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ORIGINAL ARTICLE

Assessing the decarbonization roadmap of a RoPax ferry

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Abstract

The reduction of emissions from shipping is necessary to combat climate change. One viable option is to change the fuels utilized. In this study, we investigate the environmental and economic performance of marine diesel oil (MDO), liquified natural gas (LNG), liquified biogas (LBG), and a mixture of LNG and LBG. We study a real case of a roll-on/roll-off passenger ship (RoPax) in Finland. Life cycle thinking is applied to assess the environmental impact, covering emissions from well to propeller (raw material extraction, fuel production, transportation, storage, and combustion), while the economic implications are estimated through future fuel prices and carbon pricing from 2023 to 2050. The carbon pricing covers different carbon tax schemes, namely stated policies scenario (STEPS), sustainable development scenarios (SDS), and net-zero emissions (NZE). STEPS reflects the existing measures and policies under development; SDS pursues to meet the goal of Paris Agreement, while NZE aims to reach net zero. Adopting LNG would improve carbon dioxide emissions, but the overall climate change impact was not significantly lower than MDO. It is also found that the biggest environmental improvement can be obtained by switching to LBG, although future availability can be an issue. The economic assessment shows that LBG has the highest fuel price uncertainties, although its carbon cost will be the lowest. Alternatively, using LNG & LBG mixture can serve as a transition path to contain climate change while dealing with its price uncertainty and availability.

Keywords Decarbonization · Short-sea shipping · Liquefied natural gas · Liquefied biogas · Marine diesel fuel · LCA

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1 Introduction

Shipping is a considerable contributor to greenhouse gas (GHG) emissions, responsible for 1076 million tonnes in 2018 or some 3% of global GHG emissions (IMO 2021). Recent international consensus outlines a path towards net-zero GHG emissions shipping around 2050. Yet, the sector's emissions are expected to grow as the demand for shipping increases with world trade (Traut et al. 2018). This puts both the sector and the individual shipowners and operators in a difficult situation. While most emissions originate from large ocean-going cargo vessels (Aakko-Saksa et al. 2023), emissions from short-sea shipping are important at local level and for the sector to move towards zero emissions.[1] Short-sea shipping is also interesting because it involves passenger travel, notably on the so-called *roll-on roll-off* passenger vessels (RoPax). According to the fourth IMO GHG study (IMO 2021), Ferry-RoPax vessels were responsible for some 37 million tonnes of CO_2 emissions in 2018 (out of 1056 million tonnes for all shipping). These ships typically show higher consumption figures per transportation work due to different speed profiles and the compromises made while serving both the needs of cargo and passengers. Yet, short-sea and RoPax shipping have received less attention in the scientific literature on maritime GHG emissions reduction, with just a few notable exceptions (Zis et al. 2020).

Decarbonization often comes with a considerable investment cost for shipowners. Some investments can indeed be profitable (Schwartz et al. 2020), but especially when we move to complete carbon neutrality and new power sources the increased costs are more difficult to cover with current freight prices (e.g. liquified biogas was in 2023 30–87% more expensive than MDO/MGO, see Table 3). While such investments indeed serve to differentiate the services provided by a shipping company, the transition towards carbon-neutral shipping cannot rely only on voluntary initiatives. Owing to economic and technological barriers, incentives at various regulatory levels are needed (Christodoulou and Cullinane 2021). Moreover, several studies have pointed out that the price premium for zero-emissions shipping is very small (Schwartz et al. 2022; World Economic Forum 2021). Regarding passenger traffic, the issue is less clear-cut as the value chain is shorter, and the price increase more hits the passenger directly. Hence, the issue boils down to customers' willingness to pay, which in practice is still lacking. Another issue concerns appropriately dividing the emissions burden between passengers and cargo, something of particular relevance, of course, for RoPax vessels (for a general overview, see Fridell et al. 2018). Moreover, RoPax like RoRo (roll-on, roll-off) vessels are prone to the double load factor problem, that is, the failure to effectively utilize the capacity of both the vessel and the trucks onboard the vessel, which leads to high emissions per transportation work (Hjelle 2011). Adding to that, RoPax vessels are typically also subject to substantial daily, weekly, and seasonal fluctuations in capacity utilization.

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[1] While there appears to be no exact definition of short-sea shipping, the term is often used in contrast to intercontinental, deep sea shipping and refers to transport over relatively short sea distances, such as routes between two ports within the EU.

The situation is challenging for shipowners and operators as regulations are evolving. There is also considerable uncertainty on the price of alternative fuels that hold the biggest GHG emissions reduction potential. Liquefied biogas (LBG), however, offers technically an easy way out, for ship owners with LNG fleets. Hence, this article assesses a decarbonization roadmap that builds on a gradual shift from MDO/LNG to LBG and its cost implications for a RoPax ferry. The contribution is a thorough analysis of a real-case ferry, exploring different input parameters. The analysis includes the environmental and economic aspects of using different types of fuels and carbon pricing. Any trade-off occurring among different fuel scenarios or carbon pricing schemes will provide valuable information for both ship owners and regulators.

The article is organized as follows. We first provide an overview of current regulations and available GHG emissions abatement measures in the maritime industry. Next, we present our method and the case company we have investigated. We then present and discuss the GHG footprint analysis results and the cost implications of the various abatement measures proposed by the case company. We conclude with some implications for the industry and some ideas for further research.

2 Literature overview

2.1 The need for decarbonization of shipping

A significant part of the literature highlights the International Maritime Organization's (IMO) strategic initiatives to curtail GHG emissions from shipping (Chen et al. 2019; Xing et al. 2020; Schwartz et al. 2022). IMO has recently revised its greenhouse gas (GHG) strategy, now aiming to establish a target of achieving net-zero emissions from international shipping by 2050 (Comer and Carvalho 2023). This target indicates a significant shift in the sector's approach to environmental stewardship (IMO 2021). This reflects a notable shift from IMO's previous goal of a 50% reduction, emphasizing a transition towards alternative, low-emission fuels by 2030, relative to 2008 levels. The strategy introduces regulatory measures like the Carbon Intensity Indicator (CII): a regulatory tool to enforce reductions in CO_2 and the implementation of the Energy Efficiency Existing Ship Index (EEXI). The purpose is to enforce emissions reductions, with plans for these tools to be updated by 2026 for enhanced effectiveness (Chen et al. 2019; Comer and Carvalho 2023; Pape 2020).

The European Union's regulatory interventions are also a focal point in the literature, illustrating a proactive approach to integrating maritime emissions into broader GHG reduction targets. The MRV regulation (No. 2015/757), effective from 2017, establishes a comprehensive framework for monitoring, reporting, and verifying CO_2 emissions from ships exceeding 5000 GT and operating in EU and EEA ports (European Council 2023). Building on this, the 'Fit for 55' package aims for a 55% cut in emissions from shipping by 2030, introducing measures such as the inclusion of shipping in the EU Emissions Trading System (ETS) and the Fuel EU Maritime initiative to promote the uptake of low-GHG fuels (DNV 2023).

According to Xing et al. (2020), to enhance maritime energy efficiency and mitigate CO_2 output, MARPOL Annex VI mandates the implementation of the Energy Efficiency Design Index (EEDI) for newly built ships and the Ship Energy Efficiency Management Plan (SEEMP) applicable to all vessels. Furthermore, aligning with global efforts against climate change, the Initial IMO Strategy for Reducing GHG Emissions from Ships was established in April 2018. Therefore, the question about why transitioning is important has long been answered by these voluntary commitments, mandates, and regulations, being introduced systematically at all stakeholder levels, transforming to new shift in industrial competitive edge for different players in the industry.

Another initiative, the revision of the Energy Taxation Directive (ETD), implies a removal of the current tax exemptions on marine fuels sold within and for use within the European Economic Area (EEA) European Commission (2022). The existing mandatory tax exemption for marine fuels is abolished while, at the same time, new tax exemptions are introduced to stimulate the use of fuels with lower GHG emission factors (EF). While the former initiative would motivate the use of alternative fuels, the latter would make them more competitive than fossil fuels. Europe is furthermore determined to reduce transportation emissions to 60% of 1990 levels by 2050 due to concerning statistics on greenhouse gas emissions (Bicer and Dincer 2018). This ambitious goal requires a collective approach that involves exploring alternative fuels, promoting technological development, enforcing strict regulations, and adopting sustainable methods.

2.2 Decarbonization measures in shipping

There are many strategies currently underpinning the maritime industry's quest to reduce or eliminate its GHG emissions. Measures can be divided into five categories (Xing et al. 2020).

1. Technical measures which include ship resistance reduction, propulsion efficiency improvement, and marine power plant development (e.g. waste heat recovery).
2. Operational measures including slow steaming, cold ironing (shore power), voyage optimization, human factors (awareness of energy consumption and savings), and optimized maintenance.
3. Eco-friendly or alternative fuels that can be grouped into LNG, biofuels, and electrofuels (i.e. fuels produced by using renewable electricity) and conventional fossil fuels with carbon capture and storage.
4. Alternative power sources such as wind, solar, nuclear energy, or battery-electric systems are examples.
5. Onboard carbon capture and storage (CCS).

Although these methods show significant potential in reducing GHG emissions, their implementation can result in additional costs due to increased requirements for installation, operation, and maintenance (Deniz and Zincir 2016; Seithe et al. 2020).

As a result, the most implemented measures have so far tended to be those with small energy efficiency gains and low additional costs (Rehmatulla et al. 2017).

In the long run, alternative fuels possess the biggest GHG abatement potential (Ampah et al. 2021). Various fuels, such as methanol, biodiesel, ammonia, biogas, hydrogen, and LPG, are being investigated (Deniz and Zincir 2016). Generally, both LNG and LPG are predominantly considered transitional fuels, and it is argued that biofuels lack the required scalability to become a dominant fuel in shipping (Englert et al. 2021a, b). A study conducted by Perčić et al. (2020) points out that as of March 2018, roughly 248 ships were using LNG in their operations, particularly in passenger ferries across Nordic coastal regions. This can be attributed to the adoption of dual-fuel engine technology in the shipping sector. Furthermore, a press briefing from Wärtsilä indicated that there were about 100 LNG-fuelled ships in operation, 72 ships in discussions for retrofitting to LNG, and 101 LNG-fuelled ships newly ordered in Germany and Norway (Wärtsilä 2017). However, it is important to note that while reducing CO_2 emissions, unburnt methane emissions (methane slip) pose environmental concerns (Grönholm et al. 2021). Recent measurements showed methane slip from newly built engines can achieve values as low as 1.4 g/kWh (Kuittinen et al. 2023). Overall, each alternative fuel has its unique characteristics and obstacles to overcome like the methane slip for LNG. The common challenge is their price compared to fossil ones, although price differences are expected to decline gradually (Brynolf et al. 2018).

The electrification of propulsion systems should be separately mentioned as a technical measure to improve energy propulsion efficiency, and as an alternative power source in the form of battery energy storage systems (BESS). The shift from mechanical to electric propulsion is made feasible through advancements in various energy sources. Decarbonization and electrification have fostered a mutual relationship, culminating in the creation of fully integrated electric power systems. Electrification, especially with the surge in renewable energy and innovations in battery technologies, is crucial for sustainable short-distance travel (Inal et al. 2022). For example, popular pure battery-electric ships such as ‘Ampere’ and ‘BB Green’ are RoPax ferries. The former uses a 1-MWh lithium battery module and can transport 120 cars and 360 passengers with a maximum speed of 10 knots. According to Fan et al. (2021), the boat in question has a 200-kWh lithium battery module and can reach up to 30 knots for 30 min. In China, a 2000 t bulk carrier called ‘Blowfish’ uses lithium batteries and supercapacitors as its power sources, with a battery capacity of about 2400 kWh and an endurance of 80 km (Fan et al. 2021). According to a study by Korberg et al. (2021), battery-electric propulsion in large ferries is more economically meaningful than all fuel options except for biofuels, like e-biomethanol and BioDME, in internal combustion engines (ICE).

3 Materials and methods

The environmental and economic implications of different marine fuels were investigated in an actual case study of Aurora Botnia, a Finnish roll-on/roll-off passenger (RoPax) ferry on the Vaasa (Finland)–Umeå (Sweden) route (Fig. 1). The energy

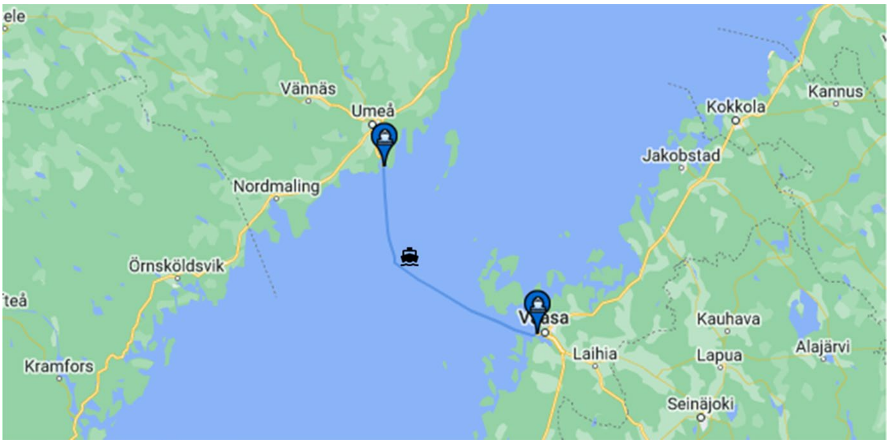

Fig. 1 Aurora Botnia sea route

carriers are marine diesel oil (MDO), liquefied natural gas (LNG), and liquefied biogas (LBG). Aurora Botnia is the only ferry that covers Vaasa-Umeå route with a total of 20–22 sailings each week. On each voyage, the ferry cruises at an average speed of 14 knots with a crossing distance of 53 nm. Its gross weight and deadweight are 24,300 tonnes and 3500 tonnes, with a 1500-m lane and 935 passenger capacity. It has dual-fuel engines that can burn MDO/MGO, LNG, and/or LBG.

3.1 Life cycle thinking

The study applies the *life cycle thinking* (LCT) concept in assessing the environmental impacts. LCT is a holistic and structured approach to incorporating sustainability considerations into decision-making (Sala et al. 2019). This approach goes beyond the conventional method of evaluating environmental impacts solely at the production site, by extending the assessment to encompass the entire life cycle of a product, service, or organization, from raw material extraction to final disposal (Life Cycle Initiatives 2023). In the shipping industry context, the assessment covers the emissions generated during fuel production (well-to-tank or WtT) and fuel burning in the use stage (tank-to-propeller or TtP). The coverage of WtT and TtP is also known as well-to-propeller (WtP). By applying life cycle assessment (LCA), a standardized tool to quantify environmental impact built on the LCT perspective, those emissions can be categorized and classified into different environmental impacts (Sala et al. 2021).

This study applies the LCA principle, where upstream emissions are considered, while following the EU MRV requirements. It provides a hands-on example of calculating emissions and presenting the results, offering added value compared to available studies focusing only on the environmental impacts. The study evaluates the fuel consumption per distance and transport work and CO_2 emissions per distance and transport work. In anticipation of the new reporting requirements of the EU ETS, methane (CH_4) and nitrous oxide (N_2O), emissions will be investigated since these gasses play a major role in climate change. The cost implications were also assessed to improve decision-making.

3.2 Goal and scope

The carbon emissions from using marine diesel oil (MDO), liquified natural gas (LNG), and liquified biogas (LBG) are evaluated through four different scenarios: (i) the use of MDO, (ii) the use of LNG with 5% MDO as pilot fuel, (iii) the use of LNG and LBG mixture with 5% MDO as pilot fuel, and (iv) the use of LBG with 5% MDO as pilot fuel. In the third scenario, the LBG was introduced stepwise in the mixture. At the beginning of year studied, 2023, it was only 0.6%, reaching 95.5% in 2050. Emissions are investigated from 2023 to 2050. The shipping operator strives to improve their environmental performance by improving efficiency (e.g. optimizing the use of batteries and new engines) and transitioning to more sustainable fuel. Hence, fuel consumption is expected to be reduced, and the use of more sustainable fuel is expected to increase annually. The study was conducted following the MRV legislation where carbon calculation is from CO_2 emissions and the mass allocation method is applied (Fridell et al. 2018). The emissions in the study cover raw material extraction, fuel production, transportation, storage, and combustion (well-to-propeller).

The functional unit (FU) for the CO_2 emissions is per transport work. FU is a reference unit for the impacts or emissions quantified that can provide more context in a study and allow comparison with other equivalent studies (Baumann and Tillman 2004). The selected functional unit is made following the EU MRV legislation, where *transport work* indicates the load carried for each nautical mile (nm) distance, distinguished between passengers (pass-nm) and cargo (ton-nm). Differentiating the FU between passengers and cargo can ensure a fair burden distribution by partitioning the system's load input.

3.3 Life cycle inventory

The data on the EF were collected from previous studies. MDO is commonly described as marine fuels composed of several blends of distillates produced by heating and evaporating residual oil (Shafran 2022). It is similar to marine gas oil (MGO) with a slight difference where MDO contains a small fraction of heavy fuel or black refinery feedstock (Oiltanking 2021; Shafran 2022). MDO/MGO does not show a significant difference in CO_2 emissions compared to heavy fuel oil (Spoof-Tuomi and Niemi 2020). The emissions data of MDO from WtT were adopted from Kollamthodi et al. (2016), whereas the TtP emissions was taken from IMO (2021) and Brynolf et al. (2014a, b).

We use data on gas extraction in the North Sea and LNG production in Norway. The gas is assumed to be transported cryogenically to Finland before distribution. The WtT emissions was adopted from (Spoof-Tuomi and Niemi 2020), who have adjusted the LNG production and distribution to suit the Finnish context. The EF

Table 1 Summary of EF from different fuels

Emissions	WtT (g/kg fuel)			TtP (g/kg fuel)		
	MDO	LNG	LBG	MDO	LNG	LBG
CO_2 (fossil)	627.8	504	478.2	3225	2707	49.3
CO_2 (biogenic)	–	–	–	–	–	2564
CH_4	0.90	8.6	16.8	0.06	19.7	20.2
N_2O	0.007	0.008	0.016	0.16	0.11	0.11

factor for the LNG combustion (TtP) was obtained from Prussi et al. (2020) and Kuittinen et al. (2023).

Bio-LNG, commonly called LBG, can be produced from different organic sources such as manure, biowaste, agriculture residue, and landfill gas. This study assumes LBG is produced from municipal organic waste treated in anaerobic digestion. The WtT emissions of LBG was adopted from Kollamthodi et al. (2016). For TtP emissions, the data were mainly taken from Brynolf et al. (2014a, b) and Spoof-Tuomi and Niemi (2020). The LBG produced from organic waste generates fuel that contains biogenic carbon, hence the low fossil carbon emissions during the combustion stage. The summary of carbon emissions of three different fuels is presented in Table 1.

Data regarding the number of passengers, cargo load, fuel consumption, annual number of trips, and distances are necessary to calculate carbon emissions based on the functional unit. This information was obtained from the shipping operator for the year

Table 2 Summary of voyages in the year 2022

Item	Value	Unit
Year	2022	n.a
Fuel consumption	4928 (65,711)	Tonne (MWh)
Trips	1132	Number
Total distance	88,296	nm
Average speed	14.1	Knot
Passengers	267,757	Pax
Cars	55,661	Number
Busses	413	Number
Trailers	22,200	Number
Time at sea	6262	Hours
Fuel cost	5,970,000	€
Revenue	29,293,000	€
Operating profit	3,294,000	€
Bus ticket*	170	€
Car package**	175	€
Adult ticket	43	€
Children ticket	19	€

*Price for the bus only

**Price for the car with passengers of 4 (max 3 children)

2022, combined with publicly available data (Shippax 2023; Wasaline 2022), as shown in Table 2.

The passengers and cargo load from 2023 until 2050 were assumed to increase steadily annually, until they reached 50% ferry capacity in 2040. After this, passengers and cargo loads are assumed to remain unchanged until 2050. At the moment, passenger occupancy is around 36% while cars, buses, and cargo is about 30%. Since the study applies mass allocation, the total mass of passengers and cargo should be calculated. Assumptions of the weight of passengers and their luggage, cars, buses, and trailers were taken from European standards for calculating and reporting GHG emissions from transportation (Finnish Standards Association 2013). The shipping operator provided the data on fuel consumption projections from 2023 until 2050 based on their transition plan. The latter was also used to calculate the LNG and LBG mixture in scenario 4. There, LBG is introduced in 2023 and incorporated gradually until it makes up 95% of the fuel composition in 2050. The complete information concerning the transition plan and the trajectory of the ferry load can be found in Supplementary material Tables 1 and 2.

3.4 Emissions calculation

Total annual fuel consumption information had to be collected to calculate the parameters required by the MRV. The overall emissions can be estimated using fuel consumption and EF, as shown in Eq. (1).

$$EM_i = \sum EF_i^f . Q_f, \tag{1}$$

where EM_i shows the overall emissions i, EF_i^f represents EF factor of emissions i generated by fuel f, and Q_f indicates the quantity of fuel f. Reporting emissions for a RoPax vessel involves an additional step whereby the total burden of emissions is properly allocated between passengers and freight. The allocation can be done using mass or area methods, which generate different results (Fridell et al. 2018). This study applied mass allocation, which has been widely used whenever reliable data are available. The mass calculation should be based on the number of passengers, their accompanied cars/caravans/busses, and total mass cargo (e.g. trailers) (Finnish Standards Association 2013). The expression for mass allocation can be found in Eqs. (2) and (3).

$$Al_p = \frac{Pax.m_p + C.m_c + B.m_b}{Pax.m_p + C.m_c + B.m_b + T.m_t} \tag{2}$$

$$Al_c = \frac{T.m_t}{Pax.m_p + C.m_c + B.m_b + T.m_t}, \tag{3}$$

where Al_p and Al_c are mass allocation for passengers and cargo, respectively. $Pax, C, B,$ and T are the annual number of passengers, cars, busses, and trailers. Data were obtained from the ship operator. The weights of the passenger and its luggage, car, bus, and trailer are shown by $m_p, m_c, m_b,$ and m_t.

Equations (4) and (5) calculate the transport work for passengers and cargo.

$$TW_p = Pax.\frac{Dist}{Trip} \tag{4}$$

$$TW_c = Cargo.\frac{Dist}{Trip}, \tag{5}$$

where TW_p and TW_c indicate transport work for passengers and cargo. *Pax* and *Cargo* are the annual numbers of passengers and cargo weight; *Dist* and *Trip* refer to annual distance and number of trips. All the equations above are used to calculate emissions per transport work, as shown in Eqs. (6) and (7). Em_{pax} shows carbon emissions per passenger transport work (gram CO_2/pax-nm) and Em_c is carbon emissions per cargo transport work (gram CO_2/ton-nm).

$$Em_{pax} = \frac{EM_i.Al_p}{TW_p} \tag{6}$$

$$Em_c = \frac{EM_i.Al_c}{TW_c}. \tag{7}$$

Formulas similar to Eqs. (6) and (7) are used to calculate fuel consumption per transport work by replacing EM_i with fuel consumption.

3.5 Cost calculation

The cost elements include the annual fuel and carbon prices, since the study focuses on the impact of fuel choice and its implications for carbon emissions. The cost is calculated based on the annual energy consumption and fuel prices. Predictions of fuel price levels (Table 3) were mainly taken from previous studies (DNV 2022; Ship and Bunker 2023; Siu et al. 2022), complemented with estimates of experts (Sea\LNG Ltd 2020; Ship and Bunker 2022).

To illustrate the costs incurred from the emissions, we incorporate carbon pricing through taxation mode which is more straightforward and suitable for

Table 3 Fuel price prediction

Year	MDO/MGO (€/tonne)		LNG (€/tonne)		LBG (€/tonne)	
	Low	High	Low	High	Low	High
2023	677.7	919.4	769.9	1338.5	882.7	1721.3
2030	640.6	869.0	538.9	936.9	772.4	1522.7
2050	358.0	664.0	322.3	612.4	639.9	1301.9

Table 4 Different carbon taxation schemes

Tax scheme	Carbon price in different years (€/t-CO_2)	
	2030	2050
STEPS	57.5	79.6
SDS	106.1	176.8
NZE	114.9	221

our study. It provides ideas to ship operators regarding the possible economic implications of carbon pricing.

Three different carbon tax schemes were applied, namely stated policies scenario (STEPS), sustainable development scenarios (SDS), and net-zero emissions (NZE), as shown in Table 4 (Bui et al. 2022). STEPS follows the existing policies and measures under development; SDS aims to meet the Paris Agreement goal, while NZE is a path to reach net-zero carbon emissions by 2050.

The costs are calculated using Eq. (8).

$$Cost = F.F_p + C.C_p, \tag{8}$$

where F and F_p are fuel consumption (tonne) and fuel price (€/tonne), whereas C and C_p are CO_2 emissions (t) and carbon price (€/t-CO_2). Next, we impute the change in cost, associated with the fuel and carbon prices, in the passenger ticket. The calculation is done by comparing known information about the RoPax fuel cost in 2022, the mass of passengers and cargo, and the actual ticket price at the time (Table 2). There are different ticket types. For illustration, the tickets included in the calculation were for adult passengers, child passengers, and bus and car packages. The data from Shippax (2023) showed that fuel costs represented around 23% of total operating costs, and the profit was 11% of the revenue. Based on this information, the fuel costs charged on the tickets for the bus, adult passenger, children passenger, and car package were 34.65 €, 8.76 €, 3.87 €, and 35.67 €, respectively. The costs associated with fuel and carbon in the ticket are calculated using Eq. (9).

$$Cost_y = \frac{Costpax_y}{Costpax_{ref}}.Cost_{ref}, \tag{9}$$

where $Cost_{ref}$ and $Cost_y$ indicate the fuel cost charged onto the tickets in 2022 and the calculated ones in year y, respectively. $Costpax_{ref}$ refers to the total annual costs associated with fuel in the year 2022, and $Costpax_y$ shows the calculated costs associated with fuel and carbon in year y. All results are presented for 2023, 2030, and 2050 to provide insights on the dynamics between fuel costs and associated emissions costs.

4 Results

Several parameters were calculated following MRV requirements: fuel consumption per distance, fuel consumption per transport work, CO_2 emissions per distance, and CO_2 emissions per transport work (Fridell et al. 2018).

4.1 Fuel consumption

The study shows the results between 2023 and 2050, where the vessel operator determined the efficiency improvement trajectory and the fuel type. Fuel projections were reported as unit energy (MWh) converted into fuel in mass units; hence, the quantity of fuel consumption differs despite the same energy value.

Figure 2 shows the fuel consumption per distance (kg fuel/nm). MDO showed the highest consumption per distance compared to LNG, LNG & LBG, and LBG. This is explained by its lower calorific value compared to the other fuels. It is estimated that the calorific values of MDO, LNG, and LBG in MJ/kg are 43, 48, and 49.3, respectively (Bengtsson et al. 2011; Spoof-Tuomi and Niemi 2020). MDO consumption per distance was around 10–12% higher than in the other scenarios. The operator's trajectory plan for improving efficiency would bring fuel consumption down to about 23% in 2050 compared to 2023 in all scenarios.

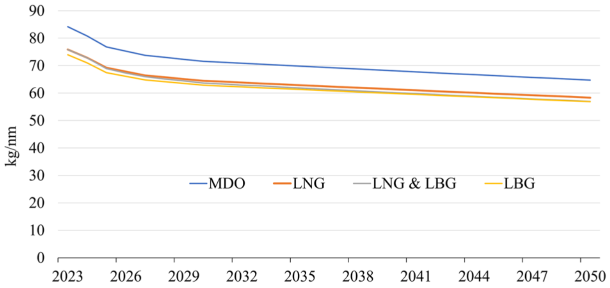

Fig. 2 Fuel consumption per distance

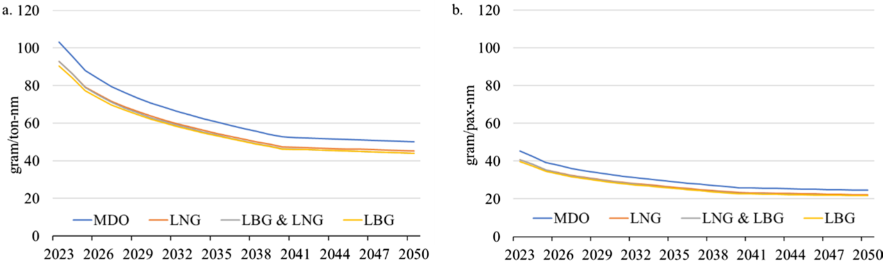

Fig. 3 Fuel consumption per transport work

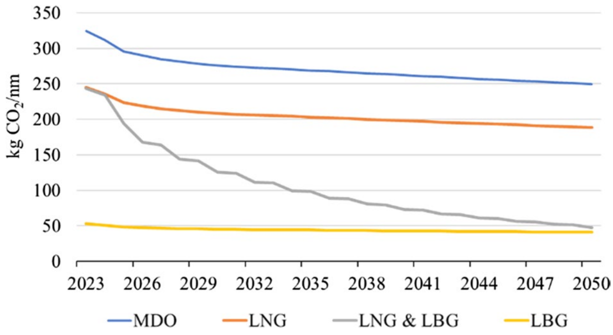

Fig. 4 CO_2 emissions per distance

Figure 3 presents the fuel consumption per transport work for cargo and passengers. The same pattern was found between fuel consumption per distance and transport work. MDO showed the highest consumption per ton-nm and pax-nm, 10–12% higher than other fuel types. Fuel consumption per ton-nm was about two times higher than the consumption per pax-nm. This was caused by the mass allocation method, which generated a higher burden for the cargo than the passengers and their accompanying vehicles. Allocation creates partitioning of input or output to distribute the impacts. From 2023 to 2050, calculations showed that the mass allocation for cargo and passenger ranged between 87–87.5% and 13–12.5%, respectively. The transition plan entails a fuel efficiency improvement that would reduce fuel consumption per transport work from 2023 to 2050 by 45% and 51% for passenger and cargo transport works across all scenarios (for a review of the reduction potential of various abatement measures, see Bouman et al. 2017).

4.2 Carbon emissions

MDO showed the highest carbon emissions per distance, followed by LNG, LNG & LBG, and LBG, as shown in Fig. 4. MDO consumption was only 10–13% higher than other fuels. However, the emissions of MDO per distance were much higher than other fuels.[2] Carbon emissions from MDO was 24% higher than LNG and 84% higher than LBG throughout the studied years. Carbon emissions from MDO varied between 25 and 81% higher than scenario 3 (LNG & LBG) throughout the studied years due to the stepwise addition of LBG into the fuel mixture. MDO and LNG are fossil fuels that cause higher environmental impacts than LBG. The total EF (gram CO_2 per MJ) during WtT and TtP for MDO, LNG, and LBG are 89.6, 66.5, and 10.7, respectively. Therefore, the pattern for the emissions per distance was different compared to fuel consumption per distance. This shows that the fuels have

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[2] MDO has higher emission factors which are associated with higher emissions; moreover its heating value is lower in comparison to LNG or LBG.

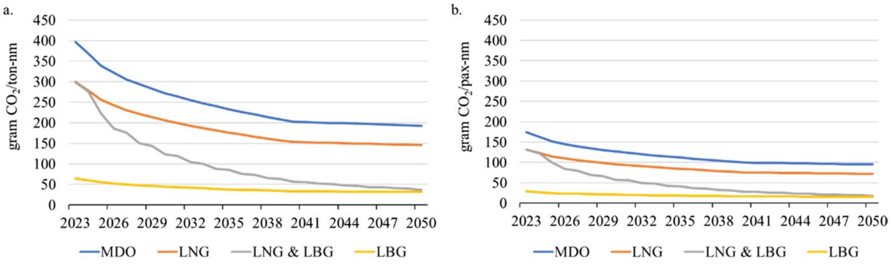

Fig. 5 CO_2 emissions per transport work

reasonably small differences in calorific value, while the carbon emissions among fuels are significantly different.

Figure 5 shows carbon emissions per transport work across all scenarios. Similar trends were found among the results of emissions per distance and per transport work, where MDO emissions was significantly higher than LBG. Mass allocation resulted in the emissions per (cargo) ton-nm being about two times higher than pax-nm. This number aligned with the comparison of fuel consumption per ton-nm and pax-nm (Fig. 3).

Contribution analysis was also applied to investigate which lifecycle stage contributes the most to emissions. Figure 6 displays (a) the average contribution analysis of CO_2 emissions across four scenarios from 2023 to 2050 based on lifecycle stage, and (b) the average contribution analysis of different emissions to climate change impact. Scenarios 1 and 2, where MDO and LNG were used, showed similar results. The main contributor was from the TtP stage, which accounted for about 83.7% and 84.2% of the total carbon emissions of MDO and LNG, respectively. Similar trends were shown by the average result of LNG & LBG, where TtP was the biggest contributor, covering 71% of total carbon emissions. The opposite pattern was found in LBG. The upstream WtT was responsible for 68% of its total carbon emissions, since carbon emissions during TtP was considered biogenic. The TtP emission contribution was mainly from the 5% MDO that was used as pilot fuel.

The contribution analysis also assessed the climate change impact per distance. The characterization factors for CH_4 and N_2O were 25 and 298, respectively (Statistics Netherlands 2020). It was found that N_2O was insignificant across the four scenarios. Different results were shown for CO_2 and CH_4, where the former gas was the

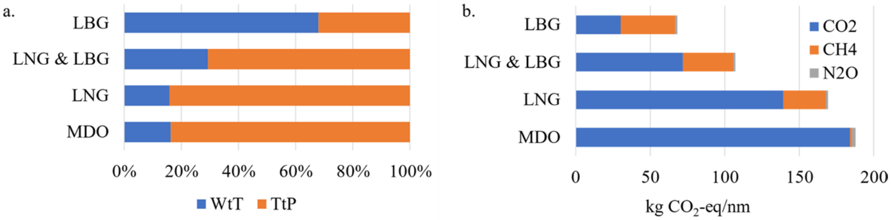

Fig. 6 Contribution analysis of **a** CO_2 emissions, **b** climate change impact

Table 5 Summary of fuel and carbon costs

Year	Fuel or carbon costs (STEPS, SDS, Net Zero)	MGO/MDO		LNG		LNG & LBG		LBG	
		Fuel (low)	Fuel (high)	Fuel (low)	Fuel (high)	Fuel (low)	Fuel (high)	Fuel (low)	Fuel (high)
2023	Fuel (€)	3,430,244	4,652,953	3,487,589	5,998,329	3,489,982	6,007,341	3,873,391	7,451,308
	STEPS (€)	0	0	0	0	0	0	0	0
	SDS (€)	0	0	0	0	0	0	0	0
	Net Zero (€)	0	0	0	0	0	0	0	0
2030	Fuel cost (€)	2,755,446	3,737,624	2,110,536	3,616,937	2,506,844	4,631,479	2,890,616	5,613,931
	STEPS (€)	970,249	970,249	875,475	875,475	609,773	609,773	352,475	352,475
	SDS (€)	1,791,229	1,791,229	1,616,261	1,616,261	1,125,734	1,125,734	650,722	650,722
	Net Zero (€)	1,940,498	1,940,498	1,750,950	1,750,950	1,219,545	1,219,545	704,949	704,949
2050	Fuel cost (€)	1,393,042	2,583,869	1,136,898	2,156,973	2,087,720	4,228,394	2,133,008	4,327,057
	STEPS (€)	1,215,273	1,215,273	1,096,565	1,096,565	471,271	471,271	441,488	441,488
	SDS (€)	2,700,607	2,700,607	2,436,812	2,436,812	1,047,269	1,047,269	981,084	981,084
	Net Zero (€)	3,375,759	3,375,759	3,046,015	3,046,015	1,309,086	1,309,086	1,226,355	1,226,355

main contributor to climate change in MDO and LNG, making up 98% and 82% of the total impact, respectively. Meanwhile, CH_4 was the main contributor to climate change in LBG. The total climate change impact from CH_4 was about 31% and 54% for LNG & LBG and LBG scenarios, respectively. The separate emissions of CH_4 and N_2O are shown in Supplementary material Table 3.

4.3 Economic impacts

This section discusses the economic implications of using different fuels and applying different carbon tax schemes. Table 5 summarizes fuel and carbon costs in the years 2023, 2030, and 2050. MDO had the narrowest high/low difference, with the largest being that of LBG. The results also indicate that the more renewable options were always more expensive than the fossil ones.

The carbon costs showed consistent trends among three schemes: STEPS, SDS, and Net Zero. Net Zero is the scenario that aims to reduce carbon emissions to zero by 2050, hence the highest carbon price. The results of carbon costs also corresponded positively with the emissions calculations, where the lowest was from LBG, followed by LNG & LBG, LNG, and MDO. The carbon price was also set to be higher in 2050 for each scheme, as displayed in Table 5. A complete illustration of total costs from the combinations of different fuel and carbon prices can be found in Supplementary Material Fig. 1.

There are different passenger ticket prices. We have price information, fuel cost, operating profit, and revenue for the year 2022. We use this information to estimate the share of fuel cost in total costs. Applying a similar method, complemented by calculations of fuel carbon cost in the future, we estimated the share of fuel and carbon costs in the ticket price (Fig. 7). The high price of fuel and Net Zero carbon price were used to calculate the change in ticket price. The high fuel price was applied because the values between the estimated fuel cost in 2023 and the actual fuel cost in 2022 reported by Shippax (2023) were aligned. The fuel cost associated

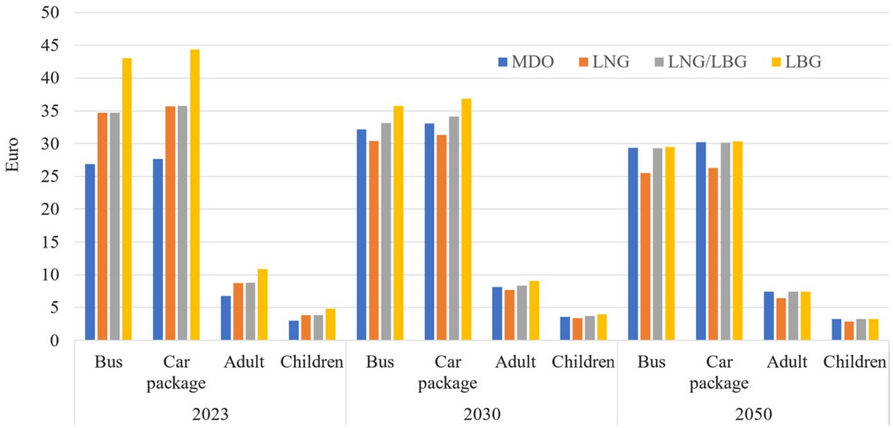

Fig. 7 Summary of the fuel and carbon costs' contribution in the tickets with the Net Zero carbon tax scheme

with passengers in the year 2022 was about € 778,185, while the estimated calculation for 2023 was € 778,931. The Net Zero scheme anticipated the highest possible cost incurred from carbon pricing.

The results indicate different trends among various fuel types. These differences were affected by the dynamics between fuel prices and carbon tax. Although fuel prices were predicted to decline in the future, the opposite trend was found with the carbon tax, which would increase with time. LBG will cause the highest costs until 2030 and level out with MDO in 2050. The opposite results are seen in MDO, with the lowest costs in 2023, becoming the most expensive option in 2050, due to the high costs associated with carbon emissions from MDO. Overall, LNG showed consistent costs, which were not the most expensive in 2023 and became the least expensive in 2023 and 2050.

5 Discussion

5.1 Environmental and economic impacts

Most vessels still use HFO and MDO, accounting for about 76% and 20% of total maritime fuel consumption, respectively (IMO 2021). At the same time, there is an increase in LNG demand in the maritime sector. This trend can be fuelled by climate change concerns and the European MRV legislation. Switching to LNG can reduce carbon emissions by 25%, compared with MDO. However, the overall climate change impact from using LNG is not significantly lower than MDO since LNG has higher CH_4 emissions due to methane slip (unburned methane) (see Fig. 6), although engine manufacturers are progressing in reducing the slip. These findings are also confirmed by previous studies (Brynolf et al. 2014a, b; Gilbert et al. 2018; Spoof-Tuomi and Niemi 2020). Shipping needs to switch to a renewable fuel option, such as LBG, to meet emissions targets and contribute in preventing the catastrophic effects of climate change. Although its methane emissions are as high as those of LNG, the CO_2 emissions is mainly biogenic and can considerably reduce overall climate change impacts. Even a stepwise introduction of LBG as a mixture with LNG can provide long-term climate benefits (Fig. 6).

However, ship operators do not necessarily have a strong incentive to change if carbon pricing is not high enough. Siu et al. (2022) reported that the switch from fossil to renewable fuels in the maritime sector will happen if the carbon pricing is no less than 213 €/ton CO_2, making the adoption of LBG and biomethanol likely in the late 2040s. Similar outcomes were found between those authors' model and our calculations, where we show that the transition will likely happen by 2050 only if the carbon pricing follows the net-zero scenario. Assuming the latter scenario is applied, the carbon costs of using MDO or LNG will range between 52–73 and 43–74%, respectively, depending on whether the fuel price is on the lower or higher side (see Fig. 7). The carbon costs of using a mix of LNG-LBG and LBG will be around 21–39% and 12–23%, respectively. The expensive carbon costs will likely make ship operators consider alternative fuels. Another way to address the issues is to introduce bunker levy schemes, as also considered by the IMO (Kosmas and

Acciaro 2017). However, opposite to carbon pricing, bunker levy schemes cause an increase in overall costs, leading to speed adjustments for fuel efficiency which in the long run is expected to drive the adoption of environmentally friendly technologies in shipping.

Introducing a carbon price within the maritime sector would increase fuel expenses, consequently raising voyage costs. Under the different assumptions on fuel types, fuel prices, and assumptions on carbon pricing between 9 and 45 €/ton CO_2 eq, the transport cost increased by about 0.4–16% (Rojon et al. 2021). An analysis of Danish cargo shipping suggests that a carbon tax between 350 and 450 €/ton CO_2 eq would be needed to meet the Paris Agreement and result in a 100% increase in cargo transport costs (ben Brahim et al. 2019).

Our results are between those of previous studies, considering the assumptions of carbon pricing ranged from about 57 to 221 €/ton CO_2 eq. As ferry operators face higher fuel costs due to the carbon tax, they may adjust their pricing strategy to cover these additional expenses. In the absence of competition, this can result in higher ticket prices for passengers and cargo. The extent of the price increase will depend on the level of the carbon tax, the efficiency of the ferry's fuel consumption, and competition in the ferry industry. In our case, the RoPax operator has the option to try to promote green travel or transportation and try transferring the increased fuel costs into the price of different types of passenger tickets, accompanying vehicles, cabins, and into lounge and cargo prices. This can of course make passengers opt for other modalities (road or air) and it can decrease the volume of goods being transported, resulting in an increase in the price of imported goods (Rojon et al. 2021). Previous studies have shown that the cost impact on the end products is very small, especially for the higher value-added goods (Schwartz et al. 2022; World Economic Forum 2021), often carried by RoPax vessels. Still, the impact of increasing shipping costs may have serious effects as, for example, shown by a recent analysis of possible modal shifts caused by sulphur regulation (Zis et al. 2019).

Our study moreover shows that the impact on passenger ticket prices is relatively higher and boils down to passengers' climate change concerns and willingness to pay. Recent evidence from the aviation industry shows that passengers' willingness to offset their carbon footprint for money remains low (Berger et al. 2022). However, carbon compensation has recently suffered from a bad reputation, and a direct offsetting mechanism may be more attractive to passengers. A low CO_2 footprint for cargo owners may even provide a competitive advantage, distinguishing their products from competitors using transportation with a higher CO_2 footprint.

Over time, as ferry operators adapt to the carbon tax and invest in cleaner technologies, the emissions associated with ferry travel could decrease, reduce the carbon tax burden, and potentially stabilize ticket prices in the long run.

5.2 Uncertainties

ISO 14040 defines allocation as *'partitioning the input or output flows of a process or a product system between the system under study and one or more other product systems'* (ISO 2006). Different allocations are commonly applied when dealing with multiple inputs or outputs, such as economic or mass allocations (Baumann and Tillman 2004). The standard does not specify certain methods and lets users select between mass and area allocations (Finnish Standards Association 2013). However, applying different methods can yield different outcomes, as shown by Fridell et al (2018), where one method could generate a result that is six times higher than the other method; discrepancies between methods can even be as high as ten times (Backstrom 1999). No single scientifically correct method exists; hence, the method can be chosen based on consensus within the RoPax industry (Fridell et al. 2018). Consequently, comparison between results across different studies should be carried out carefully, considering the allocation methods used. This study applied mass allocation due to its straightforward manner and data availability. The area method will require more estimation, such as the area occupied by the passengers and their accompanied vehicles.

Other than methods, uncertainties in the value of variables could lead to results' variability across different studies in both environmental and economic aspects. For the environmental impacts, uncertainty can stem from emissions generated by different fuels. However, the source of differences is usually not difficult to trace and is usually related to the product life cycle stage, such as transport distance or different electricity mix between countries (Brynolf et al. 2014a, b; Spoof-Tuomi and Niemi 2020). Moreover, the LCT perspective requires practitioners to be transparent with all the data used and assumptions applied. Higher uncertainties emerged from the economic analysis since fuel prices are notoriously difficult to predict, especially when extraordinary events, like the pandemic, occur. The world shut down, and oil producers could not sell their products as demand plummeted, causing crude oil to reach negative price levels (Le et al. 2021). Hence, we introduced two fuel price levels and three carbon pricing schemes to provide comprehensive results showing different possible outcomes from economic uncertainties.

5.3 Fuel availability

Switching from fossil fuel to LBG will present a challenge, in view of the many uncertainties surrounding the potential of LBG in shipping. First, it is unclear how much LBG will be available, as this will depend on several factors, such as feedstock cost and availability, as well as the supporting policies (Energy Transitions Commission 2021). It has been predicted that feedstock demand would increase due to various human activities, likely leading to a rise in feedstock prices due to limited availability. Second, the level of competition between different biomass uses will determine the level of LBG production that will be shared between the power/heat sector and the transport sector (IEA Bioenergy 2017). Siu et al. (2022) reported that the current annual production of LBG is about 62,800 tonnes, produced from different sources such as biowaste, fishery waste, agricultural waste and residue, and landfill gas. It was shown that 73% of the total LBG was produced in Europe, and the remaining 23% was from the United States. In Finland, Gasum is the only player in LBG production; its annual production is around 4300 tonnes.

Due to its availability, blending LNG and LBG can serve as a transitional step towards a cleaner energy future, especially in sectors where transitioning directly to LBG might not be possible due to availability and infrastructure limitations (DNV 2019). These fuels can be mixed at any ratio (shown by scenario 3 in this study) according to availability, regulations, and price, which will determine the fuel's emissions reduction potential and overall environmental impact.

6 Conclusions

The environmental and economic aspects of employing diverse marine fuels alongside varying carbon pricing strategies have been examined. Our study explored different fuels namely MDO, LNG, a blend of LNG-LBG, and LBG. The results of emissions monitoring vary across different vessels; nevertheless, our methodology is transferable to other vessels, RoPax or not, and acceptable by MRV standards. We also emphasized transparency in data collection, methodology, and calculation. For example, the choice between mass and area allocation can cause significant differences in emissions, as we show, with cargo emissions from cargo being twice as high as those attributable to passengers. The public data of EU MRV (EMSA 2023) show variations in carbon emissions per nm and carbon emissions per transport work, without any specific pattern. Disclosing the monitoring plan, selected methods, and emissions are the basis of MRV aiming at decarbonization. Moreover, the impending requirement, set by the EU MRV, for separate reporting of CH_4 and N_2O emissions by 2024 could prompt ship operators to explore renewable fuel alternatives. The explored alternatives would not only decrease CO_2 emissions but also improve the impact of climate change.

Integrating carbon pricing will result in a rise in overall operating costs. In principle, it is more feasible to pass the costs to cargo than to passengers, given the lower price elasticity of the former and the rather limited share of transport costs in final prices. For bulkers and tankers instead, transport costs represent a higher share of final prices but, even in this case, the impact should be limited given the low price elasticity of the transported goods (commodities and oil).

LBG appears promising in addressing climate change caused by shipping, but its high CH_4 emissions still require technological solutions going forward. Moreover, biomass availability and competition among sectors vying for LBG can lead to price increases. Relevant stakeholders must reassess the balance between environmental impact, economic performance, and the trade-offs of future fuels and carbon prices. A potential solution involves gradually blending LNG with LBG and progressively increasing the LBG part. This approach could help mitigate environmental impact while addressing concerns about LBG availability and price fluctuations.

In a situation where fuel is scarce, a RoPax ship would be priority as it transports both passengers and cargo and, as a result, it could be used to ration fuel usage. It is also important to understand that, from a technological perspective, a dual-fuel engine gives operators a competitive edge, due to the ease of switching from one type of fuel to another (also known as fuel flexibility). On the other hand, fuel prices will continue to behave as those of any other commodity in a free market. This means that the market forces of demand and supply of biofuels, especially LNG and LBG in this case, will obviously influence the prices and quantities of these fuels in future energy markets.

Our analysis assessed the situation up to 2050. In reality, unforeseen changes are likely to occur. Nonetheless, the study aligns with IMO strategy, hopefully benefiting shipowners, especially those in RoPax shipping, in their decisions on decarbonization. Future research can focus on other potential fuels, such as biomethanol or electrofuels. This is especially important since switching to methanol will require engine retrofit, leading to increased costs. Methane slip is another important issue of using LNG or LBG, and its elimination requires further research and development. On the side of economics, there may be merit in exploring ways for the logistics chain to bear the increased costs, and to assess the potential added value to end users from green transportation.

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