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Cost assessment of alternative fuels for maritime transportation in Ireland

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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 decarbonisation 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.

1. 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 decarbonisation, 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 decarbonisation from the IMO, the European Union (EU) has been pushing to introduce more stringent legislation on reducing GHG emissions within its jurisdiction (DNV, 2022). For

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instance, the “Fit for 55” package launched in 2021 aims to move the EU maritime sector towards decarbonisation, 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, 2022). 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., 2021). 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 1, Section 2 reviews the relevant literature. Section 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 4 indicates the scope of the conducted research, alongside the input data to estimate the required quantities. Section 5 contains the obtained results as well as the surrounding discussion, while section 6 offers our conclusions on this topic.

2. 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, 2020). 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 and 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 decarbonisation impacts of the outlined alternative fuels, to help understand their potential in meeting the IMO-2050 and EU-2030 targets.

3. Methodology – Analytical equations

3.1. Scenario development: Estimation of 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 (American Bureau of Shipping, 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 (tons), 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 (tons), 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):

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

where FT^{C}_{hf} refers to the total green hydrogen fuel *hf* consumed in scenario C, annually (tons), 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^{C}_{hf} 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):

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

where FT^{D}_{af} refers to the total green ammonia fuel *af* consumed in scenario D, annually (tons), 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^{D}_{af} 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):

$$FD^{A,B,C,D} = ((FT^{A,B}_{mf} + FBOG^{A,B}_{mf}) + FT^{A,B}_{pf}) + (FT^{C}_{hf} + FBOG^{C}_{hf}) + (FT^{D}_{af} + FBOG^{D}_{af} \tag{6}$$

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

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):

$$FBOG^{A,B}_{mf} = (b^{A,B}_{mf} \times 365/100) \times FT^{A,B}_{mf} \tag{7}$$

where $FBOG^{A,B}_{mf}$ indicates the stored main fuel *mf* which evaporated as BOG (annually) in scenarios A and B (tons), $b^{A,B}_{mf}$ is the boil off rate of the main fuel in scenarios A and B (%/ day) and $FT^{A,B}_{mf}$ refers to the total main fuel consumed, for the respective scenarios of A and B, annually (tons).

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):

$$FBOG^{C}_{hf} = (b^{C}_{hf} \times 365/100) \times FT^{C}_{hf} \tag{8}$$

$$FBOG^{D}_{af} = (b^{D}_{af} \times 365/100) \times FT^{D}_{af} \tag{9}$$

where $FBOG^{C}_{hf}$ and $FBOG^{D}_{af}$ indicate the stored green hydrogen fuel *hf* and green ammonia fuel *af* which evaporated as BOG (annually) in scenarios C and D, respectively (tons), b^{C}_{hf} and b^{D}_{af} is the boil off rate for green hydrogen fuel and green ammonia fuel, in scenarios C and D, respectively (%/ day) while FT^{C}_{hf} and FT^{D}_{af} refer to the total green hydrogen fuel and green ammonia fuel consumed, for the respective scenarios of C and D, annually (tons).

3.2. Estimation of 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., 2017, 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):

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

where E^{Base} represents annual baseline emissions (tons), 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^i_{ME} and EF^i_{AE} 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):

$$E^{A,B} = \sum_i T \times \left[P_{DF} \times LF_{DF} \times EF^{A,B}_i \right] \times 10^{-6} \tag{11}$$

where E^A and E^B represents emissions from the use of LNG and methanol in scenarios A and B, respectively (tons), 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 $EF^{A,B}_i$ 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^C_{hf}) with that of emission factor (EF^C_i):

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

where E^C represents emissions from the use of green hydrogen in scenario C (tons), 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^C_i 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^D_{af}) with that of emission factor (EF^D_i):

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

where E^D represents emissions from the use of green ammonia in scenario D (tons), 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^D_i indicates the emission factors for the application of green ammonia as the ship fuel in scenario D (g/kWh).

3.3. 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):

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

where FC^{Base} indicates the annual fuel costs for the baseline scenario (€), bf refers to the considered baseline fuels, FT^{Base}_{bf} represents the total fuel consumed by ships in the baseline scenario, for each of the considered baseline fuel bf, annually (tons) 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):

$$FC^{A,B} = \left(FT^{A,B}_{mf} + FBOG^{A,B}_{mf} \right) \times FP_{mf} + FT^{A,B}_{pf} \times FP_{pf} \tag{15}$$

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 (tons), $FBOG_{mf}^{A,B}$ refers to the stored main fuel which evaporated in the form of BOG, for scenarios A and B, annually (tons) 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 (tons), 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 (tons) and FP_{hf} and FP_{af} is the price for the green hydrogen fuel and green ammonia fuel (€/ton), respectively.

3.4. Evaluation of 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 (tons) 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 (tons) 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 (tons) 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 (tons) while *CTR* is the considered tax rate for each ton of emitted CO_2 (€/ton).

3.5. Cost-benefit analysis of alternative 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}):

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

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.

4. Application

4.1. 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, 2021a). 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 (Central Statistics Office, 2022). 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

Table 1
Particulars of the selected 20 ships.

Ship Name	Capacity		Enginepower (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

Source: Refinitiv Eikon (2022a).

[a] Main Engine

[b] Auxiliary Engine.

[c] Knots.

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 1.

4.2. 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 and 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).

4.3. *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 4.1 and section 4.2 have been utilised, while the obtained emission factors are shown in Table 2.

4.4. *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 (2020). 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).

4.5. *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 3 indicates the updated (year 2019) external cost factors used in this study, for the specific reference of Ireland.

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 decarbonisation 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).

Table 2
Emission factors (g/kWh) of pollutants under 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).

Table 3
Updated (year 2019) external cost factors for Ireland (€/ton).

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

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

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

4.6. 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 4.2, section 4.4 and section 4.5. While the total capital costs will be determined by compiling the prices of installed equipments, 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). Taking into account 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

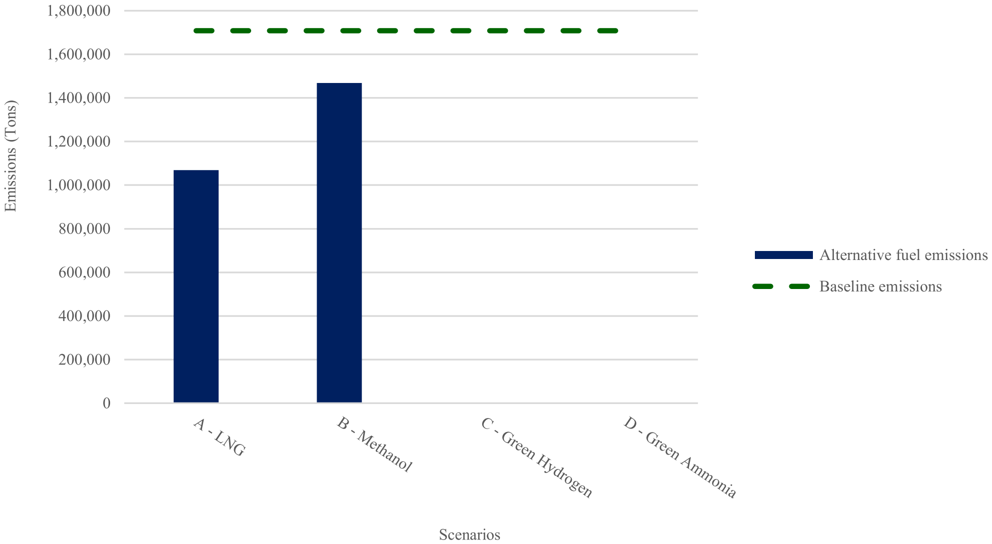

Fig. 1. Estimated shipping emissions for the selected baseline and alternative fuel scenarios.

%, 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. Results and discussion

5.1. Results

In the baseline scenario, the total emissions from ships while at-sea stood at 1,707,994 tons, for the year under investigation, 2019. Fig. 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.

It is observable from Fig. 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 4 depicts the breakdown of estimated baseline and alternative fuel emissions, based on the different pollutants of CO_2, NO_x, SO_2 and $PM_{2.5}$.

It has been shown in Table 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. Fig. 2 shows the external costs and carbon tax attributed to the considered baseline and alternative fuel scenarios.

As shown in Fig. 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, 2010), 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 compares the capital and operational costs (year 1) for the considered scenarios of alternative fuel technologies.

The given results in Table 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

Table 4
Estimated shipping emissions (by pollutants) for the selected baseline and alternative fuel scenarios (tons).

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

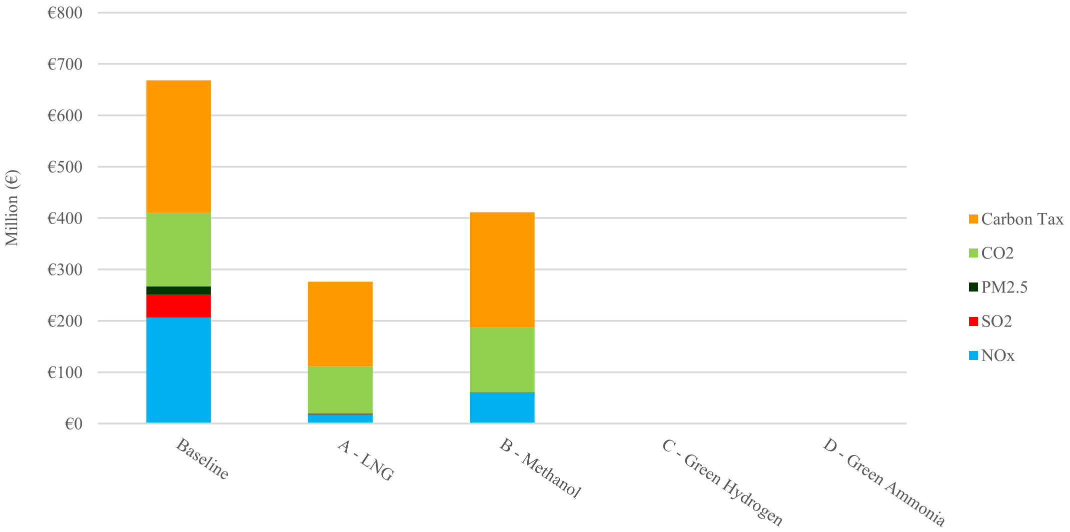

Fig. 2. External costs and carbon taxes for the selected baseline and alternative fuel scenarios.

Table 5
Capital and operational costs (Year 1) for the selected 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

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

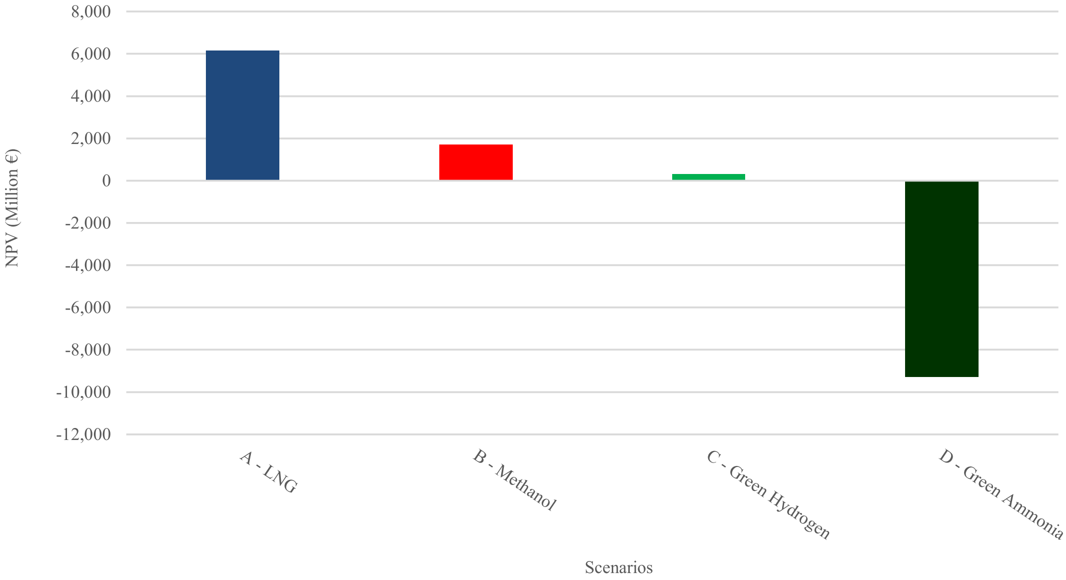

Fig. 3. NPV over 25 years for the identified alternative fuel scenarios.

deemed financially ‘profitable’ from a societal perspective. Fig. 3 shows the estimated NPV for the discussed alternative fuel technologies, over 25 years.

Fig. 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.

5.2. Discussion

From the analysed results in section 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, 2020), expecting to reduce to €1,500/ton by 2025, a drop of 62 % from the current levels (DiChristopher, 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.

Fig. 4 depicts sensitivity analysis based on NPV, considering a change in LNG, methanol, green hydrogen and green ammonia fuel price in either direction.

It is shown in Fig. 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, 2020). 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). Fig. 5 depicts sensitivity analysis based on NPV, considering a change in carbon tax rate in either direction.

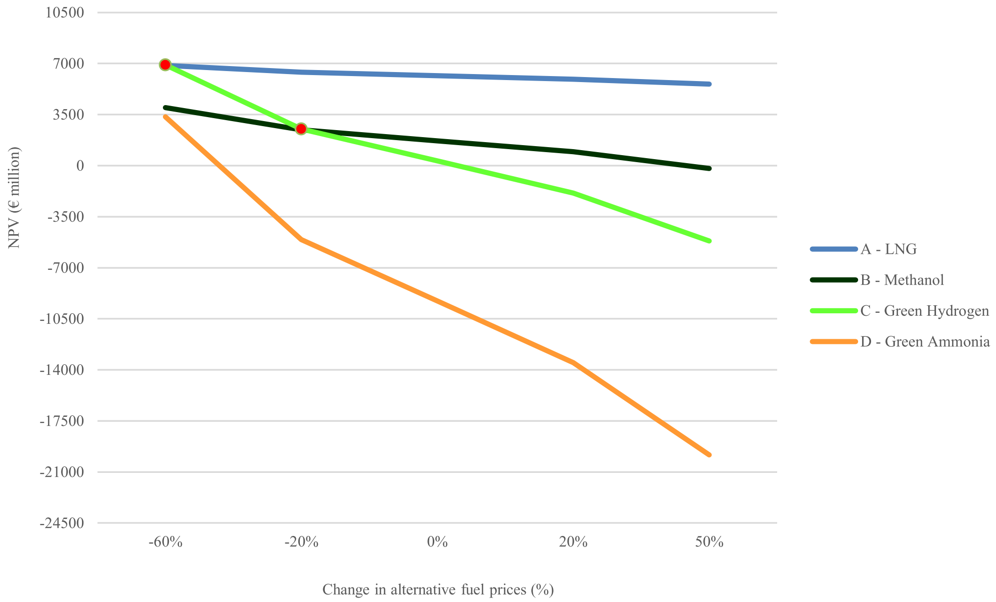

Fig. 4. NPV sensitivity to alternative fuel price variation in the considered scenarios.

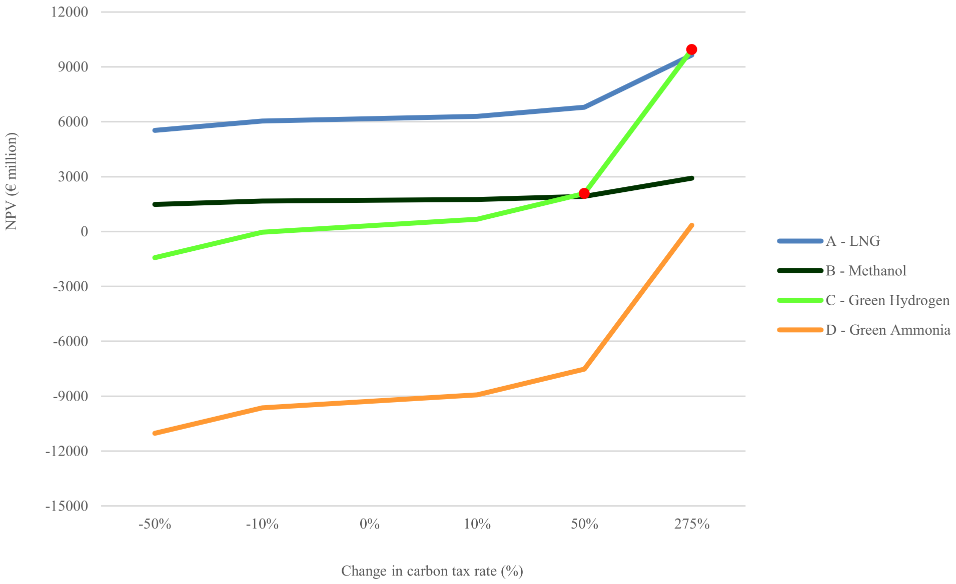

Fig. 5. NPV sensitivity to carbon tax rate variation in the considered scenarios.

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).

It is shown in Fig. 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 European Environment Agency (2021) emissions database, which was found to be 181,107,996 tons.

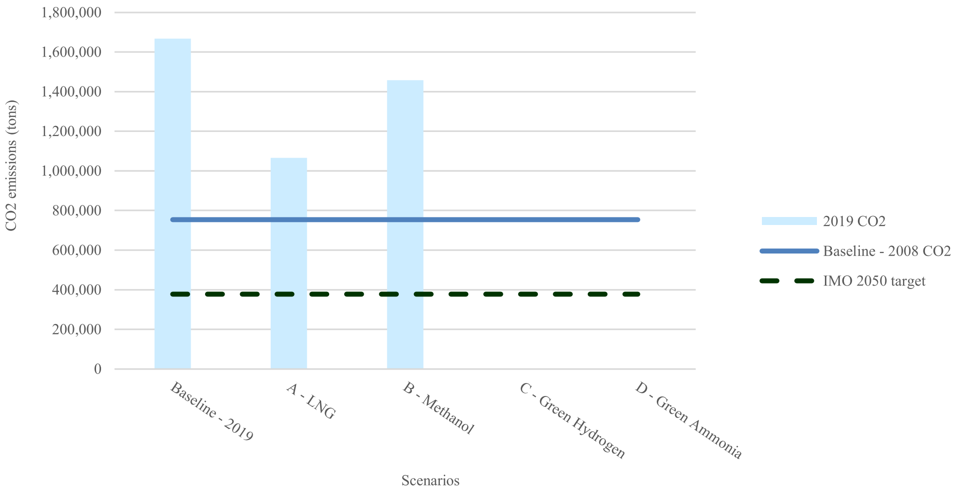

Fig. 6. Year 2008 (baseline) and Year 2019 (baseline and alternative fuels) CO_2 emissions, and the expected IMO-2050 target to achieve.

(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, 2021b). 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 tons. 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 tons). Fig. 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.

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 European Environment Agency (2021) emissions database, which was found to be 109,537,299 tons.
(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 tons.

To achieve the "Fit for 55" target, it is expected that these emissions will have to be less than 205,219 tons (55 % reduction). Fig. 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.

From the above Fig. 6 and Fig. 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, 2020). 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.

6. 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 decarbonisation 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 tons, 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.

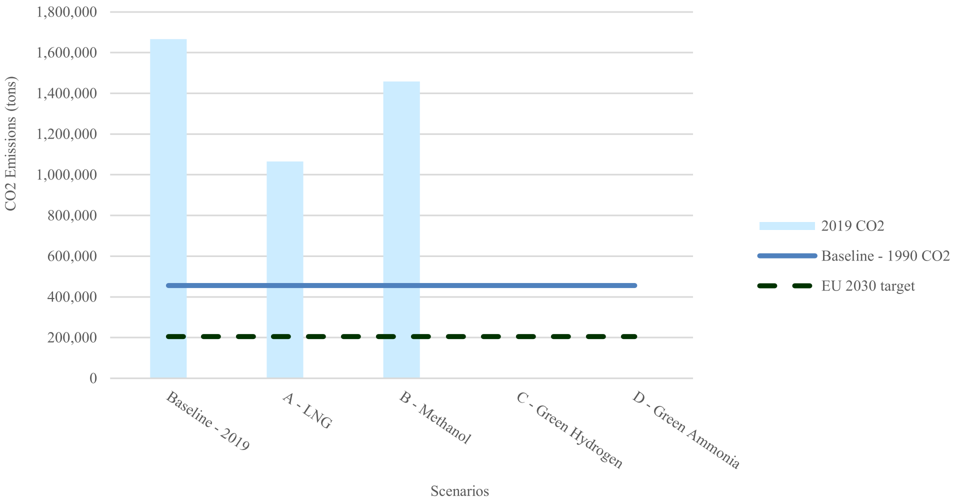

Fig. 7. Year 1990 (baseline) and Year 2019 (baseline and alternative fuels) CO_2 emissions, and the expected EU-2030 target to achieve.

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.

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CRediT authorship contribution statement

Ketan Gore: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft. **Patrick Rigot-Müller:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Visualization. **Joseph Coughlan:** Writing – review & editing, Supervision, Visualization.

Declaration of Competing Interest

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

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