E_i^{Base} represents the baseline emissions for the pollutant i, which is CO_2 (tonnes) and CTR is the considered tax rate for each ton of emitted CO_2 (€/ton).

The annual saved carbon taxes with different scenarios of utilising alternative fuels can be calculated by following Eq. (22):

$$\Delta\, CT^{A,B,C,D} = CT^{Base} - CT^{A,B,C,D} \tag{22}$$

Where $\Delta\, CT^{A,B,C,D}$ represents the avoided carbon taxes with the employment of each alternative fuel scenario (€), CT^{Base} indicates the total carbon taxes payable for the baseline scenario (€) while $CT^{A,B,C,D}$ represents the total carbon taxes payable for the use of different alternative fuels under the considered scenarios (€). Carbon taxes for the different scenarios of alternative fuel usage are calculated using the following Eq. (23):

$$CT^{A,B,C,D} = E_i^{A,B,C,D} \times CTR \tag{23}$$

Where $CT^{A,B,C,D}$ represents the paid carbon taxes under each scenario (€), i refers to the pollutant: CO_2, $E_i^{A,B,C,D}$ indicates the total CO_2 emissions, under each scenario of alternative fuel usage (tonnes) while CTR is the considered tax rate for each ton of emitted CO_2 (€/ton).

5.5.5. Cost-benefit Analysis of Alternative Low-to-Zero Carbon fuels

To perform a cost-benefit evaluation of the considered scenarios of alternative fuel usage, NPV analysis was conducted, as indicated in Eq. (24). This method was developed using the approach given in Jiang et al. (2014), where alongside the saved external costs, we have also added the benefits attained from saved carbon taxes ($\Delta\, CT^{A,B,C,D}$) and avoided baseline fuel costs (FC^{Base}):

$$NPV^{A,B,C,D} = -\,CAPEX^{A,B,C,D} + \sum_{t=1}^{n} \left((\Delta\, EC^{A,B,C,D} + \Delta\, CT^{A,B,C,D} + FC^{Base}) - (OPEX^{A,B,C,D}) \right) / (1+r)^t \tag{24}$$

Where $NPV^{A,B,C,D}$ indicates the net present value for the different scenarios of using alternative fuel systems (€), $CAPEX^{A,B,C,D}$ is the capital costs for the installation of respective alternative fuel systems (€), n is the duration of the installed alternative fuel systems (years), $\Delta\, EC^{A,B,C,D}$ refers to the saved external costs for the use of alternative fuel systems under different scenarios (€), $\Delta\, CT^{A,B,C,D}$ represents the saved carbon taxes with the employment of each alternative fuel scenario (€), FC^{Base} indicates the total baseline fuel costs, i.e. fuel benefits achieved from switching to alternative fuels (€), $OPEX^{A,B,C,D}$ represents the operational costs of alternative fuel systems in different scenarios, which includes the total fuel and maintenance costs as well as the lost fuel costs from the evaporated BOG (€), r is the discount rate and t represents time periods.

5.6. Application

5.6.1. Research scope

Being an island nation, international shipping has been at the foundation of Ireland's economic progress, as it provides indispensable connectivity to the EU as well as non-EU markets (Irish Maritime Development Office [IMDO], 2020). The commercial traffic moving through Irish ports has been at a steady rise post the 2008 global financial crisis (IMDO, 2020). Ireland has been one of the most popular destinations for Ro-Ro ferry arrivals, as they accounted for approximately 32% of the total tonnage of goods handled in 2019, which was the highest in the EU (Eurostat, 2021). Irish ports welcomed nearly 4.2 million passengers in 2019, providing a significant boost to its tourism sector (IMDO, 2020). Albeit shipping has been at the forefront of Ireland's economic growth, its attached emissions has impacted the local population negatively, as Ireland occupied 6th position globally in 2015 when it comes to number of premature deaths due to shipping emissions (per 100,000 population) (Rutherford and Miller, 2019). This higher death rate could be attributed to the fact that nearly 40% of the total population resides within 5 km of the coastline, especially in the major port cities of Dublin, Belfast, Cork and Limerick (CSO, 2022a). Owing to its maritime dependency and vulnerability to the attached emissions, Ireland was identified as the base case for our research. The island of Ireland has been divided into two separate jurisdictions: the Republic of Ireland and the Northern Ireland.

There are a total of 24 ports on the island, with 18 being in the Republic and the remaining 6 in Northern Ireland. For the considered 24 ports, we obtained information on all the ship calls being made by the passenger, bulker, container, Ro-Ro cargo, tanker and general cargo ships through Refinitiv Eikon (2022a) Automatic Identification System (AIS) dataset. The year under consideration for this study was 2019. According to AIS, 1,594 ships visited Irish ports during 2019, registering 20,720 ship calls. Of the total calls, approximately 50% (10,528) calls were made by 14 passenger and 6 Ro-Ro cargo ships. These 20 ships mainly operate on the increasingly popular Irish-British and Irish-French routes. Owing to their increased significance within the Irish maritime sector, we assessed the economic and environmental potential of the use of alternative fuel technologies by these 20 ships. The main particulars of the selected 20 ships were obtained from Refinitiv Eikon (2022a), as presented in Table 5.1.

Table 5.1. Particulars of the selected 20 ships

Ship Name	Capacity		Engine power (kW)		Speed (kn[c])	Route
	Vehicle	Passenger	ME[a]	AE[b]		
European Causeway	375	410	31,680	1,800	22.6	Larne-Cairnryan
European Highlander	375	410	31,680	1,800	22.6	Larne-Cairnryan
Stena Superfast VIII	100	604	46,000	7,820	27	Belfast-Cairnryan
Stena Superfast VII	192	604	57,425	9,762	27	Belfast-Cairnryan
Stena Adventurer	500	1,500	25,920	2,074	22	Dublin-Holyhead
A Nepita	770	1,200	46,080	7,834	27.1	Dublin-Holyhead
Ulysses	1,342	1,948	42,416	1,520	22	Dublin-Holyhead
Epsilon	150	920	21,600	3,672	23.5	Dublin-Cherbourg
Isle of Inishmore	855	2,200	32,628	5,547	21.5	Rosslare-Pembroke
Stena Nordica	375	405	53,836	11,880	25.1	Rosslare-Cherbourg

W.B. Yeats	1,220	1,750	35,169	5,979	22	Dublin-Cherbourg
Stena Lagan	186	950	26,555	4,514	26	Belfast-Birkenhead
Seatruck Power	150	12	16,000	840	21	Dublin-Liverpool
Stena Mersey	186	950	26,555	4,514	26	Belfast-Birkenhead
Seatruck Panorama	120	12	18,480	645	22	Dublin-Heysham
Seatruck Progress	150	12	16,000	840	21	Dublin-Liverpool
Norbay	281	114	33,312	5,760	22	Dublin-Liverpool
Stena Scotia	120	12	15,680	700	17.6	Belfast-Heysham
Stena Hibernia	120	12	15,680	700	17.6	Belfast-Heysham
Seatruck Pace	120	12	18,500	645	22	Dublin-Liverpool

[a] – Main Engine, [b] – Auxiliary Engine, [c] – Knots

Source: Refinitiv Eikon (2022a)

5.6.2. Input data: fuel consumption and boil off gas

For baseline as well as alternative fuel scenarios, the data in relation to time spent at-sea (in 2019) for the considered 20 ships was obtained from the EU-MRV (2019) database. Information on ME and AE power for the concerned vessels was retrieved from the Refinitiv Eikon (2022a) AIS dataset. For three ships, namely “Stena Lagan”, “Stena

Mersey” and “W.B. Yeats”, engine powers were not available. For these ships, the installed ME power was obtained as a function of gross tonnage, using the non-linear regression procedure of the 2010 world fleet analysed in Trozzi et al. (2019). Then, based on the available AE power data for the remaining 17 ships, a fraction of installed AE to ME power (%) was determined and utilised to obtain the missing auxiliary engine powers.

In the baseline scenario, load factor was assumed to be 80% (for ME) and 30% (for AE) (Whall et al., 2010). The specific fuel consumption (SFC) values for ME and AE were derived based on the considered engine and fuel types, for which several assumptions were made, as follows:

1) In baseline, ships were assumed to use namely three fuel types: i) HFO (i.e., Residual Oil (RO)) ii) Marine Distillate Oil (MDO) and iii) MGO. Fuel types used by each individual ship was assigned according to ship types (passenger or Ro-Ro cargo), based on the information provided by Whall et al. (2010).

2) For ships operating between Dublin/Rosslare and Cherbourg, MGO was assumed to be the primary fuel type for the entire journey, as these ships have to traverse through the English-channel ECA.

3) In terms of the employed engine profiles, Medium Speed Diesel (MSD) was assumed as the main engine type for all the ships, based on the given ship engine configuration in Whall et al. (2010). For auxiliary engine, an assumption was made that all vessel types had medium speed or high speed diesel engines without distinction (M/H SD) (Whall et al., 2010).

4) Based on the given engine and fuel types, main engine SFC was considered to be 213 g/kWh (for MSD/RO) and 203 g/kWh (for MSD/MDO and MSD/MGO), while auxiliary

engine SFC was 227 g/kWh (for M/H SD/RO) and 217 g/kWh (for M/H SD/MDO and M/H SD/MGO) (Whall et al., 2010).

For scenarios A and B, a dual-fuel engine type was considered, where a set proportion of main fuel type (LNG or methanol) and pilot fuel type (MGO) is used for the purpose of ship propulsion. The proportion of main fuel and pilot fuel for scenario A (LNG) was considered to be 99% and 1%, respectively (Perčić et al., 2021), while that for scenario B (methanol), the proportion of main fuel and pilot fuel was 89% and 11%, respectively (Ammar, 2019). To assign dual-fuel engine power, load factor and specific fuel consumption values, the following assumptions were made:

1) For comparative purposes, in this study, we have assumed that the total power output of the dual-fuel engine will be equivalent to that of the combined ME and AE conventional powers of the ships.

2) The load factor for the considered dual-fuel engine system was assumed to be 75% (Perčić et al., 2021).

3) The SFC for scenarios A and B were assigned based on the proportion of main and pilot fuels in dual-fuel system. Hence, for scenario A, the SFC for LNG and MGO stood at 148.5 g/kWh and 1.7 g/kWh, respectively, while for scenario B, the SFC for methanol and MGO stood at 339.09 g/kWh and 18.7 g/kWh, respectively (Gilbert et al., 2018).

To obtain annual fuel consumption for scenarios C and D, the following assumptions were made:

1) Similar to the dual-fuel engines, we considered that the power output of the fuel cell in scenario C (green hydrogen) and scenario D (green ammonia) will be equivalent to that of combined ME and AE powers of the ships (Perčić et al., 2021).

2) As the optimal load range of a conventional engine, genset or fuel cell lies between 70-85% (Kim et al., 2020), we assumed the load factor of the fuel cell to be the same as a dual-fuel engine (75%), to maintain linearity of the obtained results.

3) The fuel cell efficiency of 48% was assumed for this study (Perčić et al., 2021). For scenario D, the efficiencies of the cracker and purifier were assumed to be 80% and 90%, respectively as per Perčić et al. (2021).

4) The net calorific values for green hydrogen and green ammonia were assumed as 33.3 kWh/kg and 5.17 kWh/kg, respectively (Perčić et al., 2021).

For estimating the total liquid alternative fuel lost as BOG, the boil off rates were assumed as 0.12%/day for LNG (scenario A), 0.002%/day for methanol (scenario B), 1.063%/day for green hydrogen (scenario C) and 0.04%/day for green ammonia (scenario D) (Al-Breiki and Bicer, 2020, Kim et al., 2020, Smith et al., 2022).

5.6.3. Input data: shipping emissions

To estimate shipping emissions under baseline and alternative fuel scenarios, data in relation to time spent at-sea, ship engine power, load factor, fuel cell efficiency (for scenario C and D) and cracker and purifier efficiency (for scenario D) as discussed in section 5.1 and section 5.2 have been utilised, while the obtained emission factors are shown in Table 5.2.

Table 5.2. Emission factors (g/kWh) for baseline and alternative fuel scenarios

Pollutants	CO_2	NO_x	SO_2	$PM_{2.5}$
Scenario				
Baseline (MSD/RO)	11.24	14	677.91	1.32
Baseline (M/H SD/RO)	11.98	14.7	722.54	1.32
Baseline (MSD/MDO)	3.97	13.2	646.08	0.43
Baseline (M/H SD/MDO)	4.24	13.9	690.71	0.45
Baseline (MSD/MGO)	0.4	13.2	646.08	0.17
Baseline (M/H SD/MGO)	0.42	13.9	690.71	0.17
A (LNG)	412	1.17	0.003	0.027
B (Methanol)	563.70	3.792	0.039	0.021
C (Green Hydrogen)	0	0	0	0
D (Green Ammonia)	0	0	0	0

Source: Inner City Fund (2009), Gilbert et al. (2018), Ammar (2019), Perčić et al. (2021)

5.6.4. Input data: fuel costs

For the baseline scenario, fuel prices for RO (classified as Intermediate Fuel Oil 380), MDO (classified as MGO (1.5%)) and MGO (classified as Low-sulphur Marine Gasoline Oil (0.1% sulphur)) were obtained from Shipandbunker (2022), based on the average Rotterdam bunker prices over the period "26 April 2019 – 1 January 2020". The prices listed in $/ton were converted to €/ton using 2019 USD to EURO average conversion rates by European Central Bank (2022), over a similar period. The considered fuel prices for RO, MDO and MGO were €310.1/ton, €536.4/ton and €533.6/ton, respectively.

For scenario A, the fuel price of LNG was obtained as €222.7/ton, based on the average (year 2019) "Dutch title transfer facility gas prices" given in the Refinitiv Eikon (2022b) database. As the gas price was listed in $/MMBtu, it was converted into €/ton based on the given average currency conversion rate (USD to EURO) in 2019 (European Central Bank, 2022) and the unit conversion rate (S&P Global Platts, 2021). The fuel price of methanol for scenario B was obtained as €318.3/ton, considering an average "Methanex European" price in 2019 (Methanex, 2021). In both scenarios A and B, the fuel price for MGO was taken to be €533.6/ton (Shipandbunker, 2022).

For scenario C, the fuel price of green hydrogen fuel was obtained as €4000/ton, based on the "median EU green hydrogen price" given in European Commission (2020b). For scenario D, the fuel price of green ammonia fuel was considered to be €1,069/ton (Argus, 2021). As the price was listed in $/ton, it was converted to €/ton using the year 2019 "average" USD to EURO currency conversion rate by European Central Bank (2022).

5.6.5. Input data: External costs and carbon tax

To estimate the external costs for each of the baseline and alternative fuel scenario, external cost factors for NO_x, SO_2 and $PM_{2.5}$ as given in the New Energy Externalities Development for Sustainability (NEEDS) report with specific reference to Ireland have been utilised in this research. The NEEDS project is seen to be the most appropriate methodology for estimating the relevant external costs from shipping at-sea emissions (Winkel et al., 2016, Nunes et al., 2019). Korzhenevych et al. (2014) updated the external cost factors for the major pollutants of NO_x, SO_2 and $PM_{2.5}$, available in the NEEDS project (Preiss et al., 2008) to 2010 prices using country specific gross domestic product per capita figures, for all EU countries. For CO_2, an average value of the given low-estimate and high-estimate damage costs in Europe was considered (Van Essen et al., 2011). It should be noted that external cost factors provided in Van Essen et al. (2011) and Korzhenevych et al. (2014) refer to the year 2008 and 2010 prices, respectively and it is considered appropriate to utilise the Consumer Price Index (CPI) for Ireland as available in the Organisation of Economic Co-operation and Development (OECD) statistical profiles (OECD, 2022) to bring them in line with the year under consideration through the adjustment of given CPI. According to OECD (2022), the Irish CPI in 2019 was 101.8, while the CPI was 95.5 and 100.9 in the year 2010 and 2008, respectively. Table 5.3 indicates the updated (year 2019) external cost factors used in this study, for the specific reference of Ireland

Table 5.3. Updated Irish External Cost Factors (€/ton)

Pollutants	CO_2	NO_x	SO_2	$PM_{2.5}$
External cost factor	86	6,046	7,397	17,552[a]

[a] - "Rural" $PM_{2.5}$ cost factor was considered

Source: Van Essen et al. (2011), Korzhenevych et al. (2014)

In terms of carbon tax rate, the IMO most recently reached on a consensus to price the emitted CO_2 (alongside other GHG pollutants) from shipping, as a part of a basket of mid-term measures (Muchira, 2022). While there has not been any agreement yet on the amount of carbon tax to be paid out, a recent report by University Maritime Advisory Services and University College London (Parker et al., 2021) has suggested a pricing of $173/ton to achieve the set IMO-2050 decarbonization goals, and to improve the cost-competitiveness of zero-carbon fuels to that of fossil-based fuels. Hence, based on the information as in Parker et al. (2021), we have considered a carbon tax rate of $173/ton, which is equivalent to €154.6/ton, based on the given currency conversion rates as in European Central Bank (2022).

5.6.6. Input data: Cost-benefit analysis

For the conducted NPV analysis to determine costs and benefits of the four alternative fuel scenarios, the saved external and carbon tax costs, possible baseline fuel benefits and the related operational (fuel, maintenance and lost BOG) costs will be calculated based on the given information as in section 5.2, section 5.4 and section 5.5. While the total capital costs will be determined by compiling the prices of installed equipment's, for each of the discussed alternative fuel scenarios. Installation of alternative fuel systems can be done in mainly two ways: modification of the existing ship system (i.e., retrofitting) or implementing it on a newly built ship (Ellis and Tanneberger, 2015). The adaptability of alternative fuels to newly built ships has been termed most optimal, mainly because of the difficulties involved in the application of such fuel systems to existing ships, owing to inadequate space and the highly complex procedure of modifying the engine system (Deniz and Zincir, 2016). Considering this fact, and also intending to draw a clear comparison of the alternative fuels in terms of their cost-competitiveness over a specific period, we have considered the cost estimates of "newly built" ships, assuming that these will replace all the existing ships.

The conversion rate for a "newly built" LNG system has been regarded as €1160/kW, which includes the costs for the dual-fuel engine and other additional equipment's (e.g., LNG storage tank) (Perčić et al., 2021). Storage of LNG onboard can be done mainly in three tank types, type A, type B or type C (IMO, 2016). Traditionally, type C tanks have been used for storing LNG onboard at low temperatures, where the outer shell of tank is insulated by using polyurethane foam (Wärtsilä, 2015). A maintenance conversion factor of €0.015/kWh was used for the LNG fuel system (Iannaccone et al., 2020). The conversion rate for a "newly built" methanol system was around €750/kW, which includes engine and other related costs such as fuel tanks (Perčić et al., 2021). As methanol remains in liquid state at atmospheric pressure, the method of its storage onboard will be similar to that of diesel fuels like HFO (Wärtsilä, 2021). Although, owing to its lower volumetric energy density (4.99 MWh/m^3) to that of diesel fuel (11.7 MWh/m^3) (McKinlay et al., 2021), the size of methanol tank will be nearly double that of a diesel tank (Wärtsilä, 2021). Also, there is a requirement of additional cofferdams for methanol tanks to prevent any potential leaks into machinery spaces (Wärtsilä, 2021). A maintenance conversion rate of €0.014/kWh was assumed for methanol system (Perčić et al., 2020).

For installation of the green hydrogen fuel system, the capital cost will include a PEM fuel cell, at the conversion rate of €368/kW, which is also increased by 20% to consider increased equipment needs (Perčić et al., 2021). A conversion rate of €1,072/kW was considered for the purpose of "newly built" liquified hydrogen storage tank onboard (Lindstad et al., 2021), and as the price was given in USD, it was translated to EURO using the year 2019 "average" currency exchange rate (European Central Bank, 2022). The total maintenance costs will be the replacement of the fuel cell once in the ship's lifetime (Perčić et al., 2020), which will be equivalent to its capital cost (Perčić et al., 2021). Also, for safety purposes, the required mass of hydrogen was increased by 20%, based on Perčić et al. (2021). In the instance of green ammonia, the conversion rate for the installation of PEM fuel cell (€368/kW) was incremented by 30%, to consider the required cracker and purifier costs (Perčić et al., 2021). A conversion rate of €536/kW was assumed for the installation of "newly built" liquified ammonia storage tank onboard (Lindstad et al., 2021), which was translated from USD to EURO using "year 2019" average currency exchange rate (European Central Bank, 2022). The maintenance cost will remain the same as in the case of hydrogen, which is the replacement of the fuel cell once in the ship's lifetime (Perčić et al., 2020, Perčić et al., 2021). Similar to LNG, a type C storage tank can also be used for storing liquified hydrogen and ammonia fuels at low temperatures (Fathom World, 2022), although, it should be noted that the size of liquified hydrogen and ammonia storage tanks is expected to be nearly 2.5 times and 1.5 times higher than the LNG tank size, respectively (McKinlay et al., 2021).

For the NPV analysis, we have assumed the maximum duration of using alternative fuel systems to be 25 years, which is equivalent to the lifespan of newly built ship. The social discount rate was taken as 4% (Department of Public Expenditure and Reform, 2019).

5.7. Results and Discussion

5.7.1. Results

In the baseline scenario, the total emissions from ships while at-sea stood at 1,707,994 tonnes, for the year under investigation, 2019. Figure 5.1 depicts the total shipping emissions associated with the four alternative fuel scenarios: A (LNG), B (Methanol), C (Green hydrogen), and D (Green ammonia), compared against the estimated baseline emissions.

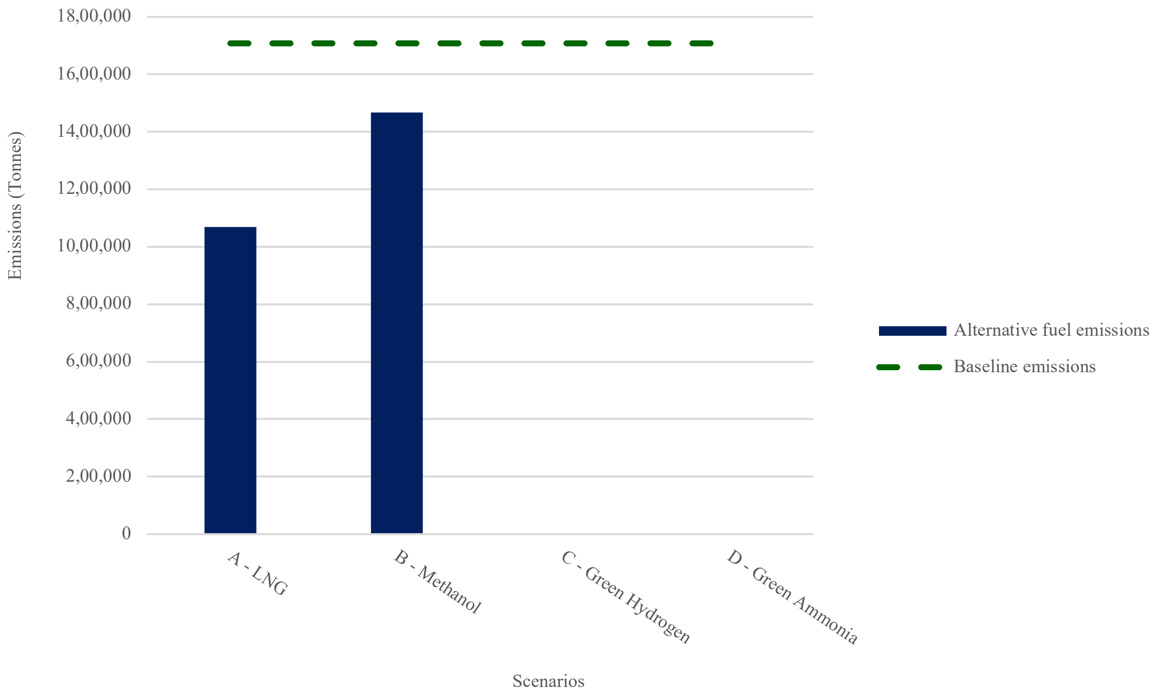


Figure 5.1. Estimated shipping emissions for the considered scenarios

It is observable from Figure 5.1 that adoption of green hydrogen and green ammonia with the PEM fuel cell technology will effectively eliminate emissions. The replacement of existing diesel-powered ships with that of newly built LNG-powered ships will lead to a 37% drop in the total emissions, while the use of methanol-powered ships will offer the lowest emission reduction capability (14%) among the selected alternative fuels.

Table 5.4 depicts the breakdown of estimated baseline and alternative fuel emissions, based on the different pollutants of CO_2, NO_x, SO_2 and $PM_{2.5}$.

Table 5.4. Shipping emissions for baseline and alternative fuel scenarios (tonnes)

Scenario	SO_2	NO_x	CO_2	$PM_{2.5}$
Baseline	6,008	34,090	1,666,957	938
A – LNG	8	3,026	1,065,735	70
B – Methanol	101	9,809	1,458,143	54
C – Green Hydrogen	0	0	0	0
D – Green Ammonia	0	0	0	0

It has been shown in Table 5.4 that although the alternative fuels of LNG and methanol are highly successful in mitigating SO_2, NO_x and $PM_{2.5}$ emissions, CO_2 emissions were only reduced by 36% and 12%, respectively, which is quite minimal when compared to green hydrogen and green ammonia, which offer a 100% reduction. This is attributed to the fact that both hydrogen (H_2) and ammonia (NH_3) have essentially "zero-carbon" (C) content. While methanol (CH_3OH) and LNG (CH_4) do have a higher hydrogen/carbon ratio than the present hydrocarbon-based fuels, the carbon emissions from the combustion of such fuels will remain significant, although at lower levels than that of diesel fuels (McKinlay et al., 2021).

Based on the calculated emissions, it was also important to estimate the total socio-environmental external costs and carbon tax associated with the implementation of various alternative fuel technologies, to derive the benefits incurred in the form of reduced external costs and saved carbon tax against the baseline. Figure 5.2 shows the external costs and carbon tax attributed to the considered baseline and alternative fuel scenarios.

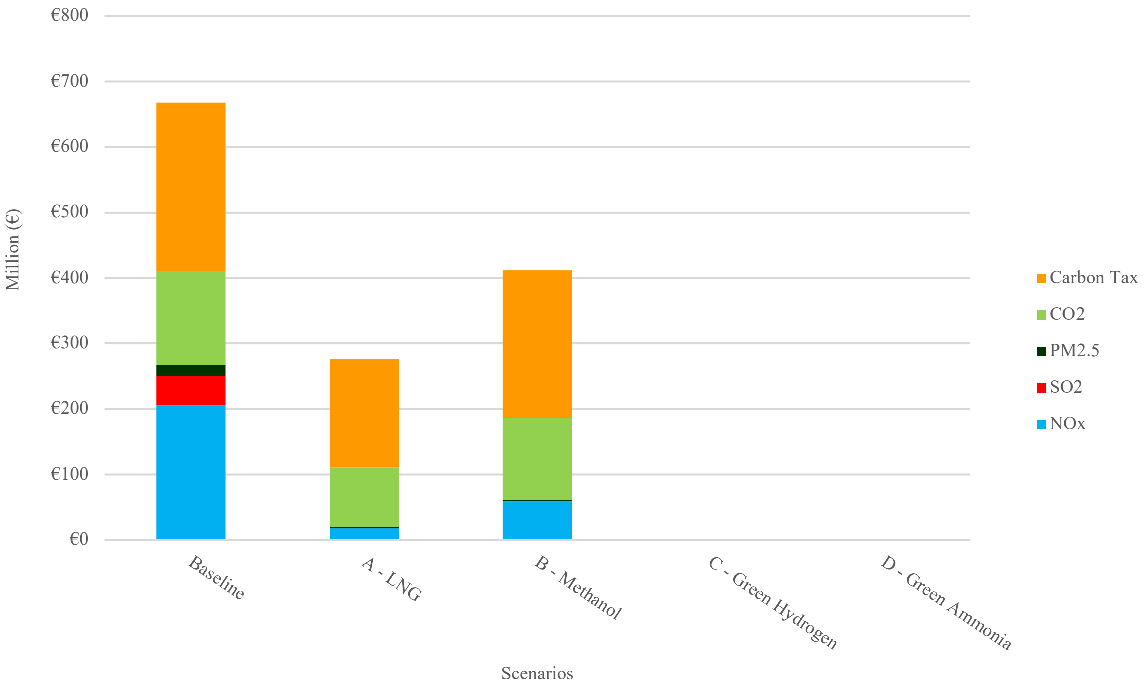


Figure 5.2. External costs and carbon taxes for the considered scenarios

As shown in Figure 5.2, even though CO_2 made up the bulk of the total baseline emissions (97.6%), the externalities imposed by it remained significantly lower than that of NO_x, which only contributed 2% of the total baseline emissions. NO_x made up 50.2% of the total share of baseline external costs, followed by CO_2 (34.9%), SO_2 (10.8%) and $PM_{2.5}$ (4.1%). Further, it was observed that even with remarkable reductions in NO_x, SO_2 and $PM_{2.5}$ emissions with the use of LNG and methanol fuels, their combined external costs were significant. This could be attributed to the impact of NO_x, SO_2 and $PM_{2.5}$ emissions tending to be more at the local (i.e., societal) level, in comparison to that of CO_2 which is more likely to cause environmental damage (Tzannatos, 2010a), and this is where the importance of hydrogen and ammonia increases, owing to them being the ‘emission-free’ alternatives. Another major advantage of using green hydrogen and ammonia fuels is that any paid carbon taxes could be avoided in their entirety.

While results have already shown that the use of alternative fuel technologies will be highly successful in reducing shipping emissions and the associated externalities to a large extent, the use of such fuels will require significantly higher investments in terms of the installation of suitable systems alongside the attached operational and maintenance costs, in comparison to the baseline scenario. Table 5.5 compares the capital and operational costs (year 1) for the considered scenarios of alternative fuel technologies.

Table 5.5. Private Costs (Year 1) for baseline and alternative fuel scenarios (€)

Scenario	Capital	Operational	Total
Baseline	0	260,853,755	260,853,755
A – LNG	805,252,100	140,001,657	945,253,758
B – Methanol	520,637,134	353,307,825	873,944,959
C – Green Hydrogen	1,199,547,956	817,155,038	2,016,702,995
D – Green Ammonia	704,179,078	1,560,101,631	2,264,280,709

The given results in Table 5.5 indicate that although green hydrogen and green ammonia were identified as the most successful alternative fuels when it comes to mitigating the shipping emissions, their overall capital and operational costs were substantially higher than the other fuels as well as the baseline costs. The high capital costs for hydrogen are understandable due to its complex storage requirements, while the increased operational costs for ammonia seem to be resulting from its higher fuel consumption, especially when used as a ‘hydrogen carrier’, where a combination of a fuel cell, purifier and cracker has been utilised. This outcome was also supported from the findings of Kim et al. (2020), where the fuel consumption of ammonia was found to be around 25% higher when used as a carrier of hydrogen in combination with PEM fuel cell than that of using it in an internal combustion engine.

Based on the estimated capital and operational costs and benefits in the form of saved external and carbon tax costs alongside the avoided baseline fuel costs, we also investigated the cost-effectiveness of each of the discussed alternative fuel technology, by conducting a NPV analysis for the considered period of 25 years. In general, the alternative fuel technology having a positive NPV will be deemed financially ‘profitable’ from a societal perspective. Figure 5.3 shows the estimated NPV for the discussed alternative fuel technologies, over 25 years.

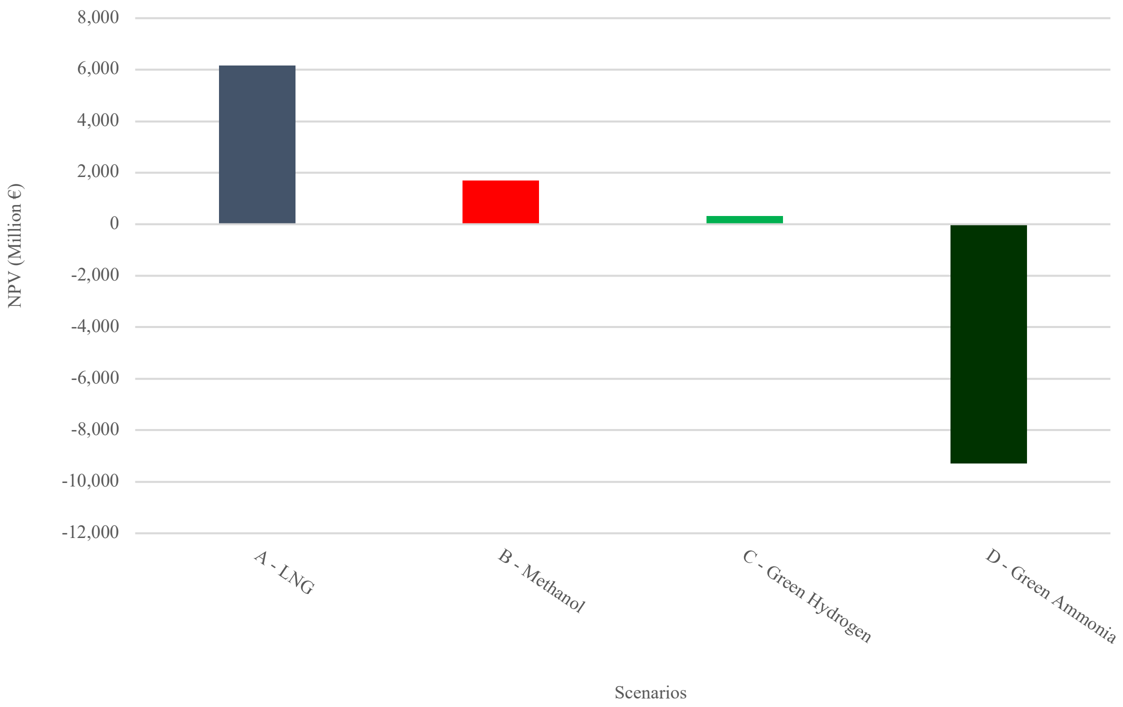


Figure 5.3. NPV over 25 years for the identified alternative fuel scenarios

Figure 5.3 shows that among the discussed alternative fuels, the scenarios of LNG (€6,166 million), methanol (€1,705 million) and green hydrogen (€319 million) will return a positive NPV. It was shown that although the use of green ammonia will undoubtedly offer the highest potential in terms of reducing shipping emissions, this alternative will have a negative NPV over the considered period of 25 years. This can be attributed to its high operational costs, mainly resulting from its excessive consumption (i.e., losses) during the cracking and purifying processes, when used as a carrier of hydrogen. Also, the fuel consumption values for ammonia tend to be higher when compared to that of hydrogen, owing to its lower net calorific value (5.17 kWh/kg) than hydrogen (33.3 kWh/kg). While the inclusion of carbon tax alongside the benefits from external and baseline fuel costs did provide the impetus for green hydrogen to achieve a positive NPV, although, its use still remained less cost-competitive to that of LNG and methanol.

5.7.2. Discussion

From the analysed results in section 5.5.1, it was observed that the alternative fuel scenarios of LNG, methanol and green hydrogen can potentially mitigate shipping emissions while returning a positive NPV, with the use of green ammonia possibly being ruled out due to higher operational costs, primarily resulting from its substantial consumption during the process of cracking and purifying, when used as a carrier of hydrogen in conjunction with a fuel cell and its lower net calorific value. Although, it has to be noted that the considered alternative fuel prices are subjected to fluctuate due to changes in market conditions and technological progress. For instance, it was seen that a global economic rebound post the COVID-19 pandemic combined with supply and operational constraints lead to a record high in LNG prices (Boccara et al., 2022), with the average European spot price in 2021 being \$16.46/MMBtu, up by 70% to that of 2019 price (Refinitiv Eikon, 2022b). Similarly, an increase of 42% was recorded in the year 2022 (June) methanol fuel price compared to that of 2019 price (Methanex, 2022). Owing to increased technological investments in EU-based green hydrogen production facilities and a drop in electrolyser costs, the price of green hydrogen is expected to decline (European Commission, 2020b), expecting to reduce to €1,500/ton by 2025, a drop of 62% from the current levels (Di Christopher, 2021). A similar trend is also projected in green ammonia prices (Gielen et al., 2022). Based on these factors, it was important to conduct a sensitivity analysis to gauge changes in NPV for change in alternative fuel prices.

Figure 5.4 depicts sensitivity analysis based on NPV, considering a change in LNG, methanol, green hydrogen and green ammonia fuel price in either direction.

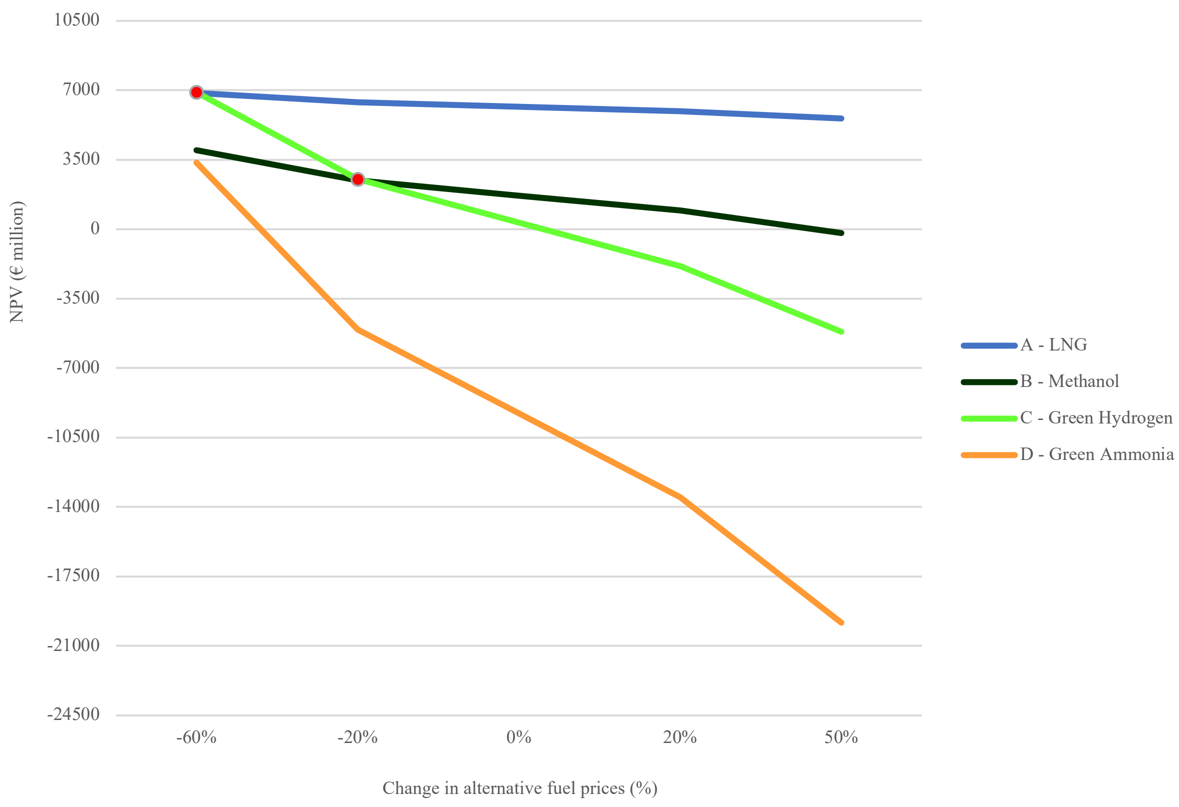


Figure 5.4. NPV sensitivity to fuel price variation in the considered scenarios

It is shown in Figure 5.4 that for a fall of 20%, the scenario of using green hydrogen will achieve a higher NPV than that of using methanol fuel. Further, a fall of 60% in the prices will ensure that NPV of using green hydrogen will be the highest among the discussed alternative fuels. Currently, there is a price gap of €2,500 (62.5%) between green hydrogen (€4,000/ton) and grey hydrogen (€1,500/ton) (European Commission, 2020b). Hence, it can be said that when the current green hydrogen price reaches the same level as that of grey hydrogen, it will become the most viable solution to implement among all the alternative fuels. In any instance of increment in alternative fuel prices, LNG will retain the highest NPV among all the fuels. Alongside the fuel prices, the NPVs will also vary with any change in the considered carbon tax rate. While there has not been any consensus on the set tax rate, we considered the rate of €154.6/ton (Parker et al., 2021). Figure 5.5 depicts sensitivity analysis based on NPV, considering a change in carbon tax rate in either direction. This analysis could be of utmost importance from the IMO perspective, to understand at which tax rate could the use of zero-carbon fuels (green hydrogen and ammonia) become profitable than that of low-carbon fuels (LNG, methanol).

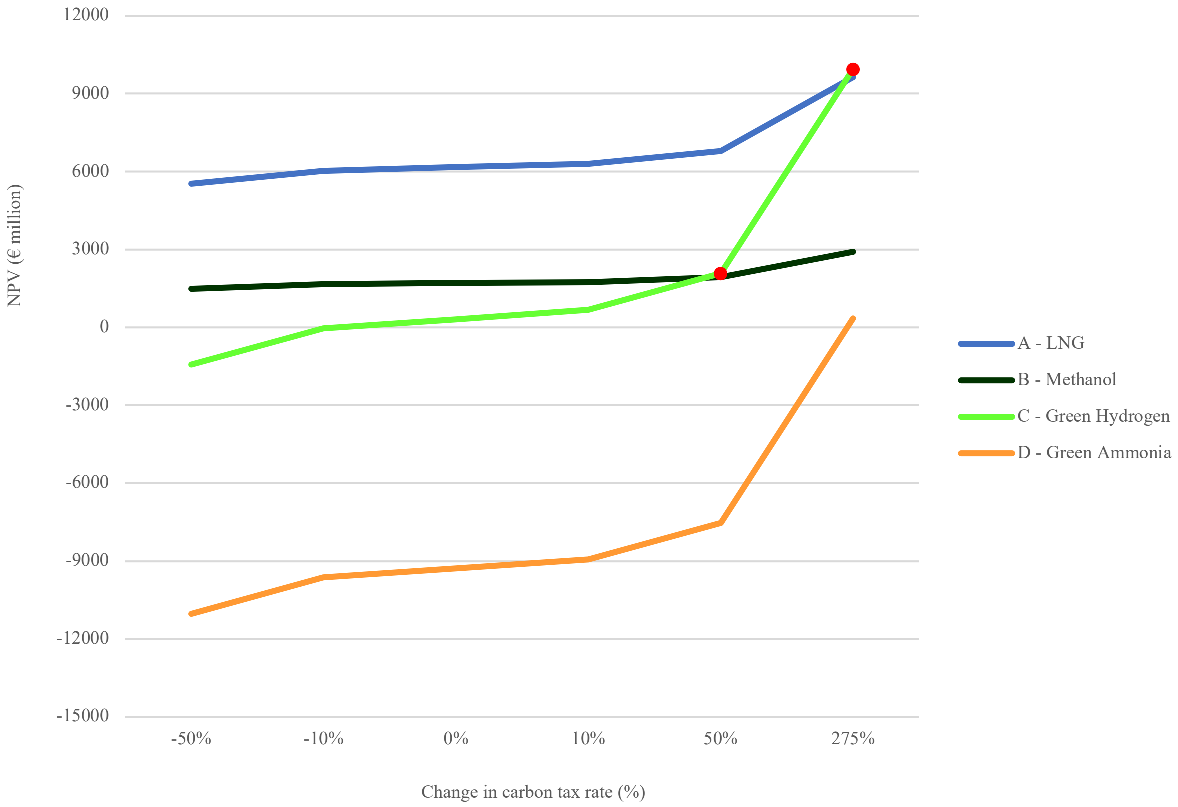


Figure 5.5. NPV sensitivity to carbon tax rate variation in the considered scenarios

It is shown in Figure 5.5 that only when there is an increment of 50% and 275% in the considered carbon tax rate, will the use of green hydrogen become more cost-competitive than that for methanol and LNG, respectively. Green ammonia will remain the fuel with lowest NPV for any variance in the carbon tax rate. This result contradicts the outcome as given in Parker et al. (2021), as a significantly higher carbon tax rate than that of outlined $173/ton (i.e., €154.6/ton) will be required improve the cost-competitiveness of zero-carbon fuels in relation to that of low-carbon fuels.

Alongside the cost-benefits of alternative fuels, we also measured their potential in meeting the ambitious IMO target of reducing GHG emissions by at least 50% by 2050 compared to 2008 levels, as well as the EU target of alleviating GHG emissions by at least 55% by 2030 compared to 1990 levels. To understand the effectiveness of LNG, methanol, green hydrogen, and green ammonia in meeting such targets, we will compare the total reduction in CO_2 emissions offered by such fuels, using the analysed year 2019 results, against an estimated "baseline 2008" and "baseline 1990" emission levels, respectively. As there was no historical data available in the AIS database with regards to ship movements, several assumptions will have to be made, which were as follows:

1) Firstly, to compare the effectiveness of the considered alternative fuels in meeting the IMO-2050 targets, we obtained the EU-28 '2008 international navigation' CO_2 emissions from the EEA (2021) emissions database, which was found to be 181,107,996 tonnes.

2) Further, we identified that 2,289,021 ship calls were made in EU-28 ports in 2008, of which 19,060 (0.84%) calls were made in Ireland (Eurostat, 2022e). In this study, as we have analysed approximately 50% of Ireland's ship calls in 2019, we applied this percentage to 2008 data, and found that these calls equated to approximately 0.42% of the EU-28 calls.

3) Based on their contribution in the EU-28 ship calls, we assumed that these ships also represented 0.42% of the EU-28 'international navigation' CO_2 emissions in 2008, which stands at 754,016 tonnes. While this linear aggregation is not perfect, it does provide a good indication of the scale of the issue.

To achieve the IMO-2050 targets, it is expected that these emissions will need to be reduced by 50% (377,008 tonnes). Figure 5.6 compares the year 2019 CO_2 emissions from the discussed baseline and alternative fuel scenarios of LNG, methanol, green hydrogen, and green ammonia against the "baseline 2008" CO_2 emissions levels and the expected IMO-2050 target to achieve.

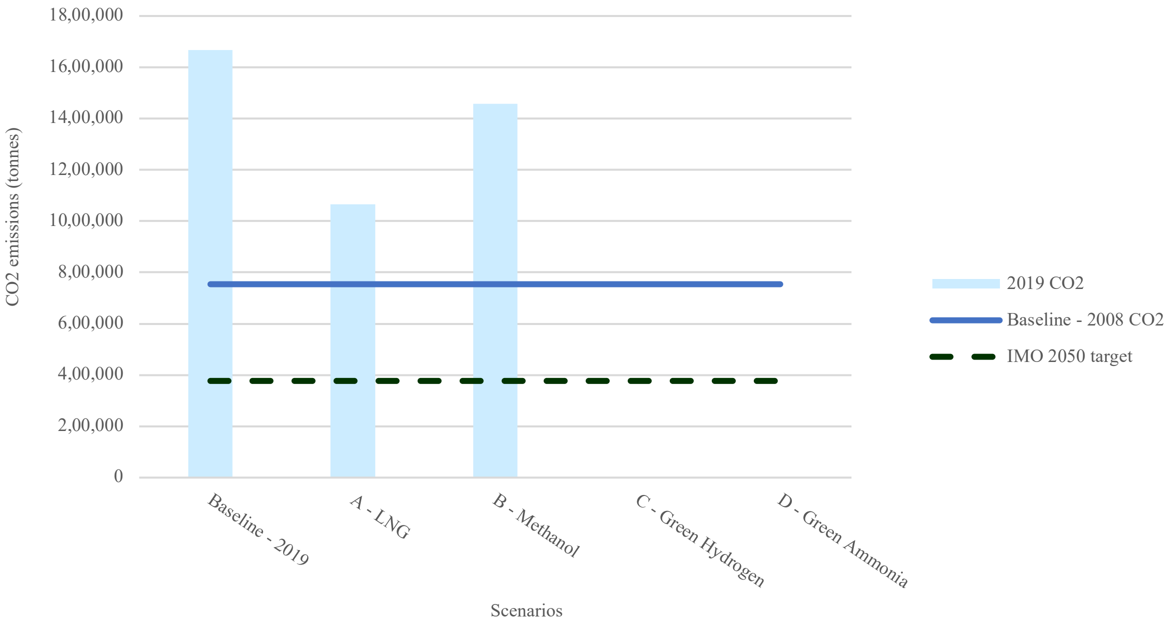


Figure 5.6. Baseline and alternative fuel CO2 emissions, against IMO-2050 target

Similarly, to analyse the effectiveness of alternative fuels in meeting EU's "Fit for 55" targets, the assumptions were:

1) We obtained the EU-28 '1990 international navigation' CO_2 emissions from the EEA (2021) emissions database, which was found to be 109,537,299 tonnes.

2) As there was no historical data on EU-28 and Irish ship calls in 1990 from the Eurostat database, we assumed a similar share of the studied Irish ship calls (0.42%) in the total EU-28 calls for the year 1990 as well.

3) Based on this proportion, we can say that the total "baseline 1990" CO_2 emissions from the studied ships stood at 456,042 tonnes.

To achieve the “Fit for 55” target, it is expected that these emissions will have to be less than 205,219 tonnes (55% reduction). Figure 5.7 compares the year 2019 CO_2 emissions from the discussed baseline and alternative fuel scenarios of LNG, methanol, green hydrogen, and green ammonia against the “baseline 1990” CO_2 emissions levels and the expected EU-2030 target to achieve.

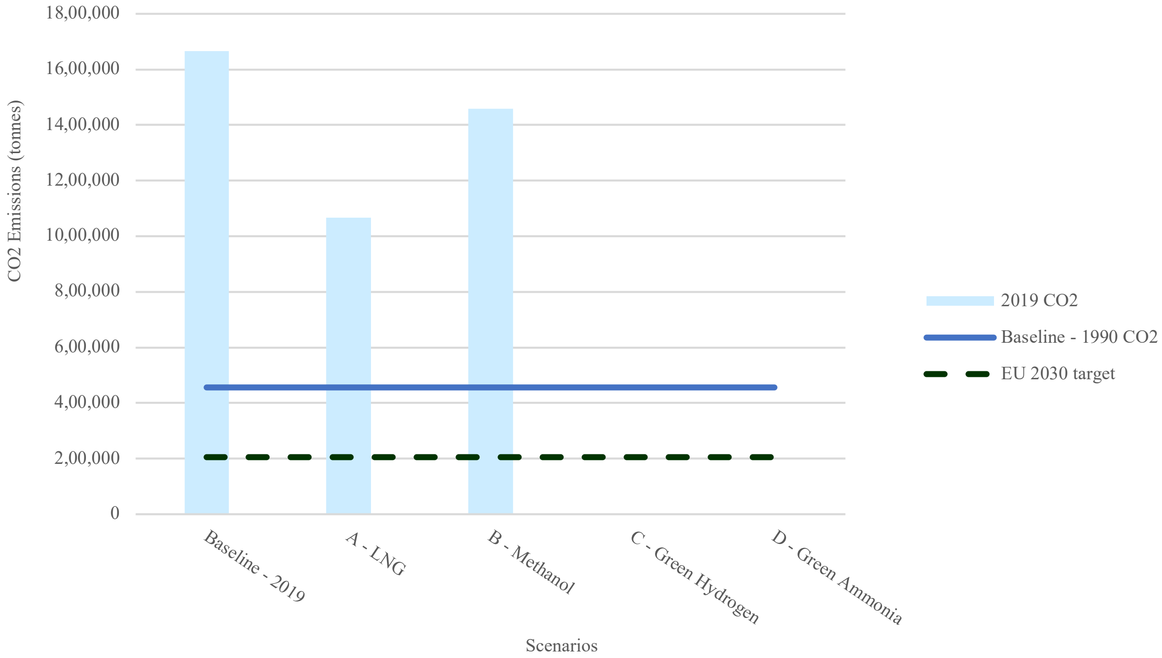


Figure 5.7. Baseline and alternative fuel CO2 emissions, against EU-2030 target

From the above Figure 5.6 and Figure 5.7, it can be seen that the baseline CO_2 emissions in 2019 have risen considerably than that of 2008 and 1990 levels, respectively. Further, even if all the studied ships were to switch from diesel fuels to LNG or methanol recently, the estimated CO_2 emissions remained higher than the “baseline 2008” and “baseline 1990” emissions, and hence, the reduction targets set by IMO and EU look far from achievable. While the use of green ammonia can help achieve the set IMO and EU targets, its use remains inviable unless there is a significant decrease in its fuel price or a drastic increment in the carbon tax rate. Hence, the only alternative fuel which reflects a positive NPV, and at the same time reduces CO_2 emissions below the estimated IMO and EU targets is green hydrogen. Although the biggest disadvantage with the use of hydrogen is its low maturity of technology when compared to LNG and methanol, as around 0.2% of the global maritime fleet have already switched to the latter by June 2021 (DNV, 2021b). While a number of projects have been initiated recently to explore the potential use of hydrogen in shipping industry, especially in larger ships (5000 deadweight tonnage or more), its scaled commercialisation is not expected to happen before 2030, but most likely in the decade of 2030-2040 (DNV, 2021b). Also, a significant decrease in green hydrogen prices has been predicted by 2030, mainly resulting from reduced electrolyser costs (European Commission, 2020b). Hence, assuming that there is indeed a peak in the commercialisation of hydrogen in the next decade and lowering of green hydrogen fuel prices, it can be said that the outlined IMO-2050 targets can be realised successfully. Although in such an instance, the EU's target to reduce GHG emissions by 55% by 2030 appears unachievable.

5.8. Conclusion

To achieve the ambitious targets set by regulatory bodies such as the IMO and the EU for emission mitigation, alternative fuels within the maritime industry have received increased attention over the years from policymakers, shipping companies as well as academic researchers. To assist the decision-makers with the selection of the most cost-effective alternative fuel option, we conducted an NPV analysis on the use of LNG, methanol, green hydrogen, and green ammonia, for the considered tank-to-wake scope. Through this, we contribute to the literature which is limited in terms of discussing the feasibility of using alternative fuels while incorporating the benefits attached through saved external costs, in addition with carbon tax costs. We also compared the identified alternative fuels in terms of their impact on mitigating the CO_2 emissions and thus, successfully achieving the decarbonization goals set by IMO and EU in a financially feasible manner. This research was conducted for the top 20 most frequently calling ships from Irish ports in 2019.

The total NO_x, SO_2, CO_2 and $PM_{2.5}$ baseline emissions stood at 1,707,994 tonnes, with a combined external cost of €410.4 million and carbon tax cost of €257.7 million. The application of green hydrogen and green ammonia (as hydrogen carrier) fuels in combination with PEM fuel cells offered the highest tank-to-wake emission reduction potential of 100% among the considered fuels, which was followed by the use of a dual-fuel engine for LNG (37%) and methanol (14%). In terms of cost-benefit analysis, LNG was seen as the most profitable option, as it has the highest NPV of €6,166 million, followed by methanol (€1,705 million) and green hydrogen (€319 million). Green ammonia fuel incurred a negative NPV, with the reason being its substantially higher operational costs, which mainly resulted from its excessive consumption during cracking and purifying processes, when used as a carrier of hydrogen in combination with fuel cell and its lower net calorific value. We considered the sensitivity of these NPVs to change with variance in fuel prices, and it was observed that the use of green hydrogen will generate the highest positive NPV if its current fuel price is reduced by at least 60% i.e., brought in line with the present-day grey hydrogen prices. We also observed the variance in the alternative fuel NPVs with changes in the carbon tax rate. It was shown that the considered carbon tax of €154.6/ton will have to be incremented by 50% and 275% to make the use of zero-carbon fuel like green hydrogen more cost-competitive than low-carbon fuels like methanol and LNG, respectively. When comparing the alternative fuels in terms of their success in achieving the estimated IMO and EU targets, green hydrogen and green ammonia are the fuels which can most help meet the ambitious emission reduction goals. Although green hydrogen remains the only alternative fuel that can achieve the established targets, while remaining profitable.

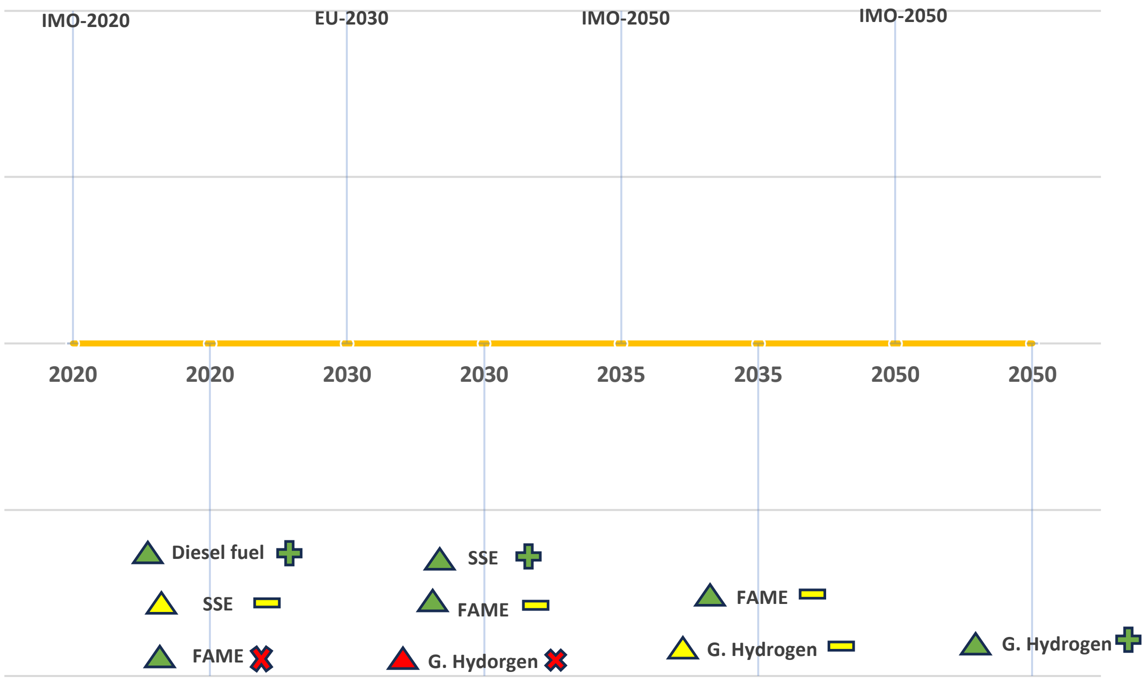
With regards to the reliability of the collected data, significant efforts were made to obtain precise information on ship activities using the AIS and EU-MRV databases. Although information on issues such as engine and fuel type profiles, load factors, specific fuel consumption, emission factors, external cost factors as well as the costs for using the alternative fuel technologies were obtained from high quality sources, they may have some inherent variation. Also, the comparisons made against the historic CO_2 emission levels are based on several assumptions and hence, are bound to have considerable uncertainty. Despite these limitations, the methodological framework of this research could be of utmost importance for future studies to explore the cost-effectiveness of upcoming solutions such as dimethyl ether, straight vegetable oil and other biofuels as well as for battery-powered ships. It will also be interesting to see if the discussed alternative fuel solutions retain their cost-effectiveness when used for long-distance container, bulker and tanker ships.

CHAPTER SIX: DISCUSSION AND CONCLUSION

6.1. General research contributions

In the recent years, significant efforts have been made at global and regional levels to alleviate externalities imposed from marine shipping movements via stringent emission targets, largely aimed at steering the maritime sector from using fossil fuels towards cleaner alternative technologies. For instance, the EU has previously introduced its directive (2005/33/EU) requiring all ships berthing in EU ports for more than two fours to either use MGO, or switch to SSE. While the directive 2014/94/EU requires all Ten-T ports to assess and prioritise the use of SSE, if the offered environmental benefits of implementing such technology are higher than that of financial costs. These directives has recently been updated as part of FuelEU maritime proposal under its "Fit-for-55" package, which mandates all the passenger and freight ships berthing in Ten-T EU ports to be switched to SSE by 2030. Also, it is expected that the supplied electricity for ships will be procured from energy grid, which should be predominantly a renewable source of electricity, as part of the European Green Deal. The Fit-for-55 package also desires the maritime sector to reduce its GHG emission footprint by 55% by 2030 compared to 2008 levels, aiming to achieve "zero-emission" shipping within the region by 2050. In consideration of these directives, this thesis investigated the possibility of transitioning away from the use of fossil fuels by shipping sector towards cleaner alternative technologies. Ireland was considered to be the case study, which relies remarkably on its maritime sector for economic trade, while at the same time, has shown reluctance when it comes to the roll out of low-to-zero emission technologies for the maritime sector. For the mandate concerning the emissions from ships at berth, this research thesis found that while the implementation of SSE will be viable in certain scenarios under the current (2019) grid energy mix, its utilisation will become increasingly more cost-competitive than that from using fossil fuel (i.e., MGO) by 2030. This outcome stems from the fact that significantly higher benefits will be generated as the EU progresses towards using renewable energy sources for grid energy mix, since the supplied electricity will not only be cheaper in monetary terms, but it will also be a "cleaner" as opposed to its generation from non-renewable sources like gas, oil and coal. For compliance with 2030 GHG targets under the Fit-for-55 package, the use of low-to-zero carbon fuel technologies like LNG, methanol, green hydrogen and green ammonia was also investigated within this thesis. The utilisation of green hydrogen and green ammonia were found to be the only alternative fuel technologies which would adhere to the set emission thresholds. Although, the use of green ammonia (as a hydrogen carrier) was found to be potentially unviable due to higher operational costs, resulting from excessive ammonia consumption (i.e., losses) during the cracking and purifying processes and its lower net calorific value. This outcome solidifies the position of green hydrogen as the only feasible solution which could meet the 2030 targets. This is notwithstanding the biggest disadvantage with the use of hydrogen, which is its low level of technology maturity when compared to LNG and Methanol, with scaled commercialisation only likely to happen post-2030. Further, the conducted research also indicated that a significant reduction in green hydrogen fuel price (from current levels - 2019) will be required to improve its cost-competitiveness over LNG and Methanol. This is only expected to happen by the latter half of 2020s within the EU, with an increase in technological investments in green hydrogen production facilities and a drop in electrolyser costs (European Commission, 2020b). Hence, it can be concluded that under the present circumstances, the increased use of green hydrogen technology looks impractical within the EU maritime sector by 2030, which should make the Fit-for-55 targets unachievable. Although, it is expected that with a peak in the commercialisation of hydrogen in the next decade and lowering of green hydrogen fuel prices, the outlined IMO-2050 targets have potential to be realised.

Considering that the near term (EU - 2030) targets look unlikely to be achieved, the use of biofuels could be seen as suitable option to help transition the maritime industry towards the long term targets, the feasibility of which was also analysed within this thesis. Among the studied biofuels, the use of blended FAME (within MGO) was found to be the most cost-effective biofuel to be used, while it also offered considerable reduction in CO_2 emissions, specifically when compared against the fossil-based options of MGO and scrubbers (operating on HFO). While the use of FAME will not evoke any major modifications in ship engine and design to enable its use, it will certainly demand significant upscaling in the current production levels from the available feedstocks to be able to meet the shipping demands. Figure 6.1 summarises the estimated timelines for ship onboard and fuel infrastructure readiness for the low-to-zero emission technologies, in view with the set IMO and EU targets. The detailed contributions from each individual study conducted in this thesis have been outlined in this chapter, in the subsequent sub-sections, while further highlighting the policy implications for the conducted research alongside the general limitations and suggestions for future studies.



Onboard infrastructure : ▲ Available △ Potentially available ▲Not available

Inland infrastructure: ✚ Available ▬ Potentially available ✖Not available

Figure 6.1. Potential timeline for ship onboard and inland fuel infrastructure readiness

6.2. Contributions from Paper 1: Shore Side Electricity for berthing ships

Considering the requirements of the 2005/33/EU directive and the FuelEU maritime proposal, in this study, the cost-effectiveness of SSE technology adoption was investigated, for passenger ships calling to the two most populated Irish port cities of Dublin and Belfast. This study incorporated both “port-side” and “ship-side” financial costs for retrofitting the required SSE-related equipment, alongside the benefits from saved external costs and MGO fuel costs from the utilization of Auxiliary Engines by ships while berthing.

The first contribution of this study is that it analysed the impact of the current (year 2019) and future (year 2030) energy mix for grid supply, an important aspect when assessing the profitability of long term investments such as SSE. Within the EU, significant changes are expected in the future energy mix, with an estimated increase in the uptake of renewable energy sources from 34% (year 2019) to 65% (year 2030), as a part of newly proposed European green deal (European Commission, 2020a, European Environment Agency, 2022). Considering this change in grid energy mix in combination with the 2014/94/EU directive and the EU "Fit-for-55" package, it is important to help stakeholders to understand the potential viability of investing in SSE, by determining if the acquired benefits from switching to present and future grid energy mix are superior than that of using MGO. It was observed that the present (year 2019) Irish energy mix was mainly reliant on non-renewable sources (Gas, Coal, Oil, Peat, Imports, Wastes), as electricity generated from these sources represented 62.5% of the total grid composition, with renewable sources (Hydro, Wind, Solar, Others) representing 37.5% of the total energy mix. This grid composition is expected to change in the future (year 2030), as the Irish government has prioritised the use of renewable sources (wind and solar) (by 80%) for energy generation, with coal and oil expected to be completely phased out, and natural gas remaining the only major non-renewable source (by 20%). Based on the obtained results, it was found that the use of SSE will be more profitable when ships are supplied with electricity from the grid which is dominated by renewable sources for energy production (year 2030). This result was mainly based on the fact that higher environmental benefits were generated in the form of saved external costs, as well as the lower supplied electricity costs, due to the increased use of renewable energy sources for electricity generation in the future. This outcome indicates that from policy perspective, the use of SSE at Dublin and Belfast ports will be feasible as it meets the required criteria of 2014/94/EU directive as the obtained benefits outweigh the total costs, while also meeting with the expectations of ambitious "Fit-for-55" project by the EU.

The second contribution of this study was that it provided a detailed cost-benefit analysis under a range of different scenarios to assist with the identification of most profitable pathway for implementing SSE. It has been suggested in the previous literature (i.e., Tzannatos, 2010a, Ballini and Bozzo 2015, Innes and Monios, 2018) that switching high visiting frequency ships to SSE could be advantageous, hence, building on this observation, we evaluated the cost-effectiveness of SSE usage by passenger ships in Dublin and Belfast ports at six different levels of adoption, divided on the frequency of ship arrivals (Top 5/10/15/20/25/All). Based on the obtained NPVs, it was suggested that the use of SSE by Top 10 most frequently calling passenger ships in Dublin and Belfast will be the most cost-effective strategy to implement.

Another contribution here was that this is one of the first studies which assimilated both the port-side and the ship-side installation costs with that of achieved environmental benefits through reduced external costs alongside the economic benefits from saved fuel costs while conducting a SSE feasibility study. It has been found that previous studies either only determined the port-based economic costs (Ballini and Bozzo 2015, Innes and Monios, 2018), ship-based costs (Tzannatos 2010a, Dai et al., 2019), and/or external costs and drop in emissions (Winkel et al., 2016, Stolz et al., 2020). In line with the 2014/94/EU directive and the future "Fit-for-55" mandate, it is important to provide thorough cost-benefit analysis constituting port-side and ship-side costs as well as the required environmental and economic benefits, to help stakeholders determine whether or not to implement SSE technology. Further, this was also the first study that is known which considered Irish ports as the base case for a SSE cost-benefit study. This was somewhat surprising as despite the proven scale of societal and environmental damage inflicted by shipping emissions on Ireland, and that Ireland is a long standing EU member state, the usage of SSE for ship arrivals in Ireland has rarely been discussed in any depth either within academic research or at the domestic policy level .

6.3. Contributions from Paper 2: Biofuel utilization in Shipping

From 2020, the IMO, which is the global standard-setting authority for the safety, security and environmental performance of international shipping, has introduced a global upper limit on the sulphur content of fuel oil as 0.50% (reduced from 3.50%). To successfully comply with this regulation, the IMO has outlined namely three pathways: 1) Use of low-sulphur fuel oil (e.g., MGO), 2) Use Exhaust Gas Cleaning System (e.g., Scrubbers), 3) Use alternative fuel types containing low or zero sulphur, such as Liquified Natural Gas, or blend of biofuels. Based on this directive, this study investigated the cost-effectiveness of three blended biofuels (Fatty Acid Methyl Ester (FAME), Hydrotreated Vegetable Oil (HVO) and Fischer-Tropsch (FT) Diesel), alongside that of using MGO and scrubbers. Ro-Ro ferry ships operating from Irish ports were selected as the case study. NPV analysis was conducted, assimilating the financial, external and carbon tax costs.

The first contribution of this study is that it is one of the first attempts to analyse the cost-effectiveness of using blended biofuels, which has been notified as one of the pathways to comply with the "IMO-2020" sulphur directive. From the previous academic literature (Jiang et al., 2014, Fan et al., 2020, Zhu et al., 2020, Zhao et al., 2021), as well as within industry practice (Blenkey, 2021, Kinyua, 2022, Grainger, 2023, Javaid, 2023), it has been observed that use of low-sulphur fuel oil like MGO and the installation of scrubber systems have been the most popular options to be discussed or implemented for IMO-2020 compliance. With limited discussion surrounding the potential use of other available options such as biofuels, as outlined by the IMO.

Within the EU, significant interest has arisen in improving energy sovereignty and moving towards the goals of circular economy, due to the concerns about the global depletion of fossil reserves and the ever-changing geo-political situation. To achieve this ambitious target, biofuels, which are produced from crops, wastes, and residues have been noted by the EU Commission as renewable alternatives to existing fossil fuels, especially within the transport industry. Meanwhile, considering the set future decarbonization targets, the IMO has also stepped up its discussions on the use of biofuels within maritime industry, especially regarding their role as "transitional fuels". Since biofuels offer higher carbon reduction compared to other popularly used options such as MGO and scrubber. Considering these recent developments, it is increasingly important to help stakeholders in determining the most optimal solution to switch to for IMO-2020 compliance, from financial and environmental perspectives. From the cost-benefit analysis conducted, it was found that the use of blended FAME (by 20%) will be the optimal choice, in terms of NPV, for compliance with IMO-2020 directive, followed by MGO consumption. . FAME also establishes itself as the most suitable "transitional fuel" available to steer the maritime industry towards long term decarbonization goals, as it offered highest carbon emissions reduction potential among the biofuels, over that of MGO and scrubbers.

Secondly, this research also presented some methodological contributions. Since this was one of the first studies which attempted to analyse the cost-effectiveness of biofuels, the authors were required to develop suitable mathematical models for estimating ship emissions, fuel consumption, and fuel costs, specifically considering the required blend of 20% biofuel (FAME/HVO/FT-Diesel) and 80% MGO. Thirdly, this study also had some policy implications from an Irish perspective. Ireland was selected as the base case as we found that it is primarily an energy importing economy, relying on gas and oil imports to meet its energy needs, with its net energy imports per capita higher than that of EU average.

It was noted that Irish government in the recent times have been very proactive in increasing the use of biofuels in the transportation sector, as part of its "National Climate Action" plan, with the road transport sector already required to include a percentage of biofuels (10%) in their general fuel mix. As of 2020, FAME, which was also found the most cost-effective option for Irish ferry arrivals, remained the premier and most highly produced biofuel type, constituting nearly 63% of the total Irish biofuel production capacity of 185 million litres (i.e., 165,343 tonnes) (Ó Cléirigh, 2022). The Irish government will need to significantly increment the current production capacity for FAME, by 85%, to facilitate its use by ferry ships. These fuel demands are possible to be met, considering that the requirements of biofuel utilization by ferries only represent roughly 3% of the expected biodiesel yield from the available Irish biomass feedstock (used cooking oil, tallow) as of 2020, and this feedstock is expected to increase in the next 5-10 years.

6.4. Contributions from Paper 3: Alternative low-to-zero carbon fuels

To address growing concerns surrounding the detrimental impact of shipping emissions, the IMO and the EU have taken certain proactive measures in the recent years. To mitigate SO_x and NO_x emissions, the IMO has established several SECAs (fuel sulphur limit 0.1% m/m) and NECAs (Tier III NO_x limit), while also limiting the global fuel sulphur limit to 0.5% (m/m) from 2020. Further, it has also established a long term target of reducing GHG emissions by 50% by 2050, compared to 2008 levels. In parallel to IMO's targets, the EU has also launched its "Fit-for-55" package as a stringent legislation, which aims to move its regional maritime industry towards decarbonization, by reducing its GHG emissions by at least 55% until 2030, compared to 1990 levels. In conjunction with this package, the EU parliament has recently also adopted a resolution to include shipping in Europe's emission trading scheme (EU ETS) from 2023, with shipowners required to purchase allowances for 20% of the verified emissions, increasing up to 100% by 2026 in a phased manner (Hansen et al., 2021). Non-compliance with such a scheme is expected to lead to heavy fines, and a possible ban on the ships from EU waters. To successfully comply with such stringent measures and decarbonization targets, alternative fuels such as LNG, methanol, hydrogen, and ammonia, have been proposed by such regulatory agencies to the stakeholders to opt for. This study evaluated the cost-effectiveness of such low-to-zero carbon fuels for the case of Top-20 most frequently calling ships to Irish ports, using the NPV analysis, to identify the most optimal long term solution for the stakeholders to invest in.

The primary contribution of this study is that it is one of the first attempts to analyse the cost-effectiveness of alternative fuels while comprising the achieved benefits of saved external costs from the alleviated SO_2, NO_x, $PM_{2.5}$ and CO_2 emissions. The majority of academic literature has either discussed the economic costs of using alternative fuels for shipping, and/or their environmental potential (Brynolf et al., 2014, Deniz and Zincir, 2016, Perčić et al., 2020, Lindstad et al., 2021, McKinlay et al., 2021), while not including the potential environmental benefits that can be achieved in the form of reduced external costs from the utilization of such fuels. It is expected that the exclusion of external costs from cost-benefit studies and from respective regulatory frameworks will result in little incentive for maritime firms to invest in alternative fuel systems for improving the environmental performance (Helgason et al., 2020). From the conducted analysis, it was shown that the use of green hydrogen and green ammonia (as a hydrogen carrier) offered the highest external cost savings amongst the alternative fuels, followed by LNG and methanol, respectively. Although, when comparing the overall cost-effectiveness by NPV, LNG was found to be the most optimal measure, followed by methanol and green hydrogen. The results showed that the usage of green ammonia as an alternative fuel will be unviable, mainly due to higher operational costs, resulting from excessive fuel losses during the cracking and purifying processes and its lower net calorific value.

Further, this study also presented some contributions from the policy perspective, at the regional (EU) alongside global (IMO) levels. To understand the effectiveness of alternative fuels in meeting the long term decarbonization targets, this study compared the total reduction in CO_2 emissions offered by such fuels, using the analysed year 2019 results, against an estimated “baseline 2008” and “baseline 1990” emission levels, respectively. Based on an estimated linear aggregation, while switching to LNG or methanol did reflect some reduction in CO_2 emissions compared to “baseline 2019” levels, in general, the estimated CO_2 emissions remained higher than the “baseline 2008” and “baseline 1990” emissions. Overall, only the use of green hydrogen can help achieve the set ambitious decarbonization targets, as it is an “emission-free” alternative, while also remaining viable to implement due to its positive NPV, which was not possible with the usage of green ammonia. To improve the viability of using green hydrogen over that of methanol and LNG, there will need to be a considerable drop in the current green hydrogen prices, i.e., the prices of green hydrogen will need to be on par with that of grey hydrogen to achieve the highest feasibility among the discussed alternative fuels.

6.5. Policy implications of this research

This thesis conducted cost-benefit analyses for the use of various low-to-zero emission technologies in the maritime industry, having significant implications for the major stakeholders involved in the sector (ports, shipping companies, policymakers, technology providers), at the local, regional, and international levels. From Paper-1, while analysing the cost-effectiveness of using SSE in two Ten-T core network ports (Dublin and Belfast), it was found that the use of SSE will be more profitable when the supplied electricity comes from a grid which largely depends on renewable energy sources. As of 2022, the use of fossil fuels (i.e., non-renewable) sources dominate the overall EU electricity market, with nearly 60% of the electricity being generated by non-renewable sources, with gas being the most dominant source of electricity (19.6%), followed by coal (15.8%). Within EU member states, the share of renewables and non-renewables sources within the overall energy mix differs significantly, and this is attributed to geographical conditions, endowment in natural resources, the structure of countries' economies and political choices. Figure 6.1 presents the share of renewable and non-renewables in the energy mix for EU-27 countries.

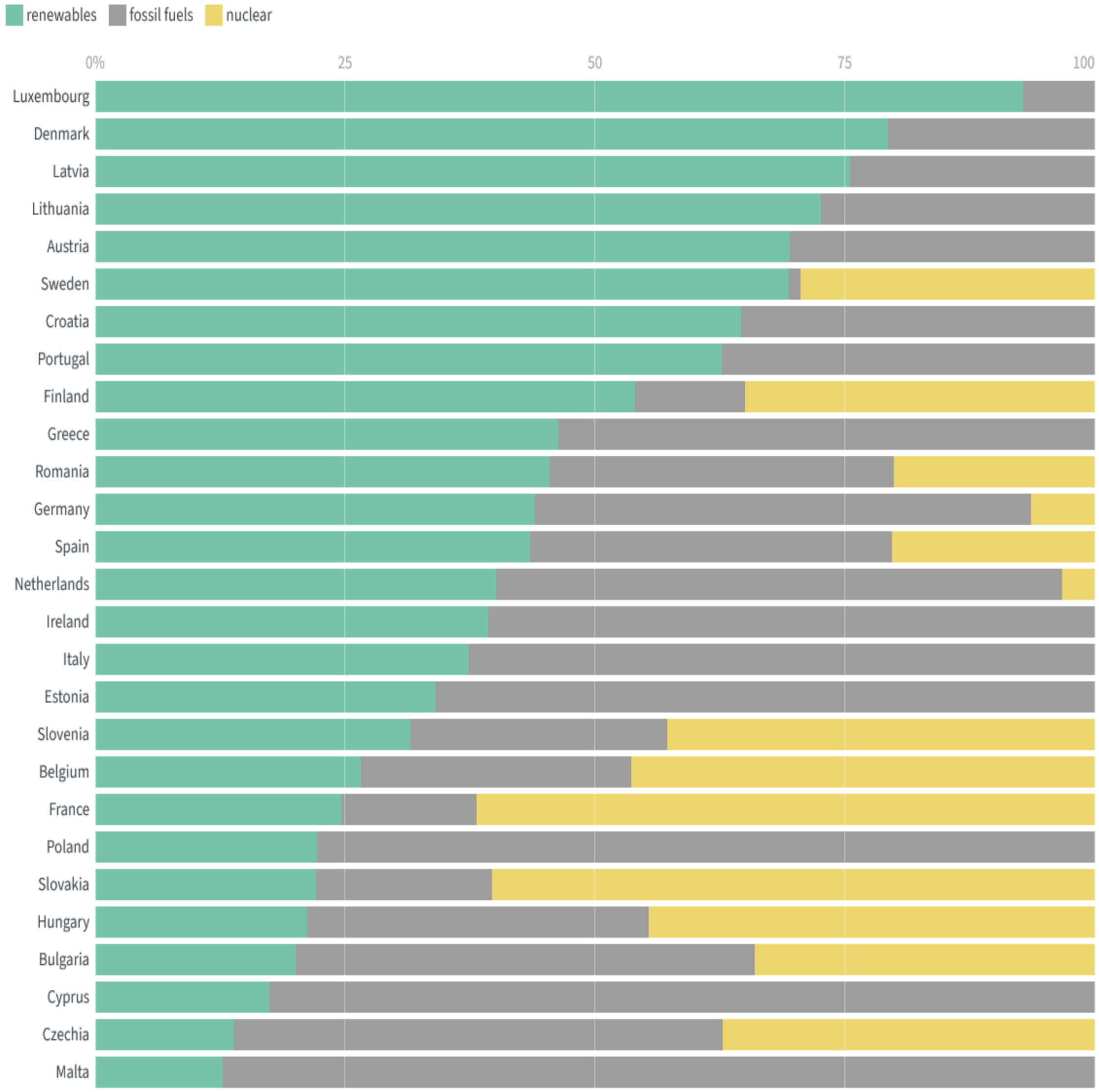


Figure 6.2. Share of renewable and non-renewable sources in grid mix (EU-27)

Source: European Council (2023b)

From Figure 6.1, it was observed that for countries which generally receive the highest share of freight and passenger (e.g., Netherlands, Belgium, Germany, France, Italy, Greece) ship arrivals, the grid energy mix is still dominated by non-renewable energy sources. While several ports in these countries already have installed, or are in the process of installing SSE infrastructure, it is expected that overall cost-effectiveness of using such technology will be higher if the supplied electricity for the berthing ships comes from a renewable-dominated grid energy mix. Further, it is anticipated that the benefits generated from using SSE which is supplied from "cleaner" grid energy mix in such countries will be even higher than that of the considered case study in this research (Ireland), considering their higher population levels and the magnitude of maritime traffic. There is an expected increase in the use of renewable energy sources for power mix in the coming years, with the EU Commission forecasting that nearly 70% of the region's power generation to be fulfilled by renewable sources by 2030, as part of its RePowerEU plan (Enerdata, 2022).

An advantage of using a renewable-dominated grid energy mix is that the supplied electricity price was found to be cheaper than being produced from non-renewable sources such as gas and coal, hence, improving the overall cost-effectiveness of using SSE. Another implication for stakeholders from this study is that while there will be definite need of investments from ports and shipowners to set up SSE infrastructure in port areas and onboard, alongside financing from the local governments. The stakeholders could decide upon a policy (business case) which could help recoup the invested costs within the lifespan of installed technology. For instance, ports could set up a fixed charge per kWh of supplied electricity for shipowners, who can further recoup the invested costs by increasing the ticket price or the carried freight cost. Preparation of such business case while deciding on SSE investment is of utmost importance as the actors who are typically requested to invest on the necessary infrastructure are not the ones which gain the highest benefits from the reduction of the emissions. Further, stakeholders could decide on initial roll out of SSE infrastructure for those ships which tend to visit the same port frequently (e.g., Ro-Ro ships) as such regular ship movements tend to have considerable negative impact on the population residing in the port cities, compared to those ships which make less frequent visits to the ports.

From Paper-2, it was observed that the use of biofuels could also be a cost-competitive option to be used in shipping for IMO-2020 compliance, against that of conventional options such as low-sulphur fuel oils and scrubbers. Biofuels are often used as drop-in fuels, mixing with similar fossil versions of the fuels, presenting an attractive "transitional" option to shipowners as it provides them with a flexible way of achieving carbon reductions without having to make large capital investments. From Paper-2, the use of FAME biodiesel was found to be the most cost-effective option for shipowners to implement for Atlantic-ECA compliance and to achieve short-term targets for carbon reduction, although, its widespread use within the maritime sector is conditional on its production and availability. The EU has been recognised as home to the world's largest FAME market and combining the markets of all 27 countries makes the EU the world's largest FAME producer. The current production capacity of EU-27 member countries is noted in the following Table 6.1.

Table 6.1. EU-27 FAME main producers (Million Litres)

Year	2015	2016	2017	2018	2019	2020	2021	2022
Germany	3,505	3,543	3,644	3,799	4,070	3,875	3,919	3,860
France	2,866	3,152	3,135	2,806	2,556	2,241	2,152	2,060

Spain	1,103	1,319	1,721	2,008	1,835	1,550	1,450	1,350
Poland	861	985	1,019	1,001	1,091	1,081	1,138	1,160
Netherlands	795	638	1,112	1,010	1,081	1,124	1,136	1,140
Italy	558	386	353	508	616	618	620	620
Belgium	535	521	511	511	568	568	568	570
Others	1,022	484	547	853	1,522	1,123	1,117	1,140
Total	11,245	11,028	12,042	12,496	13,339	12,180	12,100	11,900

Source: Flach et al. (2022)

From Table 6.1, it is observed that in 2019, a total of 13,339,000 tons of FAME biodiesel was produced within the EU-27 countries, with the highest producing member state being Germany (4,070,000 tons). Although, the overall production declined by 9% in 2020 mainly due to the impact of COVID-19. While further reductions happened in folloiwng years (2021 and 2022), due to the evolving geo-political situation in eastern Europe, as the impacted region was the one of the major exporters of feedstocks for FAME production.

To understand the need of FAME biodiesel for maritime purposes, some assumptions will have to be made based on the available information. For instance, the current energy demand of shipping is about 280 million tonnes (oil equivalent) per year (DNV, 2023). Considering that EU-27 represents 16% of world imports and exports (European Commission, 2023c), the total share of shipping energy demand for the bloc will stand at approximately 45 million tonnes. Hence, with 20% blending rate of FAME, the total need of biodiesel for the EU ship industry would stand at nearly 9 million tonnes annually. As the most recent figures available (2022) of the bunkering volume for blended biofuels in

Rotterdam was reportedly 800,000 tons (DNV, 2023), this will need to be improved by nearly tenfold to meet the needs of EU shipping. While the current FAME production in EU-27 stands at nearly 12 million tons, the majority of the biodiesel use has been allocated for road vehicles within the transportation sector, hence, this will elicit additional production demand to accommodate the EU shipping requirements.

Furthermore, the EU's Renewable Energy Directive (RED), extended under RED II, has established an overall policy for the production and promotion of energy using "advanced" biofuels in the EU. As low-carbon biofuels replace high-carbon fossil fuels (by life-cycle analysis) in the transportation sector, EU policy is structured to limit further expansion of conventional biofuels and incentivise expanding use of advanced biofuels. This is because advanced biofuels are less likely to result in land use change and may use waste-stream feedstocks or feedstocks that don't require any land use, having minimal impact on food production levels and providing long-term sustainability (Flach et al., 2022). RED II sets an overall binding renewable energy target of 14% for the transport sector, with a clause for a possible upwards revision by 2023. Within the 14 percent transport sector target, food-based biofuels have a maximum cap of 7% for each member state. Also, if the cap on first generation (conventional) biofuels in a member state is less than 7%, the country may reduce the transport target by the same amount (for example, a country with a food and feed crop cap of 6% could set a transport target at 13%). For advanced biofuels, RED II introduces two different sets of targets for feedstock listed in Part A of Annex IX and feedstock listed in Part B. Feedstock listed in Part A (e.g., biomass, non-food cellulosic material) must be supplied at a minimum of 0.2% of transport energy in 2022, 1% in 2025, and at least 3.5% by 2030. Biofuels produced from feedstocks listed in Part B (e.g., used cooking oil, animal fats) will be capped at minimum 1.7% in 2030 (Lieberz, 2022). In 2021, around 9% (23,990,600 tonnes (oil equivalent)) of the total energy consumption of transport sector (2,63,803,900 tonnes (oil equivalent)) in the EU-27 was from renewable sources. Biofuels represented 71% (17,051,400 tonnes) of the total renewable energy share, of which 49% (11,577,000 tonnes) came from food and feed crops (conventional) with the remaining 22% (5,474,400 tonnes) being derived from "advanced" feedstock compliant with REDII directive (SHARES – EUROSTAT, 2023). Hence, in the longer term, if the emerging demands from EU shipping are required to be fulfilled by "advanced" feedstocks ensuring a sustainable supply of biofuels, a major build-up in the production capacity is needed (by nearly threefold) to reach its full potential.

From the comparison of the various shipping alternative fuel technologies in Paper-3, it was found that LNG will be the most cost-effective solution using NPV analysis because of its lower financial costs compared to that of using advanced fuel technologies such as hydrogen and ammonia. Methanol was also found to have higher NPV than that of hydrogen and ammonia owing to near similar cost characteristics to that of LNG, although it offered lower external and carbon tax cost savings when compared to the latter. Both LNG and methanol can be considered as "mature" options, with available bunkering infrastructure in EU states (EMSA, 2023). It is expected that the global LNG fleet could expand by nearly 7.5% in 2023-24 with addition of nearly 140 vessels over the period (Safety4Sea, 2023a). This indicates a sharp rebound from 2022 when global LNG bunkering activity declined as fuel oils traded at significant discounts compared to global LNG prices. However, LNG prices became competitive again as of early 2023 with fuel oils which again established the longer-term fundamentals of a rapidly expanding LNG-fuelled fleet (Safety4Sea, 2023a, Walker, 2023).

The Mediterranean Shipping Company (MSC), recently placed an order of $1 billion to procure 10 LNG-powered container vessels from Zhoushan Changhong shipyard in China, which have an approximate capacity of 10,000 TEUs (Safety4Sea, 2023b). A similar trend could also be seen for methanol utilisation, with around 81 ships to be placed on order for delivery by 2028. The French shipping company of CMA CGM, which until now has been investing mostly in LNG-fuelled ships, placed an order that was valued at over $2 billion for a dozen 13,000 TEU methanol dual-fuel container vessels to be built by Hyundai in South Korea. It follows a smaller order CMA CGM placed in 2022 for its first methanol-powered vessels, with MSC also investing $1.2 billion for methanol-ready dual-fuel containers (Maritime Executive, 2023). Furthermore, some orders have also been noted for the use of ammonia and hydrogen fuel technologies, with around 90 to 130 orders being placed for ammonia-fuelled ships and 3 to 6 orders being noted for hydrogen-fuelled ships (Offshore-Energy, 2022). Also, some of the ordered ships will be fitted with an onboard ammonia cracking propulsion system (Ammonia Energy Association, 2023). Figure 6.2 depicts the level of alternative fuel uptake in the world fleet by ships and gross tonnage.

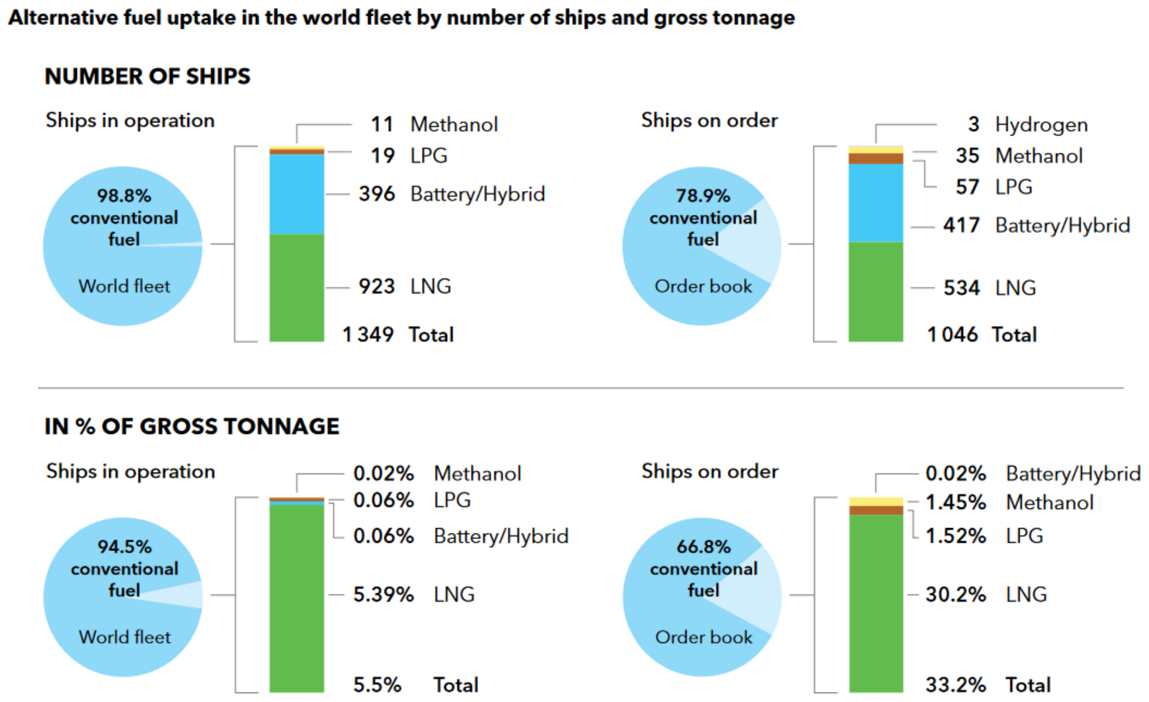


Figure 6.3. Alternative fuel uptake (world fleet) by number of ships and gross tonnage

Source: DNV (2022b)

From Figure 6.2, it could be seen that LNG has been the most preferred alternative fuel solution for shipowners, which is in agreement with the obtained results from Paper-3 as it found the highest NPV for LNG fuel. Although, when the considered alternative fuel technologies were compared on the basis of meeting EU's 2030 "Fit-for-55" and IMO's 2050 decarbonization targets, only the use of green hydrogen and green ammonia were found to be the suitable solutions to do so, while LNG and methanol despite being more economically viable options, will not be able to breach the set targets. Further, the use of LNG could also lead to increase in methane (CH_4) emissions, as evident from the fourth IMO GHG study (IMO, 2020), which showed that CH_4 emissions have increased by nearly twofold in the last few years, mainly due to the uptake of LNG fuel technology in shipping industry (IMO, 2020). The increase in CH_4 emissions is mainly due to the occurrence of "methane slip", in the form of unburned fuel emitted from the dual-fuel internal combustion engine on ships. CH_4 is a potent GHG that that traps 86 times more heat in the atmosphere than the same amount of CO_2 over a 20-year time period, causing more potential damage to the environment (Pavlenko et al., 2020). Hence, even considering the lower GHG improvements offered by LNG and methanol, it is important for stakeholders to look at other available options if they have to steer the industry towards the long-term decarbonization targets. While green hydrogen and green ammonia do seem to offer a "zero-emission solution", the use of green ammonia will be potentially unviable if it is used in onboard cracking propulsion system, mainly due to its high operating costs from the excessive consumption of ammonia for cracking propulsion. Therefore, the only available alternative fuel technology which could meet the decarbonization targets while remaining financially viable is that of green hydrogen.

A major challenge with the employment of green hydrogen for shipping purposes is its limited availability. Globally, demand for hydrogen is met almost entirely by production from unabated fossil fuels. In 2021, total global production was 94 million tonnes of hydrogen with associated emissions of more than 900 million tonnes of CO_2. Natural gas accounted for 62% of hydrogen production, followed by coal (19%) and as a by-product of naphtha reforming at refineries (18%), with low-emission hydrogen production being less than 1 million tonnes (0.7%) (IEA, 2022). A similar trend was also visible in the EU, where hydrogen made up for less than 2% of Europe’s energy consumption, primarily being used to produce chemical products, such as plastics and fertilisers, with nearly 96% of the total hydrogen (9.7 million tonnes) being produced with natural gas (Kakoulaki et al., 2021, European Commission, 2023d). As part of the RePowerEU plan, the regional bloc has been focusing on improving green hydrogen production, with the set target being to produce 10 million tonnes of clean hydrogen by 2030, along with 10 million tonnes of imported green hydrogen by the target year (European Commission, 2023d).

To facilitate this roadmap, the EU has set up a “Clean Hydrogen Alliance”, where it has agreed to increase the electrolyser manufacturing capacity by tenfold by 2025 (17.5 GW per year) in a joint declaration with the industry stakeholders (European Commission, 2022b). Although, it is projected that nearly 15 million tonnes of green hydrogen will be required annually if all ships under EU-MRV switch from using conventional fuels, with approximate capacity of 200 GW being needed through electrolysis (Hydrogen Europe, 2021), possibly over exceeding the set green hydrogen production and import targets by the EU. Also, there is currently a low level of maturity of the technology for the use of hydrogen in shipping, with certain ongoing demonstrations trying to understand its feasibility in terms of onboard storage, bunkering, and safety requirements (DNV, 2021b). Hence, it could be implied that in such scenario, the “Fit-for-55” targets set by the EU will not be achievable, although, with an expected increase in commercialisation of hydrogen as marine fuel post-2030 with further push in green hydrogen production (DNV, 2021b, European Parliament, 2023b), the set IMO-2050 targets could be met.

When looking at policy implications from the perspective of the considered case study for this research, Ireland being a member state of the EU has obligations to follow and achieve the set targets as part of the “Fit-for-55” project and the FuelEU maritime proposal. Despite having four Ten-T core network ports in the country (Dublin, Belfast, Cork, Limerick), there is no provision till date for providing SSE at berth for ship arrivals. Considering that the use of SSE it will become mandatory in 2030 for freight and passenger ships berthing in EU Ten-T core network ports, the policymakers, and other stakeholders (e.g., port operators) will be required to take swift decisions with regards to its successful implementation.

In terms of the local grid energy mix, it is expected that nearly 80% of Irish electricity production by 2030 will be through renewable sources (mainly wind and solar). This will significantly propel the profitability of using SSE in Ireland, even for those ports (e.g., Belfast) which did not reflect financial viability when using electricity produced from the current grid, which is dominated by non-renewable (fossil fuels) sources. Further, as Ireland is expected to be a part of the upcoming “North-Atlantic ECA” alongside UK, France, Norway, Spain, and Portugal, this directive will require the use of low-sulphur (<0.1%) technologies within the designated area. In this research, it was shown that the use of FAME biodiesel will be the optimal alternative when compared to that of using scrubbers and MGO, when applied on Ro-Ro ships. Ro-Ro is the most popular ship type within the Irish maritime traffic sector and make up the bulk of the total share, operating on Irish–British and Irish–French/Spanish routes, which will be covered under the designated ECA zone. Based on such results, the Irish government can play a vital role in promoting the use of blended FAME at least for Ro-Ro ships which tend to operate on a fixed route especially when the entirety of their journey will be in the ECA zone, as this will significantly lower the bunkering demands of conventional diesel fuels, while steering the shipping industry towards long term decarbonization targets and also improving the local circular economy.

A major step which could be taken in this direction will be the inclusion of Ro-Ro ships within the Irish biofuel obligation scheme, which currently requires the blends of at least 11% in the motor fuel oil for road transport. Although, this policy change will require further acceleration in the biodiesel production capacity, this is achievable considering the available feedstock reserves in the nation. In relation to alternative fuel technologies, the Irish government has recently rolled out its "National Hydrogen Strategy", which aims to boost the production of green hydrogen within the nation, by connecting 2 GW through its offshore wind facilities to green hydrogen production plants by 2030 (Department of the Environment, Climate and Communications, 2023). It is expected that such projects could yield 138,000 tonnes of hydrogen a year, significantly more than Ireland's projected 33,000 tonnes a year demand, by 2030. The impetus behind the expected production boost of green hydrogen lies in the fact that Ireland is one of the windiest countries on the planet, with average wind speed of 10 metres per second, giving it significant strategic advantage (Collins, 2023). A recent study by Aurora Energy Research indicated that Ireland has the potential to produce cheapest green hydrogen energy in Europe, at a levelized cost of €3.50/kg, nearly 8% lower than Spain and 35% lower than that of Germany, the other two major producers in Europe (Parkes, 2023).

While the current Irish green hydrogen sector is still considered to be at a very "nascent" level, significant policy action will be required in terms of supply-demand infrastructure if it has to meet the 2030 targets. There will also be need for any regulatory or fiscal measures such as subsidies on locally produced green hydrogen, as it is projected that domestically produced green hydrogen will not be cost-competitive with that of fossil-based "blue" hydrogen or against the imported green hydrogen (Parkes, 2023). From the maritime perspective, even considering a favourable scenario where Ireland reaches its full potential of producing 138,000 tonnes of hydrogen a year by 2030, it will not suffice as the requirements arising from just its usage by the most significant ship type of Irish maritime sector (Ro-Ro) will generate a demand of nearly 140,000 tonnes per year. Hence, the achievement of "Fit-for-55" targets for the Irish maritime sector looks unviable, although, considering a similar trajectory of growth in its green hydrogen production capability, the sector could potentially meet the 2050 IMO targets. Parallel to the EU and IMO targets, another significance of using green hydrogen fuel is that for the concept of green shipping corridors, which was initiated at the COP26 through "Clydebank Declaration", which includes Ireland as signatory. As majority of the green shipping corridors set up are focussed on short-sea shipping, Irish and UK and/or EU authorities could implement similar policy design for Ro-Ro ship routes, to comply with the Clydebank Declaration.

6.6. General limitations and future research

Despite the contributions that this thesis brings, it is not without limitations. Firstly, for all the three studies, considerable efforts were made to improve the reliability of the collected data, by obtaining precise information on ship activities using the Refinitiv Eikon AIS and/or EU-MRV databases. Although information on issues such as engine and fuel type profiles, load factors, SFC values, emission factors, external cost factors, prices for alternative fuels, biofuels and conventional diesel fuels, carbon tax rate, capital (installation and retrofit) costs and other related operational and maintenance costs, historic CO_2 emissions levels (in Paper-3) were obtained from high quality sources and adjusted specifically based on the requirements of the study, they are bound to have some inherent variation. In terms of external cost valuation, the cost factors used have been widely applied in the literature and an attempt was made to localise the cost factors as much as possible.

Although, future studies could employ a comparatively precise “bottom-up” (Impact Pathway Assessment) instead of “top-down” approach for external cost calculation, which will require dispersion modelling, exposure modelling, impact, and damage valuation. Secondly, this thesis considered the “Irish National Social Discount Rate” for the purpose of cost-benefit analysis of technological and operational investments, which presents a limitation. Discount rate is usually calculated as specific to a particular investor or company's situation, and a company may typically decide its discount rate for new investments based on current interest rates plus a risk premium specific to the potential investment opportunity which is under consideration (Bezek, 2022). Hence, it is expected that future studies will overcome this limitation by considering more specific discount rates for cost-benefit analysis. However, a shipowner can easily take the results of this study and vary the discount rate to estimate the outcomes for their own business given the data in the study. Thirdly, this study was limited to the Irish maritime sector, and predominantly focused on passenger and Ro-Ro ships. This mix of maritime activity is not unusual in peripheral countries around major land masses this providing results that are partially generalisable. Future studies can use the proposed methodological framework presented to calculate the costs and benefits of using emission abatement technologies for long-distance ships, to analyse if such technologies retain their cost-effectiveness when utilised in such varied scenarios. Fourthly, there were certain abatement technologies such as Di-Methyl Ether, Ethanol, Battery-powered, Selective Catalytic Reduction, Exhaust Gas Recirculation, which were not considered in this thesis, but could be included for cost-benefit assessments in future. Also, since the focus for this research was primarily on “tank-to-wake” phase, future studies could focus on the complete life cycle analysis (well-to-wake) to draw thorough comparisons between the available fuel technologies, based on their provided environmental benefits and the related economic costs.

REFERENCES

Abadie, L.M., Goicoechea, N., Galarraga, I., 2017. Adapting the shipping sector to stricter emissions regulations: Fuel switching or installing a scrubber? Transp. Res. Part D Transp. Environ. 57, 237–250. https://doi.org/10.1016/j.trd.2017.09.017

Ahearne, A., Cassidy, D, 2023. The impact of Fit for 55 on Ireland's maritime transport sector and the macroeconomy. Marit. Econ. Logist. 123, 1-25 https://doi.org/10.1057/s41278-023-00267-9

Afloat, 2023. Final Cruise Call to Belfast Harbour Marks Successful Season. https://afloat.ie/port-news/cruise-liners/item/56926-final-caller-to-belfast-harbour-marks-successful-cruise-season

Al-Breiki, M., Bicer, Y., 2020. Investigating the Effects of Boil-off Gas on Liquefied Energy Carriers During Land Storage and Ocean Transportation. IOP Conf. Ser. Earth Environ. Sci. 581, 012017. https://doi.org/10.1088/1755-1315/581/1/012017

Al-Enazi, A., Okonkwo, E.C., Bicer, Y., Al-Ansari, T., 2021. A review of cleaner alternative fuels for maritime transportation. Energy Reports 7, 1962–1985. https://doi.org/10.1016/J.EGYR.2021.03.036

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

ABS, 2020. Ammonia as marine fuel. https://safety4sea.com/wp-content/uploads/2021/01/Ammonia_as_Marine_Fuel_Whitepaper_20188.pdf

ABS, 2022. MEPC 78. https://ww2.eagle.org/content/dam/eagle/regulatory-news/2022/ABS%20MEPC%2078%20Brief.pdf

Ammar, N.R., 2019. An environmental and economic analysis of methanol fuel for a cellular container ship. Transp. Res. Part D Transp. Environ. 69, 66–76. https://doi.org/10.1016/J.TRD.2019.02.001

Ammar, N.R., Seddiek, I.S., 2017. Eco-environmental analysis of ship emission control methods: Case study RO-RO cargo vessel. Ocean Eng. 137, 166–173. https://doi.org/10.1016/J.OCEANENG.2017.03.052

Ammonia Energy Association, 2023. Cracking-based propulsion systems, new vessels on order. https://www.ammoniaenergy.org/articles/cracking-based-propulsion-systems-new-vessels-on-order/

Ampah, J.D., Yusuf, A.A., Afrane, S., Jin, C., Liu, H., 2021. Reviewing two decades of cleaner alternative marine fuels: Towards IMO's decarbonization of the maritime transport sector. J. Clean. Prod. 320, 128871. https://doi.org/10.1016/J.JCLEPRO.2021.128871

Antturi, J., Hänninen, O., Jalkanen, J.P., Johansson, L., Prank, M., Sofiev, M., Ollikainen, M., 2016. Costs and benefits of low-sulphur fuel standard for Baltic Sea shipping. J. Environ. Manage. 184, 431–440. https://doi.org/10.1016/J.JENVMAN.2016.09.064

Argus, 2021. 'Green' ammonia prices double that of regular supplies. https://www.argusmedia.com/en/press-releases/2021/green-ammonia-prices-double-that-of-regular-supplies

Ay, C., Seyhan, A. and Beşikçi, E.B., 2022. Quantifying ship-borne emissions in Istanbul Strait with bottom-up and machine-learning approaches. Ocean Eng. 258, p.111864. https://doi.org/10.1016/j.oceaneng.2022.111864

Balcombe, P., Brierley, J., Lewis, C., Skatvedt, L., Speirs, J., Hawkes, A., Staffell, I., 2019. How to decarbonise international shipping: Options for fuels, technologies and policies. Energy Convers. Manag. 182, 72–88. https://doi.org/10.1016/J.ENCONMAN.2018.12.080

Balcombe, P., Staffell, I., Kerdan, I.G., Speirs, J.F., Brandon, N.P., Hawkes, A.D., 2021. How can LNG-fuelled ships meet decarbonisation targets? An environmental and economic analysis. Energy 227, 120462. https://doi.org/10.1016/J.ENERGY.2021.120462

Ballini, F., Bozzo, R., 2015. Air pollution from ships in ports: The socio-economic benefit of cold-ironing technology. Res. Transp. Bus. Manag. 17, 92–98. https://doi.org/10.1016/J.RTBM.2015.10.007

Barker, C., 2020. Europe caustic soda Q1 price falls 10% as market readjusts. https://www.icis.com/explore/resources/news/2020/01/28/10461663/europe-caustic-soda-q1-price-falls-10-as-market-readjusts/

Batlle, C., Schittekatte, T., Knittel, C., 2022. Power Price Crisis in the EU: Unveiling Current Policy Responses and Proposing a Balanced Regulatory Remedy. https://ceepr.mit.edu/workingpaper/power-price-crisis-in-the-eu-unveiling-current-policy-responses-and-proposing-a-balanced-regulatory-remedy/

Bezek, I., 2022. What is a discount rate? https://seekingalpha.com/article/4514707-discount-rate-definition-calculation

Bicer, Y., Dincer, I., 2018. Clean fuel options with hydrogen for sea transportation: A life cycle approach. Int. J. Hydrogen Energy 43, 1179–1193. https://doi.org/10.1016/J.IJHYDENE.2017.10.157

Bilgili, L., 2021. Comparative assessment of alternative marine fuels in life cycle perspective. Renew. Sustain. Energy Rev. 144, 110985. https://doi.org/10.1016/J.RSER.2021.110985

Blenkey, N., 2021. IMO: Transition to low-sulphur fuels “extremely smooth”. https://www.marinelog.com/news/imo-transition-to-low-sulfur-fuels-extremely-smooth/

Boccara, G., Boszczyk, K., Browne, N., Heringa, B., 2022. Reflecting on 2021 global LNG and European pipeline flows | McKinsey & Company. https://www.mckinsey.com/industries/oil-and-gas/our-insights/petroleum-blog/reflecting-on-2021-global-lng-and-european-pipeline-flows

Bouman, E. A., Lindstad, E., Rialland, A. I., & Strømman, A. H. (2017). State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – A review. Transp. Res. Part D Transp. Environ. 52, 408–421. https://doi.org/10.1016/J.TRD.2017.03.022

BVNA, 2023. Alternative Fuels Infrastructure Regulation (AFIR). https://marine-offshore.bureauveritas.com/sustainability/fit-for-55/alternative-fuels-infrastructure

Brynolf, S., Fridell, E., Andersson, K., 2014. Environmental assessment of marine fuels: liquefied natural gas, liquefied biogas, methanol and bio-methanol. J. Clean. Prod. 74, 86–95. https://doi.org/10.1016/J.JCLEPRO.2014.03.052

Campling, P., Janssen, L., Vanherle Janusz Cofala, K., Heyes, C., Sander, R., 2013. Specific evaluation of emissions from shipping including assessment of possible new emission control areas. https://circabc.europa.eu/sd/a/7a24142b-d81f-4882-84a5-4216629ff562/Final%20Report_VITO_International%20Shipping_March-annexes.pdf

Cariou, P., Lindstad, E., Jia, H., 2021. The impact of an EU maritime emissions trading system on oil trades. Transp. Res. Part D Transp. Environ. 99. https://doi.org/10.1016/j.trd.2021.102992

Castells Sanabra, M., Usabiaga Santamaría, J.J., Martínez De Osés, F.X., 2014. Manoeuvring and hotelling external costs : enough for alternative energy sources? Marit. Policy Manag. 41, 42–60. https://doi.org/10.1080/03088839.2013.782441

Chatzinikolaou, S. D., Oikonomou, S. D., & Ventikos, N. P. (2015). Health externalities of ship air pollution at port - Piraeus port case study. Transp. Res. Part D Transp. Environ. 40, 155–165. https://doi.org/10.1016/j.trd.2015.08.010

Chen, X. and Yang, J., 2024. Analysis of the uncertainty of the AIS-based bottom-up approach for estimating ship emissions. Mar. Pollut. Bull. 199, p.115968. https://doi.org/10.1016/j.marpolbul.2023.115968

Collins, L., 2023. Ireland unveils national hydrogen strategy - with aim to export green H2 https://www.hydrogeninsight.com/policy/ireland-unveils-national-hydrogen-strategy-with-aim-to-export-green-h2-made-from-offshore-wind-and-no-role-for-blue/

Corbett, J. J., Winebrake, J. J., Green, E. H., Kasibhatla, P., Eyring, V., & Lauer, A. (2007). Mortality from ship emissions: A global assessment. Environ. Sci. Technol. 41, 8512–8518. https://doi.org/10.1021/es071686z

CSO, 2020. Maritime transport 2019. https://www.cso.ie/en/releasesandpublications/ep/p-tranom/transportomnibus2019/maritime/ (accessed 5.5.23)

CSO, 2022a. Regional SDGs https://www.cso.ie/en/releasesandpublications/ep/p-rsdgi/regionalsdgsireland2017/nt/ (accessed 2.15.23).

CSO, 2022b. Population Distribution - CSO - Central Statistics Office. https://www.cso.ie/en/releasesandpublications/ep/p-cp2tc/cp2pdm/pd/

CSO, 2022c. Population Projection. https://www.cso.ie/en/releasesandpublications/ep/p-plfp/populationandlabourforceprojections2017-2051/populationprojectionsresults/

[Dataset] CSO, 2023. Cruise ships and passenger visits to Irish ports 2006-2022. CSO Maritime Transport Statistics. https://data.cso.ie/table/TBA10

Dai, L., Hu, H., Wang, Z., Shi, Y., Ding, W., 2019. An environmental and techno-economic analysis of shore side electricity. Transp. Res. Part D Transp. Environ. 75, 223–235. https://doi.org/10.1016/J.TRD.2019.09.002

Dai, L., Hu, H., Wang, Z., 2020. Is Shore Side Electricity greener? An environmental analysis and policy implications. Energy Policy 137, 111144. https://doi.org/10.1016/J.ENPOL.2019.111144

Dai, L., Jing, D., Hu, H., & Wang, Z., 2021. An environmental and techno-economic analysis of transporting LNG via Arctic route. Transp. Res. Part A Policy Pract. 146, 56–71. https://doi.org/10.1016/J.TRA.2021.02.005

Dai, H., Li, N., Wang, Y. and Zhao, X., 2022, March. The Analysis of Three Main Investment Criteria: NPV IRR and Payback Period. 7th International Conference on Financial Innovation and Economic Development (ICFIED 2022), pp. 185-189. Atlantis Press. https://www.atlantis-press.com/article/125971510.pdf

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

De Jonge, E., Hugi, C., Cooper, D., 2005. European Commission Directorate General Environment Service Contract on Ship Emissions: Assignment, Abatement and Market-based Instruments Task 2a – Shore-Side Electricity Final Report ENTEC UK Limited.

De Jonge, E., Hugi, C., Cooper, D., 2005. European Commission Directorate General Environment Service Contract on Ship Emissions: Assignment, Abatement and Market-based Instruments. https://sustainableworldports.org/wp-content/uploads/EU-Commission-Directorate-General-Enviroment.pdf

DEMACO, 2022. What to do with hydrogen boil-off gas? - Demaco Holland B.V. https://demaco-cryogenics.com/blog/what-to-do-with-hydrogen-boil-off-gas/

De Meyer, P., Maes, F., Volckaert, A., 2008. Emissions from international shipping in the Belgian part of the North Sea and the Belgian seaports. Atmos. Environ. 42, 196–206. https://doi.org/10.1016/J.ATMOSENV.2007.06.059

Den Boer, E., Hoen, M., 2015. Scrubbers-An economic and ecological assessment. URL https://www.nabu.de/downloads/150312-Scrubbers.pdf (accessed 10.11.22)

Deniz, C., & Kilic, A., 2010. Estimation and assessment of shipping emissions in the region of Ambarlı Port, Turkey. Environ. Prog. Sustain. Energy. 29, 107–115. https://doi.org/10.1002/EP.10373

Deniz, C., Zincir, B., 2016. Environmental and economical assessment of alternative marine fuels. J. Clean. Prod. 113, 438–449. https://doi.org/10.1016/J.JCLEPRO.2015.11.089

Department of Public Expenditure and Reform, 2019. Public Spending Code A Guide to Economic Appraisal: Carrying Out a Cost Benefit Analysis. https://assets.gov.ie/43557/617fc33b09834fe188a952973a304544.pdf

Department of the Environment Climate and Communications, 2020. Energy. https://www.gov.ie/en/policy/9cd812-energy/#

Department of the Environment Climate and Communications, 2021. Transport Energy. https://www.gov.ie/en/policy-information/e1539-transport-energy/

Department of the Environment Climate and Communications, 2022. Major acceleration of renewables (wind, solar) and community energy as provisional results of second Renewable Electricity Support Scheme (RESS) auction announced. https://www.gov.ie/en/press-release/7f8e5-major-acceleration-of-renewables-wind-solar-and-community-energy-as-provisional-results-of-second-renewable-electricity-support-scheme-ress-auction-announced/

Department of the Environment Climate and Communications, 2023. National Hydrogen Strategy. https://www.gov.ie/pdf/?file=https://assets.gov.ie/263248/f982c10f-eca6-4092-a305-90000e5213ed.pdf#page=null

Department of Transport, 2021. Irish Maritime Directorate Strategy 2021-2025. https://www.gov.ie/en/publication/a7b8d-irish-maritime-directorate-strategy-2021-2025/

Di Christopher, T., 2021. Experts explain why green hydrogen costs have fallen and will keep falling. https://www.spglobal.com/marketintelligence/en/news-insights/latest-news-headlines/experts-explain-why-green-hydrogen-costs-have-fallen-and-will-keep-falling-63037203

DNV, 2018. Assessment Of Selected Alternative Fuels. https://sustainableworldports.org/wp-content/uploads/DNV-GL_2018_Assessment-of-selected-alternative-fuels-and-tech-report.pdf

DNV, 2021a. Fit for 55 – New EU GHG regulations for ships coming soon. https://www.dnv.com/news/fit-for-55-new-eu-ghg-regulations-for-ships-coming-soon-208746

DNV, 2021b. Maritime forecast to 2050. Energy Transition Outlook 2021. https://www.dnv.com/Publications/maritime-forecast-to-2050-2021-edition-185650

DNV, 2022a. Decarbonizing Shipping. https://www.dnv.com/maritime/hub/decarbonize-shipping/key-drivers/regulations/regional-developments/eu.html

DNV, 2022b. Maritime Forecast to 2050 – 2022 edition. https://www.dnv.com/Publications/maritime-forecast-to-2050-2022-edition-235251

DNV, 2023. Biofuels in Shipping https://www.dnv.com/maritime/publications/biofuels-in-shipping-white-paper-download.html

Dragović, B., Tzannatos, E., Tselentis, V., Meštrović, R., Škurić, M., 2018. Ship emissions and their externalities in cruise ports. Transp. Res. Part D Transp. Environ. 61, 289–300. https://doi.org/10.1016/J.TRD.2015.11.007

Dublin Port, 2019. Dublin Port Company Yearbook 2019. https://www.dublinport.ie/wp-content/uploads/2020/01/Dublin-Port-Yearbook-2019-for-issuu-website.pdf

Eason, C., 2023. Sulphur Emission Control Areas Grow. https://fathom.world/emission-control-areas-grow/

Ellis, J. and Tanneberger, K., 2015. Study on the use of ethyl and methyl alcohol as alternative fuels in shipping. https://eibip.eu/wp-content/uploads/2018/01/Study-on-the-use-of-ethyl-and-methyl-alcohol-as-alternative-fuels.pdf

EMSA, 2023. LNG Bunkering and OPS. https://www.emsa.europa.eu/sustainable-ports/lng-bunkering-ops

Enerdata, 2022. The share of renewables in the EU power mix should reach 69% in 2030. https://www.enerdata.net/publications/daily-energy-news/share-renewables-eu-power-mix-should-reach-69-2030.html

Energia, 2022. Gone With The Wind: Why Electricity Prices Change With the Weather. https://energiagroup.com/news-media/gone-with-the-wind/

EPA, 2020. Chapter 12: Environment and Energy. https://www.epa.ie/publications/monitoring--assessment/assessment/state-of-the-environment/EPA-Ireland%27s-Environment-2020-Chapter12.pdf

EPA, 2021. Ireland Air Émissions 1990-2030. https://www.epa.ie/publications/monitoring--assessment/climate-change/air-emissions/EPA-Irelands-Air-Pollutant-Emissions-report_2021Final.pdf

EPRS, 2023. Sustainable maritime fuels 'Fit-for-55': The FuelEU Maritime proposal. https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/698808/EPRS_BRI(2021)698808_EN.pdf

ESPO, 2019. ESPO ENVIRONMENTAL REPORT 2019- Eco Ports Insights 2019. https://www.espo.be/media/Environmental%20Report-2019%20FINAL.pdf

ESPO, 2021. Towards an intelligent legislative framework for Onshore Power Supply (OPS): Europe's ports fully support more OPS where it makes sense. https://www.espo.be/media/2021.11.29%20ESPO%20position%20on%20AFIR%20and%20FuelEU.pdf

ESPO, 2022. ESPO Position on the proposal for a council directive restructuring the union framework for taxation of energy products and electricity. https://www.espo.be/views/espo-position-on-the-proposal-for-a-council-direct

[Dataset] EU-MRV, 2019. CO_2 Emission report. EU-MRV Database. https://mrv.emsa.europa.eu/#public/emission-report

European Central Bank, 2022. US dollar (USD). https://www.ecb.europa.eu/stats/policy_and_exchange_rates/euro_reference_exchange_rates/html/eurofxref-graph-usd.en.html

European Commission, 2020a. Stepping up Europe's 2030 climate ambition, Investing in a climate-neutral future for the benefit of our people. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:52020DC0562

European Commission, 2020b. Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions. A hydrogen strategy for a climate-neutral Europe. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52020DC0301

European Commission, 2022a. Biofuels. https://energy.ec.europa.eu/topics/renewable-energy/bioenergy/biofuels_en

European Commission, 2022b. Hydrogen: Commission supports industry commitment to boost by tenfold electrolyser manufacturing capacities in the EU. https://ec.europa.eu/commission/presscorner/detail/en/ip_22_2829

European Commission, 2023a. European Green Deal: ambitious new law agreed to deploy sufficient alternative fuels infrastructure. https://ec.europa.eu/commission/presscorner/detail/en/ip_23_1867

European Commission, 2023b. Biofuels for transport. https://transport.ec.europa.eu/transport-themes/clean-transport-urban-transport/clean-and-energy-efficient-vehicles/green-propulsion-transport/biofuels-transport_en

European Commission, 2023c. EU position in world trade. https://policy.trade.ec.europa.eu/eu-trade-relationships-country-and-region/eu-position-world-trade_en

European Commission, 2023d. Energy Systems and Integration – Hydrogen. https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen_en

European Council, 2022. “Fit for 55”: Council agrees on higher targets for renewables and energy efficiency - Consilium. https://www.consilium.europa.eu/en/press/press-releases/2022/06/27/fit-for-55-council-agrees-on-higher-targets-for-renewables-and-energy-efficiency/

European Council, 2023a. FuelEU maritime initiative: Council adopts new law to decarbonise the maritime sector. https://www.consilium.europa.eu/en/press/press-releases/2023/07/25/fueleu-maritime-initiative-council-adopts-new-law-to-decarbonise-the-maritime-sector/

European Council, 2023b. Infographic - How is EU electricity produced and sold? https://www.consilium.europa.eu/en/infographics/how-is-eu-electricity-produced-and-sold

European Environment Agency, 2022. Share of energy consumption from renewable sources in Europe. https://www.eea.europa.eu/ims/share-of-energy-consumption-from

[Dataset] European Environment Agency, 2023a. Air pollutant emissions data viewer (Gothenburg Protocol, Air Convention) 1990-2021. https://www.eea.europa.eu/data-and-maps/dashboards/air-pollutant-emissions-data-viewer-5

[Dataset] European Environment Agency, 2023b. EEA greenhouse gases – data viewer. European Environment Agency database. https://www.eea.europa.eu/data-and-maps/data/data-viewers/greenhouse-gases-viewer

European Parliament, 2005. DIRECTIVE 2005/33/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 6 July 2005 https://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2005:191:0059:0069:EN:PDF

European Parliament, 2018. European Parliament resolution of 25 October 2018 on deployment of infrastructure for alternative fuels in the European Union: time to act. https://www.europarl.europa.eu/doceo/document/TA-8-2018-0438_EN.html

European Parliament, 2023a. European Parliament legislative resolution on the proposal for the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU https://www.europarl.europa.eu/doceo/document/TA-9-2023-0261_EN.pdf

European Parliament, 2023b. Renewable hydrogen: what are the benefits for the EU? URL https://www.europarl.europa.eu/news/en/headlines/society/20210512STO04004/renewable-hydrogen-what-are-the-benefits-for-the-eu

Eurostat, 2021. Maritime freight and vessels statistics - Statistics Explained. https://ec.europa.eu/eurostat/databrowser/view/MAR_GO_AM_IE/default/table?lang=en

[Dataset] Eurostat, 2022a. Gross weight of goods transported to/from main ports - Ireland https://ec.europa.eu/eurostat/databrowser/view/MAR_GO_AM_IE/default/table?lang=en

[Dataset] Eurostat, 2022b. Vessels in main ports by type and size of vessels (based on inwards declarations) - quarterly data. Eurostat Database. https://ec.europa.eu/eurostat/databrowser/view/MAR_TF_QM/default/table?lang=en

[Dataset] Eurostat, 2022c. Electricity prices by type of user. Eurostat Database. https://ec.europa.eu/eurostat/databrowser//product/view/TEN00117

Eurostat, 2022d. Energy production and imports. https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_production_and_imports

[Dataset] Eurostat, 2022e. Country level - number and gross tonnage of vessels in the main ports (based on inwards declarations), by type of vessel. Eurostat database. https://ec.europa.eu/eurostat/databrowser/product/view/MAR_MT_AM_CSVI

[Dataset] Eurostat, 2023a. Usually resident population on 1 January. Eurostat Database. https://ec.europa.eu/eurostat/databrowser/view/TPS00001/default/table?lang=en

[Dataset] Eurostat, 2023b. Gross weight of goods transported to/from main ports - Ireland. https://ec.europa.eu/eurostat/databrowser/view/MAR_GO_AM_IE/default/table?lang=en

[Dataset] Eurostat, 2023c. Country level - gross weight of goods handled in main ports, https://ec.europa.eu/eurostat/databrowser/view/mar_mg_am_cwhc/default/table?lang=en

Eyring, V., Isaksen, I.S.A., Berntsen, T., Collins, W.J., Corbett, J.J., Endresen, O., Grainger, R.G., Moldanova, J., Schlager, H., Stevenson, D.S., 2010. Transport impacts on atmosphere and climate: Shipping. Atmos. Environ. 44, 4735–4771. https://doi.org/10.1016/j.atmosenv.2009.04.059

Fahnestock, J., 2022. “If Green Corridors succeed, in 2030 zero-emission shipping will be a commercially viable option anywhere”. https://climatechampions.unfccc.int/green-corridors-cop27/

Fan, L., Gu, B., Luo, M., 2020. A cost-benefit analysis of fuel-switching vs. hybrid scrubber installation: A container route through the Chinese SECA case. Transp. Policy 99, 336–344. https://doi.org/10.1016/j.tranpol.2020.09.008

Faster-Capital, 2023. NPV Rule vs Payback Period: Which One is More Reliable https://fastercapital.com/content/NPV-Rule-vs-Payback-Period--Which-One-is-More-Reliable.html

Fathom World, 2022. Updated guidance on using type-c tanks for new fuels. https://fathom.world/abs-issues-updated-guidance-on-using-type-c-fuel-tanks-as-new/

Fernando, J., 2024. Net Present Value (NPV): What It Means and Steps to Calculate It https://www.investopedia.com/terms/n/npv.asp

Flach, B., Lieberz, S., Bolla, S., 2022. Biofuels Annual: European Union. https://apps.fas.usda.gov/newgainapi/api/Report/DownloadReportByFileName?fileName=Biofuels%20Annual_The%20Hague_European%20Union_E42022-0048.pdf

Gallant, C., 2024. Net Present Value vs Internal Rate of Return. https://www.investopedia.com/ask/answers/05/npv-irr.asp

Gerretsen, I., 2022. UN body makes ‘breakthrough’ on carbon price proposal for shipping. https://climatechangenews.com/2022/05/23/un-body-makes-breakthrough-on-carbon-price-proposal-for-shipping/

Gielen, D., Boshell, F., Castellanos, G., Rouwenhorst, K., Brown, T., 2022. Renewable Ammonia’s role in reducing dependence on Gas - Energy Post. https://energypost.eu/renewable-ammonias-role-in-reducing-dependence-on-gas/

Gilbert, P., Walsh, C., Traut, M., Kesieme, U., Pazouki, K., Murphy, A., 2018. Assessment of full life-cycle air emissions of alternative shipping fuels. J. Clean. Prod. 172, 855–866. https://doi.org/10.1016/J.JCLEPRO.2017.10.165

Global Maritime Forum, 2022. The 2022 Annual Progress Report on Green Shipping Corridors. https://www.globalmaritimeforum.org/content/2022/11/The-2022-Annual-Progress-Report-on-Green-Shipping-Corridors.pdf

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

Gore, K., Rigot-Müller, P., Coughlan, J., 2022. Cost assessment of alternative fuels for maritime transportation in Ireland. Transp. Res. Part D Transp. Environ. 110, 103416. https://doi.org/10.1016/J.TRD.2022.103416

Gore, K., Rigot-Müller, P. and Coughlan, J., 2023. Cost-benefit assessment of shore side electricity: An Irish perspective. J. Environ. Manage. 326, 116755. https://doi.org/10.1016/j.jenvman.2022.116755

Government of Ireland, 2019. Climate Action Plan 2019. https://assets.gov.ie/25419/c97cdecddf8c49ab976e773d4e11e515.pdf

Government of Ireland, 2023. Climate Action Plan 2023. https://www.gov.ie/pdf/?file=https://assets.gov.ie/244355/1c421172-2901-4f9e-baa5-6e4445b342f4.pdf#page=null

Grainger, T., 2023. Shipping companies are taking new look at Scrubbers https://www.pacificgreen.com/articles/shipping-companies-are-taking-new-look-scrubbers/

Grid Beyond, 2021. Ireland targets 80% renewables | Grid Beyond. https://gridbeyond.com/ireland-targets-80-renewables/

Gu, Y., Wallace, S.W., 2017. Scrubber: A potentially overestimated compliance method for the Emission Control Areas: The importance of involving a ship's sailing pattern in the evaluation. Transp. Res. Part D Transp. Environ. 55, 51–66. https://doi.org/10.1016/J.TRD.2017.06.024

Hansen, K., Roche, P., Martin, E., 2021. EU ETS and Shipping. https://www.nortonrosefulbright.com/en/knowledge/publications/f5c8d3fa/eu-ets-and-shipping

Hansson, J., Brynolf, S., Fridell, E., Lehtveer, M., 2020. The Potential Role of Ammonia as Marine Fuel—Based on Energy Systems Modelling and Multi-Criteria Decision Analysis. Sustain. 2020, Vol. 12, Page 3265 12, 3265. https://doi.org/10.3390/SU12083265

Haskell, C., 2021. Decarbonising shipping – could ammonia be the fuel of the future? https://www.lr.org/en/insights/articles/decarbonising-shipping-ammonia/

Helgason, R., Cook, D., Davíðsdóttir, B., 2020. An evaluation of the cost-competitiveness of maritime fuels – a comparison of heavy fuel oil and methanol (renewable and natural gas) in Iceland. Sustain. Prod. Consum. 23, 236–248. https://doi.org/10.1016/J.SPC.2020.06.007

Holland, M. and Watkiss, P., 2002. Benefits Table database: Estimates of the marginal external costs of air pollution in Europe Created for European Commission DG Environment by Netcen. https://ec.europa.eu/environment/enveco/air/pdf/betaec02a.pdf

Holland, M., Pye, S., Watkiss, P., Droste-franke, B. and Bickel, P., 2005. CAFE https://ec.europa.eu/environment/archives/cafe/activities/pdf/cafe_cba_externalities.pdf

Hsieh, C.-W.C., Felby, C., 2017. Biofuels for the marine shipping sector Biofuels for the marine shipping sector an overview and analysis of sector infrastructure, fuel technologies and regulations. https://www.ieabioenergy.com/wp-content/uploads/2018/02/Marine-biofuel-report-final-Oct-2017.pdf

Hua, J., Wu, Y., Chen, H.L., 2017. Alternative fuel for sustainable shipping across the Taiwan Strait. Transp. Res. Part D Transp. Environ. 52, 254–276. https://doi.org/10.1016/J.TRD.2017.03.015

Hwang, S.S., Gil, S.J., Lee, G.N., Won Lee, J., Park, H., Jung, K.H., Suh, S.B., 2020. Life Cycle Assessment of Alternative Ship Fuels for Coastal Ferry Operating in Republic of Korea. J. Mar. Sci. Eng. 2020, Vol. 8, Page 660 8, 660. https://doi.org/10.3390/JMSE8090660

Hydrogen Europe, 2021. How Hydrogen can help decarbonise the marine sector final. https://hydrogeneurope.eu/wp-content/uploads/2021/11/How-hydrogen-can-help-decarbonise-the-maritime-sector_final.pdf

Iannaccone, T., Landucci, G., Tugnoli, A., Salzano, E., Cozzani, V., 2020. Sustainability of cruise ship fuel systems: Comparison among LNG and diesel technologies. J. Clean. Prod. 260, 121069. https://doi.org/10.1016/J.JCLEPRO.2020.121069

IBIA, 2023. Plans for three new ECAs announced during MEPC 80. https://ibia.net/plans-for-three-new-ecas-announced-during-mepc-80/

IEA, 2020. Indicative shipping fuel cost ranges. https://www.iea.org/data-and-statistics/charts/indicative-shipping-fuel-cost-ranges

IEA, 2022. Global Hydrogen Review. iea.blob.core.windows.net/assets/c5bc75b1-9e4d-460d-9056-6e8e626a11c4/GlobalHydrogenReview2022.pdf

IMDO, 2018. The implications of Brexit on the use of the Landbridge. https://www.imdo.ie/Home/sites/default/files/IMDOFiles/972918%20IMDO%20The%20

Implications%20of%20Brexit%20on%20the%20Use%20of%20the%20Landbridge%20Report%20-%20Digital%20Final.pdf

IMDO, 2020. Volume 17 The Irish Maritime Transport Economist. https://www.imdo.ie/Home/sites/default/files/IMDOFiles/IMDO%20IMTE%20Vol%2017%202020.pdf

IMDO, 2021. Irish Port Companies | IMDO - Irish Maritime Development Office. https://www.imdo.ie/Home/site-area/statistics/ports-operators/irish-port-companies

IMDO, 2023. Volume 20 The Irish Maritime Transport Economist. https://www.imdo.ie/Home/sites/default/files/IMDOFiles/IMDO_Docs/IMDO%20IMTE%20Vol%2020%202023.pdf

IMO, 2016. Studies on the feasibility and use of LNG a fuel for shipping. https://greenvoyage2050.imo.org/wp-content/uploads/2021/01/STUDIES-ON-THE-FEASIBILITY-AND-USE-OF-LNG-AS-A-FUEL-FOR-SHIPPING-.pdf

IMO, 2019. IMO 2020: consistent implementation of MARPOL Annex VI. https://www.imo.org/en/MediaCentre/HotTopics/Pages/Sulphur-2020.aspx

IMO, 2020. Fourth IMO GHG Study 2020 Executive Summary. https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth%20IMO%20GHG%20Study%202020%20Executive-Summary.pdf

IMO, 2021. IMO's work to cut GHG emissions from ships. https://www.imo.org/en/MediaCentre/HotTopics/Pages/Cutting-GHG-emissions.aspx

IMO, 2022a. IMO progress on revised GHG strategy, Mediterranean ECA adopted. https://www.imo.org/en/MediaCentre/PressBriefings/pages/MEPC-79.aspx

IMO, 2022b. Maritime Environment Protection Committee 78th session. https://www.imokorea.org/upfiles/board/45.%20MEPC%2078%20%B0%E1%B0%FA%BA%B8%B0%ED%BC%AD%28%BF%B5%BE%EE%29.pdf

IMO, 2023. Revised GHG reduction strategy for global shipping adopted. https://www.imo.org/en/MediaCentre/PressBriefings/pages/Revised-GHG-reduction-strategy-for-global-shipping-adopted-.aspx

Inal, O.B., Zincir, B., Deniz, C., 2022. Investigation on the decarbonization of shipping: An approach to hydrogen and ammonia. Int. J. Hydrogen Energy. https://doi.org/10.1016/J.IJHYDENE.2022.01.189

Inner City Fund, 2009. Current Methodologies in Preparing Mobile Source Port-Related Emission Inventories Final Report. https://www.epa.gov/sites/default/files/2016-06/documents/2009-port-inventory-guidance.pdf

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

Javaid, K., 2023. The next scrubber retrofit wave will bridge the regulation gap. https://www.ship-technology.com/comment/the-next-scrubber-retrofit-wave-will-bridge-the-regulation-gap/

Jiang, L., Kronbak, J., Christensen, L.P., 2014. The costs and benefits of sulphur reduction measures: Sulphur scrubbers versus marine gas oil. Transp. Res. Part D Transp. Environ. 28, 19–27. https://doi.org/10.1016/j.trd.2013.12.005

Kakoulaki, G., Kougias, I., Taylor, N., Dolci, F., Moya, J., Jager-Waldau, A., 2021. Green hydrogen in Europe – A regional assessment: Substituting existing production with electrolysis powered by renewables. Energy Conv. & Manag. 228, 113649. https://doi.org/10.1016/j.enconman.2020.113649

Karl, M., Bieser, J., Geyer, B., Matthias, V., Jalkanen, J. P., Johansson, L., & Fridell, E. (2019). Impact of a nitrogen emission control area (NECA) on the future air quality and nitrogen deposition to seawater in the Baltic Sea region. Atmos. Chem. Phys. 19, 1721–1752. https://doi.org/10.5194/acp-19-1721-2019

Kass, M., Abdullah, Z., Biddy, M., Drennan, C., Hawkins, T., Jones, S., Holladay, J., Longman, D., Newes, E., Theiss, T., Thompson, T., Wang, M., 2018. Understanding the Opportunities of Biofuels for Marine Shipping. https://info.ornl.gov/sites/publications/Files/Pub120597.pdf

Kim, K., Roh, G., Kim, W., Chun, K., 2020. A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. J. Mar. Sci. Eng. 2020, Vol. 8, Page 183 8, 183. https://doi.org/10.3390/JMSE8030183

Kinyua, B., 2022. Shipping's next fuel of choice could be HFO. https://maritime-executive.com/article/shipping-s-next-fuel-of-choice-could-be-high-sulfur-fuel-oil

Khan, M.Y., Russell, R.L., Welch, W.A., Cocker, D.R., Ghosh, S., 2012. Impact of Algae Biofuel on In-Use Gaseous and Particulate Emissions from a Marine Vessel. Energy and Fuels 26, 6137–6143. https://doi.org/10.1021/EF300935Z

Korzhenevych, A., Dehnen, N., Bröcker, J., Holtkamp, M., Meier, H., Gibson, G., Varma, A. and Cox, V., 2014. Update of the Handbook on External Costs of Transport: final report for the European Commission: DG-MOVE http://cdn.confebus.org/u/2014-handbook-external-costs-transport.pdf

Lacey, L., Brewster, P., Fallen Bailey, D., 2019. The Development of Alternative Fuel Infrastructure in Irish Ports A Feasibility Study. https://oar.marine.ie/bitstream/handle/10793/1492/IMDO%20Development%20of%20Alternative%20Fuel.PDF?sequence=1&isAllowed=y

Lagemann, B., Lindstad, E., Fagerholt, K., Rialland, A., Ove Erikstad, S., 2022. Optimal ship lifetime fuel and power system selection. Transp. Res. Part D Transp. Environ. 102, 103145. https://doi.org/10.1016/J.TRD.2021.103145

Law, L.C., Foscoli, B., Mastorakos, E., Evans, S., 2021. A Comparison of Alternative Fuels for Shipping in Terms of Lifecycle Energy and Cost. Energies, Vol. 14, Page 8502 14, 8502. https://doi.org/10.3390/EN14248502

Lee, H., Pham, H.T., Chen, M. and Choo, S., 2021. Bottom-up approach ship emission inventory in Port of Incheon based on VTS data. J. of Adv. Trans. 2021, pp.1-16. https://doi.org/10.1155/2021/5568777

Li, K., Wu, M., Gu, X., Yuen, K.F., Xiao, Y., 2020. Determinants of ship operators' options for compliance with IMO 2020. Transp. Res. Part D Transp. Environ. 86, 102459. https://doi.org/10.1016/J.TRD.2020.102459

Lieberz, 2022. Biofuels Mandates in the EU by Member State – 2022. https://fas.usda.gov/data/european-union-biofuel-mandates-eu-member-state-2022

Lindstad, H., Sandaas, I., Strømman, A.H., 2015. Assessment of cost as a function of abatement options in maritime emission control areas. Transp. Res. Part D Transp. Environ. 38, 41–48. https://doi.org/10.1016/j.trd.2015.04.018

Lindstad, H.E., Eskeland, G.S., 2016. Environmental regulations in shipping: Policies leaning towards globalization of scrubbers deserve scrutiny. Transp. Res. Part D Transp. Environ. 47, 67–76. https://doi.org/10.1016/j.trd.2016.05.004

Lindstad, H.E., Rehn, C.F., Eskeland, G.S., 2017. Sulphur abatement globally in maritime shipping. Transp. Res. Part D Transp. Environ. 57, 303–313. https://doi.org/10.1016/J.TRD.2017.09.028

Lindstad, E., Lagemann, B., Rialland, A., Gamlem, G.M., Valland, A., 2021. Reduction of maritime GHG emissions and the potential role of E-fuels. Transp. Res. Part D Transp. Environ. 101, 103075. https://doi.org/10.1016/J.TRD.2021.103075

Lloyd's List, 2022. Bunker prices climb to highest point since early 2020. https://lloydslist.maritimeintelligence.informa.com/LL1139878/Bunker-prices-climb-to-highest-point-since-early-2020

López-Aparicio, S., Tønnesen, D., Thanh, T.N., Neilson, H., 2017. Shipping emissions in a Nordic port: Assessment of mitigation strategies. Transp. Res. Part D Transp. Environ. 53, 205–216. https://doi.org/10.1016/J.TRD.2017.04.021

Maragkogianni, A., Papaefthimiou, S., 2015. Evaluating the social cost of cruise ships air emissions in major ports of Greece. Transp. Res. Part D Transp. Environ. 36, 10–17. https://doi.org/10.1016/j.trd.2015.02.014

Marine Institute, 2020. The future is bright for Ireland's shipping and shipping services sector | Marine Institute. https://www.marine.ie/site-area/news-events/news/future-bright-ireland's-shipping-and-shipping-services-sector

Marine Traffic, 2020. Marinetraffic: Global Ship Tracking Intelligence | AIS Marine Traffic. https://www.marinetraffic.com/en/ais/home/centerx:-12.0/centery:53.2/zoom:6

Maritime Executive, 2023. Record Number of Methanol-Fueled Ships Ordered https://maritime-executive.com/article/record-number-of-methanol-fueled-ships-ordered-reports-dnv

Marketa, P., 2022. Sustainable maritime fuels - 'Fit for 55': the FuelEU Maritime proposal. https://www.europarl.europa.eu/RegData/etudes/BRIE/2021/698808/EPRS_BRI(2021)698808_EN.pdf

McDonnell, F., 2020. Belfast Harbour handles record number of passengers. https://www.irishtimes.com/business/economy/belfast-harbour-handles-record-number-of-cruise-and-ferry-passengers-1.4164361

McKinlay, C.J., Turnock, S.R., Hudson, D.A., 2021. Route to zero emission shipping: Hydrogen, ammonia or methanol? Int. J. Hydrogen Energy 46, 28282–28297. https://doi.org/10.1016/J.IJHYDENE.2021.06.066

Merien-Paul, Rumesh H., Enshaei, Hossein, Jayasinghe, Shantha Gamini, 2016. Guessing to prediction – a conceptual framework to predict LNG Bunker demand profile in Australia. In: IAMU AGA 2016. Vietnam Maritime University, Haiphong, Vietnam.

Merien-Paul, R.H., Enshaei, H. and Jayasinghe, S.G., 2018. In-situ data vs. bottom-up approaches in estimations of marine fuel consumptions and emissions. Transp. Res. Part D Transp. Environ.62, pp.619-632. https://doi.org/10.1016/j.trd.2018.04.014

Methanex, 2021. Methanex Price https://www.methanex.com/sites/default/files/methanol-price/MxAvgPrice_Feb%2027%202020.pdf

Methanex, 2022. Pricing | Methanex Corporation. https://www.methanex.com/our-business/pricing

MIT, 2021. Smarter regulation of global shipping emissions could improve air quality and health outcomes. https://news.mit.edu/2021/smarter-regulation-global-shipping-emissions-could-improve-air-quality-health-outcomes-0817

Monteiro, A., Russo, M., Gama, C., Borrego, C., 2018. How important are maritime emissions for the air quality: At European and national scale. Environ. Pollut. 242, 565–575. https://doi.org/10.1016/J.ENVPOL.2018.07.011

Muchira, N., 2022. IMO Breaks Deadlock on Carbon Pricing for Shipping. https://www.maritime-executive.com/article/imo-breaks-deadlock-on-carbon-pricing-for-shipping

NAPA, 2022. How the Fit For 55 legislation will affect the shipping industry – and how you can prepare. https://www.napa.fi/eu-fit-for-55-for-shipping/

Nerheim, A.R., Æsøy, V., Holmeset, F.T., 2021. Hydrogen as a Maritime Fuel–Can Experiences with LNG Be Transferred to Hydrogen Systems? J. Mar. Sci. Eng. 2021, Vol. 9, Page 743 9, 743. https://doi.org/10.3390/JMSE9070743

NISRA, 2014. Census 2011 https://www.cso.ie/en/media/csoie/census/documents/north-south-spreadsheets/Census2011IrelandandNorthernIrelandwebversion1.pdf

[Dataset] NISRA, 2019. Population Density : QS102NI (administrative géographies). https://datavis.nisra.gov.uk/dissemination/NINIS-redirect.html

NISRA, 2021. Population Estimates for Belfast Local Government District. https://www.ninis2.nisra.gov.uk/public/AreaProfileReportViewer.aspx?FromAPAddressMulipleRecords=Belfast@Exact%20match%20of%20location%20name:%20@Exact%20Match%20Of%20Location%20Name:%20%20Belfast@3?

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

Nunes, R.A.O., Alvim-Ferraz, M.C.M., Martins, F.G., Sousa, S.I.V., 2019. Environmental and social valuation of shipping emissions on four ports of Portugal. J. Environ. Manage. 235, 62–69. https://doi.org/10.1016/J.JENVMAN.2019.01.039

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

Ó Cléirigh, B., 2022. A Review of Requirements and Constraints on Biofuels in Ireland Arising from RED II and National Targets. https://assets.gov.ie/236620/2bc87dee-edf4-45e6-a342-b74cf71d5e21.pdf

[Dataset] OECD, 2022. Inflation (CPI) (indicator). OECD Database. https://data.oecd.org/price/inflation-cpi.htm

[Dataset] OECD, 2023. Maritime Transport CO2 emissions. OECD Database. URL https://stats.oecd.org/Index.aspx?DataSetCode=MTE#

Office for National Statistics, 2022. National population projections: 2020-based. https://www.ons.gov.uk/peoplepopulationandcommunity/populationandmigration/populationprojections/bulletins/nationalpopulationprojections/2020basedinterim

Offshore Energy, 2022. Clarksons: There are 130 ammonia-ready and 6 hydrogen-ready vessels on order. https://www.offshore-energy.biz/clarksons-there-are-130-ammonia-ready-and-6-hydrogen-ready-vessels-on-order/

Ölçer, A., & Ballini, F. (2015). The development of a decision-making framework for evaluating the trade-off solutions of cleaner seaborne transportation. Transp. Res. Part D Transp. Environ. 37, 150–170. https://doi.org/10.1016/j.trd.2015.04.023

Panasiuk, I., Turkina, L., 2015. The evaluation of investments efficiency of SOx scrubber installation. Transp. Res. Part D Transp. Environ. 40, 87–96. https://doi.org/10.1016/j.trd.2015.08.004

Parker, S., Shaw, A., Rojon, I., Smith, T., 2021. Harnessing the EU ETS to reduce international shipping emissions Assessing the effectiveness of the proposed policy inclusion of shipping in the EU ETS to reduce international shipping emissions. https://www.u-mas.co.uk/wp-content/uploads/2021/12/UMAS-2021-Harnessing-the-EU-ETS-to-reduce-international-shipping-emissions.pdf

Parkes, R., 2023. Strong winds could make green hydrogen produced in Ireland the cheapest in Europe, says analyst. https://www.hydrogeninsight.com/production/strong-winds-could-make-green-hydrogen-produced-in-ireland-the-cheapest-in-europe-says-analyst/2-1-1415342

Pavlenko, N., Comer, B., Zhou, Y., Clark, N., Rutherford, D., 2020. The climate implications of using LNG as marine fuel. https://theicct.org/sites/default/files/publications/Climate_implications_LNG_marinefuel_01282020.pdf

Perčić, M., Vladimir, N., Fan, A., 2020. Life-cycle cost assessment of alternative marine fuels to reduce the carbon footprint in short-sea shipping: A case study of Croatia. Appl. Energy 279, 115848. https://doi.org/10.1016/j.apenergy.2020.115848

Perčić, M., Vladimir, N., Fan, A., 2021. Techno-economic assessment of alternative marine fuels for inland shipping in Croatia. Renew. Sustain. Energy Rev. 148, 111363. https://doi.org/10.1016/J.RSER.2021.111363

Perčić, M., Vladimir, N., Jovanović, I., Koričan, M., 2022. Application of fuel cells with zero-carbon fuels in short-sea shipping. Appl. Energy 309. https://doi.org/10.1016/j.apenergy.2021.118463

Preiss, P., Klotz, V., Bachmann, T.M., Droste-Franke, B., Heck, T., Krewitt, W., Malthan, D., Mayerhofer, P., Pattermann, F., Schmid, S., 2008. Technical Paper n ° 7. 4-RS 1 “Description of updated and extended draft tools for the detailed site-dependent assessment of external costs”.

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

PwC, 2022. Global Economy Watch – Projections. https://www.pwc.com/gx/en/research-insights/economy/global-economy-watch/projections.html

[Dataset] Refinitiv Eikon, 2022a. Vessel By Port Search. Refinitiv Shipping Database.

[Dataset] Refinitiv Eikon, 2022b. LNG stock prices. Refinitiv Commodities Database

Rice, B., 2009. Evaluation of rape-seed oil production https://t-stor.teagasc.ie/bitstream/handle/11019/840/eopr5239.pdf?sequence=1&isAllowed=y

Russo, M.A., Leitão, J., Gama, C., Ferreira, J. and Monteiro, A., 2018. Shipping emissions over Europe: A state-of-the-art and comparative analysis. Atmos. Environ. 177, 187-194. https://doi.org/10.1016/j.atmosenv.2018.01.025

Rutherford, D., Miller, J., 2019. Silent but deadly: The case of shipping emissions - International Council on Clean Transportation. https://theicct.org/silent-but-deadly-the-case-of-shipping-emissions/

Safety4Sea, 2020a. Do you know what happens to a ship when it is too old to sail anymore? https://safety4sea.com/cm-do-you-know-what-happens-to-a-ship-when-its-too-old-to-sail-anymore/

Safety4Sea, 2020b. List of countries that restrict the use of open loop scrubbers https://safety4sea.com/list-of-countries-that-restrict-the-use-of-open-loop-scrubbers/

Safety4Sea, 2023a. World LNG Report 2023. https://safety4sea.com/world-lng-report-2023/

Safety4Sea, 2023b. MSC orders 10 LNG-powered container vessels. https://safety4sea.com/msc-orders-10-lng-powered-container-vessels/

Sahu, S., 2021. Methanol bunkers in the limelight after Maersk's latest ship orders https://www.spglobal.com/commodityinsights/en/market-insights/latest-news/energy-transition/091621-feature-methanol-bunkers-in-the-limelight-after-maersks-latest-ship-orders

S&P Global Platts, 2021. Conversion base rates. https://www.spglobal.com/commodityinsights/PlattsContent/_assets/_files/en/conversiontables/conversion_factors.pdf

Schinas, O., Butler, M., 2016. Feasibility and commercial considerations of LNG-fuelled ships. Ocean Eng. 122, 84–96. https://doi.org/10.1016/J.OCEANENG.2016.04.031

SEAI, 2020. Energy In Ireland 2020 Report. https://www.seai.ie/publications/Energy-in-Ireland-2020.pdf

SEAI, 2021. SEAI Ireland Conversion Factors - Fuels and Energy. https://www.seai.ie/data-and-insights/seai-statistics/conversion-factors/

SEAI, 2022. SEAI Energy In Ireland 2022 Report. https://www.seai.ie/publications/Energy-in-Ireland-2022.pdf

SEAI, 2022. Sustainable Biomass Fuels in Ireland. https://www.seai.ie/technologies/bioenergy/biomass-in-ireland/

Sethi, S., 2021. A guide to scrubber systems on ship. https://www.marineinsight.com/tech/scrubber-system-on-ship/

[Dataset] SHARES – EUROSTAT, 2023. Short Assessment of Renewable Energy Sources (SHARES) Database. https://ec.europa.eu/eurostat/web/energy/database/additional-data#Short%20assessment%20of%20renewable%20energy%20sources%20(SHARES)

Shipandbunker, 2022. Rotterdam bunker prices – Ship & Bunker. https://shipandbunker.com/prices/emea/nwe/nl-rtm-rotterdam

Smith, J.R., Gkantonas, S., Mastorakos, E., 2022. Modelling of Boil-Off and Sloshing Relevant to Future Liquid Hydrogen Carriers. Energies 2022, Vol. 15, Page 2046 15, 2046. https://doi.org/10.3390/EN15062046

Song, S., 2014. Ship emissions inventory, social cost and eco-efficiency in Shanghai Yangshan port. Atmos. Environ. 82, 288–297. https://doi.org/10.1016/J.ATMOSENV.2013.10.006

Song, S.K., Shon, Z.H., 2014. Current and future emission estimates of exhaust gases and particles from shipping at the largest port in Korea. Environ. Sci. Pollut. Res. 2014 2110 21, 6612–6622. https://doi.org/10.1007/S11356-014-2569-5

Spengler, T., Tovar, B., 2021. Potential of cold-ironing for the reduction of externalities from in-port shipping emissions: The state-owned Spanish port system case. J. Environ. Manage. 279, 111807. https://doi.org/10.1016/J.JENVMAN.2020.111807

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

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

Styhre, L., Winnes, H., Black, J., Lee, J., & Le-Griffin, H. (2017). Greenhouse gas emissions from ships in ports – Case studies in four continents. Transp. Res. Part D Transp. Environ. 54, 212–224. https://doi.org/10.1016/J.TRD.2017.04.033

Sustainable Shipping Initiative, 2021. Availability of sustainable biofuels. https://www.sustainableshipping.org/wp-content/uploads/2022/01/Availability-of-Sustainable-Biofuels-Report-updated-final.pdf

Tan, J., Ryan, B., 2022. Shipping in EU ETS from 2024. https://www.ukpandi.com/news-and-resources/articles/2022/shipping-in-eu-ets-from-2024/

Tan, Z., Zeng, X., Shao, S., Chen, J., Wang, H., 2022. Scrubber installation and green fuel for inland river ships with non-identical streamflow. Transp. Res. Part E Logist. Transp. Rev. 161, 102677. https://doi.org/10.1016/J.TRE.2022.102677

The Royal Society, 2020. Ammonia: zero-carbon fertiliser, fuel and energy store. https://royalsociety.org/topics-policy/projects/low-carbon-energy-programme/green-ammonia/

Thomson, H., Corbett, J.J., Winebrake, J.J., 2015. Natural gas as a marine fuel. Energy Policy 87, 153–167. https://doi.org/10.1016/J.ENPOL.2015.08.027

Tichavska, M., Tovar, B., 2015a. Port-city exhaust emission model: An application to cruise and ferry operations in Las Palmas Port. Transp. Res. Part A Polic Pract. 78, 347-360 https://doi.org/10.1016/j.tre.2015.09.002

Tichavska, M., Tovar, B., 2015b. Environmental cost and eco-efficiency from vessel emissions in Las Palmas Port. Transp. Res. Part E Logist. Transp. Rev. 83, 126–140. https://doi.org/10.1016/j.tre.2015.09.002

Tichavska, M., Tovar, B., 2017. External costs from vessel emissions at port: a review of the methodological and empirical state of the art†. Transp. Rev. 37, 383–402. https://doi.org/10.1080/01441647.2017.1279694

Tovar, B. and Tichavska, M., 2019. Environmental cost and eco-efficiency from vessel emissions under diverse SOx regulatory frameworks: A special focus on passenger port hubs. Transp. Res. Part D Transp. Environ. 69, 1-12. https://doi.org/10.1016/j.trd.2019.01.019

Trozzi, C., De Lauretis, R., Rypdal, K., Webster, A., Fridell, E., Reynolds, G., Fontelle, J.-P., Lavender, K., Kilde, N., Hill, N., Thomas, R., Winther, M., 2019. 1.A.3.d Navigation (shipping) 2019 — European Environment Agency, in: EMEP/EEA Air Pollutant Emission Inventory Guidebook 2019.

Tseng, P.H., Pilcher, N., 2015. A study of the potential of shore power for the port of Kaohsiung, Taiwan: To introduce or not to introduce? Res. Transp. Bus. Manag. 17, 83–91. https://doi.org/10.1016/J.RTBM.2015.09.001

Turner, M., Zhang, Y., 2018. 70% Renewable Electricity Vision for Ireland https://windenergyireland.com/images/Article_files/Final_Baringa_70by30_Report_web.pdf

Tzannatos, E., 2010a. Cost assessment of ship emission reduction methods at berth: The case of the port of Piraeus, Greece. Marit. Policy Manag. 37, 427–445. https://doi.org/10.1080/03088839.2010.486655

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

UNCTAD, 2023. Review of Maritime Transport – 2023. https://unctad.org/system/files/official-document/rmt2023_en.pdf

United States Energy Information Administration, 2020. U.S. Energy Information Administration - EIA - Independent Statistics and Analysis. https://www.eia.gov/todayinenergy/detail.php?id=42415

Urdahl, K., 2020. Regional sulphur emission limits at a glance. https://www.gard.no/web/updates/content/29212584/regional-sulphur-emission-limits-at-a-%20glance

Ushakov, S., Halvorsen, N.G.M., Valland, H., Williksen, D.H., Æsøy, V., 2013. Emission characteristics of GTL fuel as an alternative to conventional marine gas oil. Transp. Res. Part D Transp. Environ. 18, 31–38. https://doi.org/10.1016/J.TRD.2012.08.007

Ushakov, S., Lefebvre, N., 2019. Assessment of Hydrotreated Vegetable Oil (HVO) Applicability as an Alternative Marine Fuel Based on Its Performance and Emissions Characteristics on JSTOR. SAE Int. J. Fuels Lubr. 12, 109–120. https://doi.org/10.4271/04-12-02-0007

Vackeová, S., Noyon, X., 2022. RePowerEU: Biofuels role in boosting Europe's energy independence. https://www.euractiv.com/section/biofuels/opinion/repowereu-biofuels-play-a-strategic-role-in-boosting-europes-energy-independence/

Vaishnav, P., Fischbeck, P. S., Morgan, M. G., & Corbett, J. J., 2016. Shore Power for Vessels Calling at U.S. Ports: Benefits and Costs. Environ. Sci. Technol. 50, 1102–1110. https://doi.org/10.1021/acs.est.5b04860

Van Essen, H., Schroten, A., Otten, M., Sutter, D., Schreyer, C., Zandonella, R., Maibach, M. and Doll, C., 2011. External Costs of Transport in Europe Update Study for 2008 https://ce.nl/wpcontent/uploads/2021/03/CE_Delft_4215_External_Costs_of_Transport_in_Europe_def_1343133550.pdf

Viana, M., Hammingh, P., Colette, A., Querol, X., Degraeuwe, B., Vlieger, I. de, & van Aardenne, J. (2014). Impact of maritime transport emissions on coastal air quality in Europe. Atmos. Environ. *90*, 96–105. https://doi.org/10.1016/j.atmosenv.2014.03.046

Walker, L., 2023. LNG fleet in 2023. https://www.montelnews.com/news/1459094/lng-fleet-may-expand-75-in-2023-as-demand-grows

Wang, H., Mao, X. and Rutherford, D., 2015. Shore power at Shenzhen Port https://theicct.org/sites/default/files/publications/ICCT-WCtr_ShorePower_201512a.pdf

Wang, Y., Wright, L.A., Bergman, M., 2021. A Comparative Review of Alternative Fuels for the Maritime Sector: Economic, Technology, and Policy Challenges for Clean Energy Implementation. World 2021, Vol. 2, Pages 456-481 2, 456–481. https://doi.org/10.3390/WORLD2040029

Wärtsilä, 2015. Creating Optimal LNG Storage Solutions. https://www.wartsila.com/insights/article/creating-optimal-lng-storage-solutions

Wärtsilä, 2020. Mind the methane gap. https://www.wartsila.com/insights/article/mind-the-methane-gap

Wärtsilä, 2021. Methanol – Fuel for thought in our deep-dive Q&A. https://www.wartsila.com/insights/article/methanol-fuel-for-thought-in-our-deep-dive-q-a

Whall, C., Scarbrough, T., Stavrakaki, A., Green, C., Squire, J., Noden, R., 2010. DEFRA UK Ship Emissions Inventory Final Report https://uk-air.defra.gov.uk/assets/documents/reports/cat15/1012131459_21897_Final_Report_291110.pdf

Winkel, R., Weddige, U., Johnsen, D., Hoen, V., Papaefthimiou, S., 2016. Shore Side Electricity in Europe: Potential and environmental benefits. Energy Policy 88, 584–593. https://doi.org/10.1016/j.enpol.2015.07.013

Wong, Y., 2022a. Oil price forecast 2025-2050: Price could fall below $100/bbl. https://capital.com/oil-price-forecast-2030-2050

Wong, Y., 2022b. Natural gas price forecast 2030-2050: Can prices keep their gain? https://capital.com/natural-gas-prices-forecast-2030-2050

Xu, H., Yang, D., 2020. LNG-fuelled container ship sailing on the Arctic Sea: Economic and emission assessment. Transp. Res. Part D Transp. Environ. 87, 102556. https://doi.org/10.1016/J.TRD.2020.102556

Yoo, B.Y., 2017. Economic assessment of liquefied natural gas (LNG) as a marine fuel for CO2 carriers compared to marine gas oil (MGO). Energy 121, 772–780. https://doi.org/10.1016/J.ENERGY.2017.01.061

Yu, J., Voß, S., Tang, G., 2019. Strategy development for retrofitting ships for implementing shore side electricity. Transp. Res. Part D Transp. Environ. 74, 201–213. https://doi.org/10.1016/J.TRD.2019.08.004

Zhang, S., Li, Y., Yuan, H., Sun, D., 2019. An alternative benchmarking tool for operational energy efficiency of ships and its policy implications. J. Clean. Prod. 240, 118223. https://doi.org/10.1016/j.jclepro.2019.118223

Zhao, Y., Fan, Y., Fagerholt, K., Zhou, J., 2021. Reducing sulfur and nitrogen emissions in shipping economically. Transp. Res. Part D Transp. Environ. 90, 102641. https://doi.org/10.1016/j.trd.2020.102641

Zhou, Y., Pavlenko, N., Rutherford, D., Osipova, L., Comer, B., Bates, J., Bleuanus, S., Bradshaw, J., Kaas, M., Lauer, P., Tirovola, T., 2020. The potential of liquid biofuels in reducing ship emissions. https://theicct.org/sites/default/files/publications/Marine-biofuels-sept2020.pdf

Zhu, M., Li, K.X., Lin, K.C., Shi, W., Yang, J., 2020. How can shipowners comply with the 2020 global sulphur limit economically? Transp. Res. Part D Transp. Environ. 79, 102234. https://doi.org/10.1016/j.trd.2020.102234

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

Zis, T.P.V., Cullinane, K., Ricci, S., 2022. Economic and environmental impacts of scrubbers' investments in shipping: a multi-sectoral analysis. Marit. Policy Manag. 1–19. https://doi.org/10.1080/03088839.2021.1937742