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Life cycle greenhouse gas emissions and cost of energy transport from Saudi Arabia with conventional fuels and liquefied natural gas

Shashwat Tripathi [a,*], Christopher P. Kolodziej [a], Zifeng Lu [a], Daniel De Castro Gomez [b], Xin He [c], Jessey Bouchard [c], Farhad Masum [a], Troy Hawkins [a], Michael Wang [a]

[a] *Argonne National Laboratory, Lemont, IL, USA*
[b] *Saudi Aramco, Dhahran, Eastern Province, Kingdom of Saudi Arabia*
[c] *Aramco Americas: Aramco Research Center, Detroit, MI, USA*

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ABSTRACT

The International Maritime Organization has recently developed several regulations to reduce greenhouse gas (GHG) emissions. To meet these targets, ship builders and operators must either replace or upgrade the existing fleet with new decarbonized vessel technologies and/or switch to alternative fuels. The latter has been of interest, especially using liquefied natural gas (LNG), among other alternative fuels, which can have lower emissions than conventional fuels. In Saudi Arabia in 2023, LNG was priced about 10 times lower than in Europe. In this study, Well-to-Wake life cycle GHG emissions and cost are calculated for a SUEZMAX tanker operating with three fuel options: high sulfur fuel oil, very low sulfur fuel oil and LNG. This is done for two different trips, for Saudi Arabia to Japan and Saudi Arabia to the Netherlands. Results show 11% and 12% life cycle GHG emissions reduction with LNG for trips to the Netherlands and Japan, respectively. From a sensitivity analysis of methane slip, LNG cost and anchoring time, the cost of GHG abatement for the LNG vessel varied from 171 United States dollars (USD) to –255 USD, and from 206 USD to –191 USD per ton of GHG, for the trip to the Netherlands and Japan, respectively.

Introduction

The Paris agreement, adopted in 2015 and currently having 196 signatories, sets an overarching goal to “hold the increase in the global average temperature to well below 2 °C above pre-industrial levels, and pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels.” Based on the Paris agreement, to limit global warming to 1.5 °C, greenhouse gas emissions must peak before 2025 at the latest and decline 43 % by 2030. [1] Because of this, every transportation sector is undergoing a process of rapid deep decarbonization to reach the ambitious decarbonization targets set by different legislative bodies. In this sense, the International Maritime Organization (IMO) has set several targets and regulations to enable the decarbonization of the marine transportation sector. [2] While the main target is to achieve net-zero GHG emissions by or around 2050, there are intermediate targets of 70 % total annual GHG reduction (striving for 80 %) in 2040 and 20 % total annual GHG reduction (striving for 30 %) in 2030. These targets set by the IMO incentivize the ship or vessel operators to shift towards low GHG emissions technologies.

Decarbonizing the marine sector completely and quickly can be a

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Abbreviation: AIS, Automatic Identification System; BSFC, Brake Specific Fuel Consumption; BSPFC, Brake Specific Pilot Fuel Consumption; CAPEX, Capital Expenditure; CCA, Cost of CO_2 Abatement; CI, Carbon Intensity; CO_2, Carbon Dioxide; COVID, Corona Virus Disease; DWT, Deadweight Tonnage; ECA, Emission Control Areas; EEDI, Energy Efficiency Design Index; EPA, Environment Protection Agency; GHG, Greenhouse Gases; GREET, Greenhouse Gases, Regulated Emissions, and Energy Use in Technology; GWP, Global Warming Potential; HPDF, High Pressure Dual Fuel; HSFO, High Sulfur Fuel Oil; IMO, International maritime Organization; IPCC, Intergovernmental Panel on Climate Change; JP, Japan; LBSI, Lean Burn Spark Ignition; LCA, Life Cycle Analysis; LCC, Life Cycle Cost; LNG, Liquefied Natural Gas; LPDF, Low Pressure Dual Fuel; LSMGO, Low Sulfur Marine Gas Oil; MARPOL, International Convention for the Prevention of Pollution from Ships; Max, Maximum; Min, Minimum; MMBtu, Metric Million British Thermal Unit; MR, Medium range; MUSD, Million United States Dollar; NL, Netherlands; NOx, Nitrogen Oxides; OPEX, Operating Expense; PM, Particulate Matter; RSZ, Reduced Speed Zone; SA, Saudi Arabia; SDG, Sustainable Development Goals; SOx, Sulfur Oxides; ULCC, Ultra Large Crude Carrier; US, United States of America; USD, United States Dollar; VLCC, Very Large Crude Carriers; VLSFO, Very Low Sulfur Fuel Oil.

* Corresponding author.

E-mail address: stripathi@anl.gov (S. Tripathi).

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mammoth challenge. As per the US Department of Energy, the shipping sector is hard to decarbonize because of the wide range of vessel types and sizes, their large amount of energy usage, and the global nature of marine transportation that involves cross-border activities. [3] Also, historically, the marine sector has been using residual fuel oils for their energy demands, which is low cost with high energy density. [4] However, shifting to an alternative technology, such as the battery electric powertrain, that has high cost and lower energy density may not be a practical solution for ocean going vessels. Since international shipping is largely associated with the commercial sector, the profitability of the vessel operation is a very important factor for its operators. [5] Therefore, even though battery electric vessels may seemingly have the potential for high GHG emission reductions, their application into the marine sector may be very challenging and limited. [6] Hence, it becomes evident for the marine sector to look for other alternative technologies that will enable its decarbonization without bringing too much impact on the cost aspect.

While there have been investigations done in the past on alternative technologies for marine propulsion, very few have performed a detailed assessment for tankers. [7] Since the energy consumption of the vessels are very much dependent on their operating profile, it is very important to do dedicated analysis for the most common routes on which the vessels are operating. [8] This study evaluated the effects of two different tanker routes (Saudi Arabia to the Netherlands and from Saudi Arabia to Japan), while operating with three different fuels: High Sulfur Fuel Oil (HSFO), Very Low Sulfur Fuel Oil (VLSFO) and Liquefied Natural Gas (LNG). This selection was made keeping in mind the currently most common shipped energy carrier in tankers, i.e., crude oil. Saudi Arabia is the largest exporter of crude oil, the most common energy source in the world, with Asia and Europe being the largest destinations. Within Europe, the Netherlands was selected as the destination since it is the largest importer of Saudi Arabian crude oil among European nations. [9] While in Asia, Japan was selected as it is the second largest importer of Saudi crude oil, which accounts for 40 % of Japan's total annual crude oil imports. [10] The vessel size considered was the SUEZMAX tanker, that has a length of around 285 m and can pass though the Suez Canal, which was needed for the trip to the Netherlands. [11] Also, as of 2020, the global tanker fleet population has SUEZMAX as the third most common type of tanker.

The intent was to estimate the GHG emissions on a Well-to-Wake basis through life cycle analysis (LCA) of the SUEZMAX tankers for its voyage from the Kingdom of Saudi Arabia (KSA) to Japan and the Netherlands. The cost impact was also assessed by estimating the life cycle cost (LCC) of the vessels operating for thirty years. Further, the cost of carbon abatement was calculated to estimate the most suitable technology for decarbonization of SUEZMAX tankers among these options, when operating on similar trip profiles as in this study. This makes the study highly advanced for GHG emissions and cost of SUEZMAX tankers and provides insightful results that may help the vessel operators and policy makers of international shipping.

Methodology

The workflow followed for this study is consistent with the following parts: (1) LCA, (2) LCC, and (3) Sensitivity Analyses. Each of these parts involves literature survey and data gathering, followed by numerical calculations to get the results of emission and costs. Each of these parts are explained in detail in the following sub-sections, highlighting how it was carried out during this study.

LCA

The life cycle analysis was performed for the 100-year Global Warming Potential (GWP-100) of the greenhouse gas (GHG) emissions using Argonne's GREET (Greenhouse gases, Regulated Emissions, and Energy use in Technologies) model. [12,13] This was done using the Marine sheet within GREET that deals with the Well-to-Wake life cycle analysis of the fuels consumed. The selection of routes, vessel type, fuels, operating profile, and the resulting fuel consumption is explained in detail under the Supplementary Information provided with this document. The fuel consumption results of each segment of the trip were used to calculate the life cycle GHG emissions using the GREET database of emission factors of the different processes associated with the whole life cycle. Further, since the study is focused on fuels produced in KSA (HSFO, VLSFO, LSMGO, and LNG), a version of the GREET model developed for the Middle East and North Africa (MENA) region was used, where the emission factors of fuel production are more representative for the countries of the MENA region. [14] These emission factors are present for GHGs (i.e. CO_2, CH_4 and N_2O), as well as criteria pollutant emissions (primarily SOx, NOx, and PM). However, for this study, as only the GWP-100 is of interest, GHGs were only considered for the analysis with methane corresponding to 30 times and N_2O to 265 times of CO_2, as per the 5th assessment report of the IPCC. [12] The Well-to-Wake life cycle GHG emissions were composed of three stages: feedstock, conversion, and (on-board) combustion. The characteristics of the feedstock and conversion stages for each fuel were modeled based on the situation specific to Saudi Arabia.

Because different refining products go through different processing units within a refinery, refinery-process-level allocation is suggested to be used in LCA of petroleum-derived products. [15,16] In our previous work, based on simulation results of a detailed linear programming (LP) model of refineries, we reported a process-level energy allocation method to capture process-dependent characteristics of fuel production within refineries and allocate energy use of individual refining processes to refinery products. [15–17] In this work, we adopted the same approach to distinguish the energy use and emissions between HSFO and VLSFO during their refining processes. The processing-unit-level LP modeling data of individual refineries in Saudi Arabia in 2021 were obtained from a commercial database. [18] These data were further used in our process-level energy allocation framework to derive product-specific refining parameters of HSFO and VLSFO in each refinery.

In the case of the HSFO vessel, a scrubber was used to reduce the Tank-to-Wake SOx emissions in both the Emission Controlled Areas (ECA) and non-ECA waters. In order to match HSFO stack-out SOx emissions to that of LSMGO operation, a scrubber efficiency of 96.3 % was assumed with a baseline fuel consumption penalty of 4 %. [19] The increased fuel consumption of the vessel increased both the GHG emissions from both the Well-to-Tank (because of increased fuel production burden) as well as the Tank-to-Wake portions of the life cycle. For the VLSFO and LNG cases, fuel sulfur levels were low enough to not require a scrubber and no scrubber fuel penalty was applied. In the case of LNG, methane emissions are an important consideration across all three life cycle stages. The default methane slip of the combustion life cycle phase was based on a low-pressure dual-fuel slow speed main engine with 2 g/kWh methane emissions. [20].

The life cycle GHG analysis was performed for the two trips and then considering an annual frequency of 10 one-way trips (5 roundtrips) and a vessel lifetime of 30 years, life cycle GHG emissions were calculated. The GHG emissions were calculated on both a per life cycle basis as well as a per metric ton cargo-kilometer basis. The latter was calculated by dividing the lifetime GHG emissions by the vessel's cargo carrying capacity and the lifetime kilometers covered. The cargo capacity of the vessels was assumed to be the same between the fuel oil and LNG powered vessels, as the LNG could potentially be stored on the deck of a tanker vessel, avoiding any loss of cargo space. The deadweight tonnage (DWT) for SUEZMAX tankers was assumed to be 160,000 metric tons, as listed in the EPA's Port Emissions Inventory Guideline and 4th IMO GHG Study. [21,22] The GREET emission factors for each fuel are available for the three different phases of its life cycle: feedstock, conversion, and combustion. All the emissions related to each of these phases are grouped together and shown later in the corresponding results section.

LCC

The life cycle cost (LCC) is calculated by considering the capital expenditures (CAPEX), the operational expenses (OPEX) and the interest associated with their entire life cycle. This framework followed is similar to the NavigaTE model developed by Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping. [23] While the CAPEX was the same for the vessels on both the routes, the OPEX varied due to the varying operational profile of the two routes. However, CAPEX and OPEX comprise of several sub-components which are explained and discussed individually in the following sections and summarized in Fig. 1. The interest rate of 10 % was considered for a period of 30 years, which is the lifetime of the vessels considered in this evaluation. Where cost of debt and share of debt was assumed to be 5 % and 60 %, respectively, which are the default values considered in the NavigaTE model. [23] Further, all costs are reported in 2023 United States dollars (USD), using the current cost of the fuels and calculate its inflated value over the years together with a discount rate of 10 %. The 10 % discount shows the depreciating value of the current dollar value over the future years and the inflation of 2.5 % was considered specific to the kingdom of Saudi Arabia. It is important to note that annually only ten trips were considered for both the shipping routes. This was done by considering the time taken for each of these trips, which can be up to 30 days. Although the trip duration for both is different, the same number of trips were considered to ensure uniformity in the evaluation.

CAPEX

The CAPEX involves the cost associated with the design and shipbuilding of the vessel until it reaches the point when it starts operation. As per the NavigaTE model, the major costs considered for the cost of tankers are: base CAPEX, engines, tank & fuel system, and yard installation. The base CAPEX is the common cost shared for similarly-sized tankers, irrespective of its propulsion system. The engines, tank & fuel systems and yard installation cost was taken as in the NavigaTE model specifically for tankers. Other than these costs, the cost of scrubber systems were also investigated as they need to be included for the HSFO powered vessel. Since the NavigaTE model developers did not consider operation of vessels with HSFO, scrubber related data were not available. Therefore, the cost associated with scrubber systems were taken from the literature and was found that for a SUEZMAX tanker it can add up to $6 million of CAPEX. [24].

Since the data considered for the calculations were mostly from 2020, the final CAPEX of the vessel was more representative of the cost available in the literature for the same year. However, to get the cost specific to 2023, the inflation rate over the years was accounted and the remaining difference was identified as COVID surge. This was done by taking the 2023 cost of the new SUEZMAX tanker (approximately $85 million) and calculating the cost for the preceding year using the inflation rate. The cost obtained was matching the historical price until the year 2021, however for 2020 it showed that the historical cost was still around $10 million less. This surge observed between 2020 and 2021 is referred to as a COVID surge and has been added to the final CAPEX results to have a more representative value of the current scenario.

OPEX

The OPEX accounts for all the costs associated during the operational phase of the vessel, which spans 30 years, as considered in this study. While the major portion of OPEX is from fuel, there are other components such as port & canal fees and several other ancillary costs. In the case of the HSFO vessel with scrubber, the cost of operation of scrubber units were also accounted based on literature data, such as cost of maintenance, reagents, water cleaning, 4 % fuel penalty for additional energy demand, etc. [25] The fuel related cost was calculated using the different fuels consumed by each of the vessels and the specific cost of each fuel in the kingdom of KSA. The fuel consumption of the different fuels was calculated based on its operational profile, obtained from AIS. However, the specific cost of the different fuels was obtained using the Ship & Bunker website that has historical data for bunker fuel prices across the world as the cost is very dynamic. [26].

The data available for Saudi Arabia were from the ports of Jeddah and Dammam, where the prices at the port of Dammam will be most representative for this work. However, only the data for the port of Jeddah was up to date, and not for the port of Dammam. Therefore, for VLSFO, the current cost at Dammam ($576.4 per metric tonne) was calculated by considering the same ratio between the average annual cost at the port of Jeddah to the average annual cost at the port of Dammam. For LSMGO cost ($1149.5/metric ton), no historical values were reported at Dammam, so the same annual average cost at the port of Jeddah was used. For HSFO ($317.6/metric ton), both Dammam and Jeddah had outdated values, so its price was taken from the port of Fujairah and its equivalent cost for Dammam was calculated, like the cost calculation of VLSFO using the price at Jeddah. Finally, for LNG a fixed cost of $1.3/MMBtu specific to KSA was used, also a long-term cost of $9/MMBtu, which is more representative of current day LNG price at the port of Rotterdam, was considered for the sensitivity analysis.

Cost of CO_2 abatement

The primary motivation behind this study is to look for different decarbonization options for the marine sector, where LNG is evaluated as a potential fuel option through LCA. Moreover, the cost associated with the decarbonization of the LNG vesselwas also calculated through LCC. To assess the feasibility of the LNG ship, a common metric was calculated which is the cost of CO_2 abatement (CCA). This is the additional cost of investment needed per reduction of 1 metric tonne of GHG emissions. This is a very important metric that has been recently

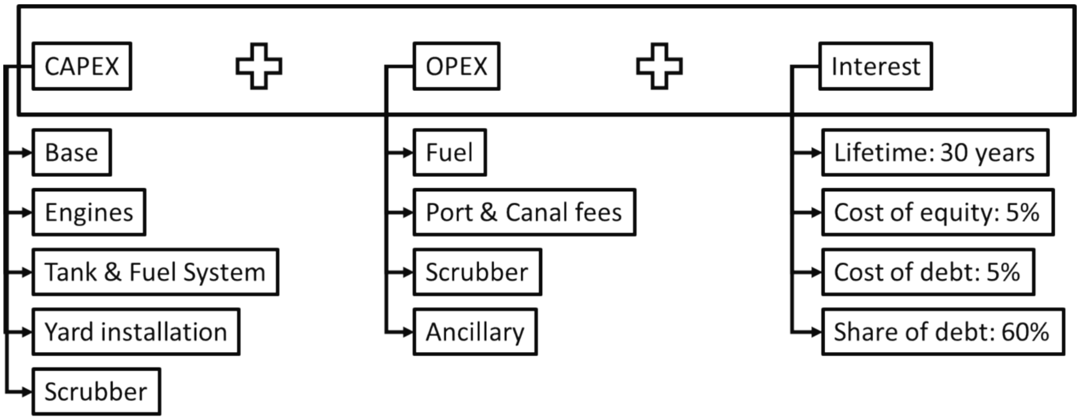

Fig. 1. Cost components considered for the LCC.

considered in most of the studies associated with assessment of decarbonization solutions. [27–29] This cost can be better understood by equation (1) that states the formula for its calculation, where LCC $_{baseline}$ and LCA $_{baseline}$ is for the HSFO+scrubber vessel, which was considered as the baseline. Similarly, LCC_{LNG} and LCA_{LNG} correspond to the LNG vessel.

$$CCA = \frac{(LCC_{LNG} - LCC_{Baseline})}{(LCA_{Baseline} - LCA_{LNG})} \quad (1)$$

Sensitivity analyses

This study also evaluated the effect of certain important parameters that can have a significant effect on the LCA and the LCC results. The different parameters considered for the sensitivity analysis are: (i) Scrubber fuel penalty, (ii) LNG cost, (iii) Methane slip and (iv) Anchoring time. Each of these parameters were varied to see their impact on the life cycle GHG emissions and cost results. More details for each of these parametric sensitivity analyses are explained in detail below.

Scrubber fuel penalty

For the HSFO vessel, scrubber systems are needed to meet the global SOx emissions levels. However, the scrubber system itself needs some energy to function, which in turn leads to added fuel consumption. In the literature, this fuel penalty level was estimated for different operating conditions and a wide variety in its range was observed. Therefore, it was found interesting to consider this parameter for the sensitivity analysis, to see the change in the overall results with the change in scrubber fuel penalty level. The variation considered in the fuel penalty was from 1 % to 7 % (with a 4 % baseline) of the base fuel consumed by the main engines (when operated without scrubber).

LNG cost

Based on the 2023 price of LNG in KSA, which was $1.3/MMBtu, the LCC of the LNG vessel was expected to be significantly lower than the other two vessels operating on fuel oils. However, over time the cost of LNG may increase and therefore a long-term price of $9/MMBtu was considered, similar to the current price at the Port of Rotterdam, which would increase the LCC of the LNG vessel accordingly. [30,31] This section mainly intends to evaluate the effect of the increased cost of LNG in the future on the LCC of the LNG vessel, and if it becomes comparable with the other two vessels. Furthermore, the effect of LNG cost on the cost of carbon abatement was also calculated. Therefore, the feasibility of LNG vessels with increasing cost of LNG was evaluated as an alternative propulsion technology in the marine sector.

Methane slip

A very common issue with LNG vessels is the methane slip or leakage that occurs from different LNG related activities such as storage, transport, etc. Methane leakage is a major issue for global warming as its 100-year global warming potential is 30 times the GWP of CO_2 based on the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (IPCC AR5). [12] Therefore, it is important to limit leakage from LNG systems. However, it is very challenging due to the volatile nature of the methane gas, which is the major component in LNG. In the current literature, a wide range of values are reported for methane slip and therefore it becomes a very interesting parameter to be considered for the sensitivity analyses. This leakage is highly variable and varies among different engine types as well as varies for different engine operating load. Based on the values for the different engine types that are most widely used for LNG vessels, three different values were considered. Low-pressure dual fuel (LPDF) 2-stroke engines were taken as the default LNG engine technology with a value of 2 g/kWh methane emissions. In the sensitivity analysis, a lean burn spark ignition (LBSI) 4-stroke engine with 4 g/kWh methane emissions and a high-pressure dual fuel (HPDF) 2-stroke engine with 0.3 g/kWh methane emissions were considered. [32] Using these values the equivalent change in the LCA and the cost of carbon abatement were calculated and discussed later in the results section.

Anchoring time

Based on AIS data for voyages from Saudi Arabia to the Netherlands, a long period of anchoring was observed somewhere near the Suez Canal. This time can be associated with the delay or waiting time for the vessel to get its turn to pass through the canal. Such times can be highly variable and will be different on a trip-by-trip basis. This can lead to a significant change in the fuel consumption per trip due to this additional duration. Therefore, this aspect was evaluated for the trip to the Netherlands for different anchoring times. The AIS observed value was approximately 217 h, however, to account the possible variation, a value of 100 h was taken for the best-case scenario and the value of 300 h was taken for the worst-case scenario. Considering this variation an estimation can be made of the corresponding change in the fuel consumption which accordingly changes both the LCA and LCC results. In summary, the different parameters used for the sensitivity analyses and the range of their variation are summarized in Table 1.

Results and discussion

Fuel consumption results

As discussed in the methods section, the fuel consumption was calculated using AIS data for the operational profile of SUEZMAX tankers on these routes. The brake specific fuel consumption (BSFC) of the different equipment on board the vessel was obtained from the 4th International Maritime Organization (IMO) GHG Study. [22] For the main engines, load factors were calculated using the vessel's average speed in each segment of the trips to Japan and the Netherlands and using the Admiralty Formula. For the auxiliary engines and boilers, the power demands were considered for SUEZMAX tankers as mentioned in the 4th IMO GHG study. [22] Fuel consumption from the different engine/equipment is shown in Fig. 2 for the one-way trip to Japan and to the Netherlands. The results show the fuel consumed during each of the trip segments for the primary and secondary fuels stored on board each vessel. The fuel consumption was calculated for the two trips based on the time spent during each segment of the trip as obtained from the AIS data. The trip to the Netherlands has an additional trip segment which is referred to as reduced speed zone (RSZ) ECA, where the fuel used is LSMGO to meet the 0.1 % fuel sulfur limit.

The primary fuel consumption for the main propulsion engines was slightly higher for the trip to Japan, while the secondary fuel consumption from rest of the equipment was more than 50 % higher for the trip to the Netherlands than Japan. This was due to the high amount of time spent anchoring during the trip to the Netherlands. Also, for the trip to Japan, the majority of the fuel was consumed was in the cruise condition, as about 98 % of the total transit time was spent in cruise. Therefore, contributions from other trip segments were minimal, such as RSZ and maneuvering. However, for the trip to the Netherlands, a significant portion of fuel consumption came from other segments of the trip, including RSZ, maneuvering, anchoring and RSZ ECA. Thus, it is

Table 1
Range of values for different parameters considered for the sensitivity analysis.

Parameter	Best case	Base case	Worst case	Effect
Scrubber fuel penalty	1 %	4 %	7 %	LCA
LNG cost	$1.3/ mmbtu	$1.3/ mmbtu	$14/ mmbtu	LCC
Methane Slip	0.3 g/kWh	2 g/kWh	4 g/kWh	LCA
Anchoring time	100 h	217 h	300 h	LCA and LCC

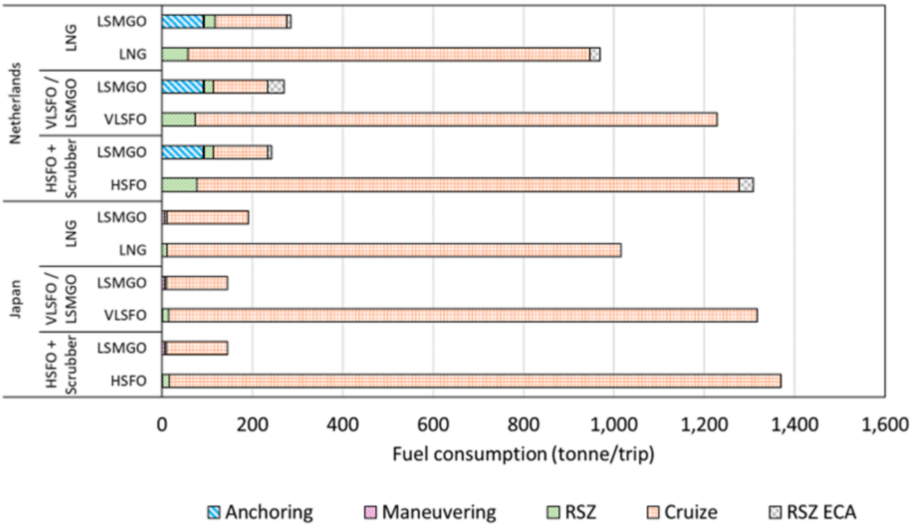

Fig. 2. Fuel consumption of the three vessels in each trip segment for the one-way trip to Japan and the Netherlands.

very important to know how the vessel operates during the trip. Despite the distance being similar between two trips, the fuel consumed can vary significantly. As seen here, the trip to the Netherlands also involves more time spent in RSZs, which will benefit it in saving some fuel as it is a condition of slow steaming, thus reducing the power demand on the main engine and reducing its fuel consumption.

Since the three vessels evaluated in the study used different fuels to run their on-board equipment, the fuel consumption for each of the vessels and energy converters was calculated separately. The lower heating value (LHV) of HSFO and VLSFO were assumed to be the same in this work, with only the sulfur content varying between the two. Therefore, for the trip to Japan, where there were no ECAs, the HSFO and VLSFO consumption were the same. However, during the trip to the Netherlands, the HSFO vessel had a 4 % added fuel penalty due to the SO_x scrubber. For the VLSFO vessel, there was reduced VLSFO consumption since part of the trip was in ECAs where LSMGO was used. This also resulted in higher LSMGO consumption for the VLSFO vessel than the HSFO vessel. The main sources of LSMGO consumption were the auxiliary engines and boilers, which were common among all the vessels. However, for the LNG vessel LSMGO consumption was the highest, as it also involved pilot injection of LSMGO in its dual fuel main propulsion engines and considered 100 % operation on LSMGO during maneuvering.

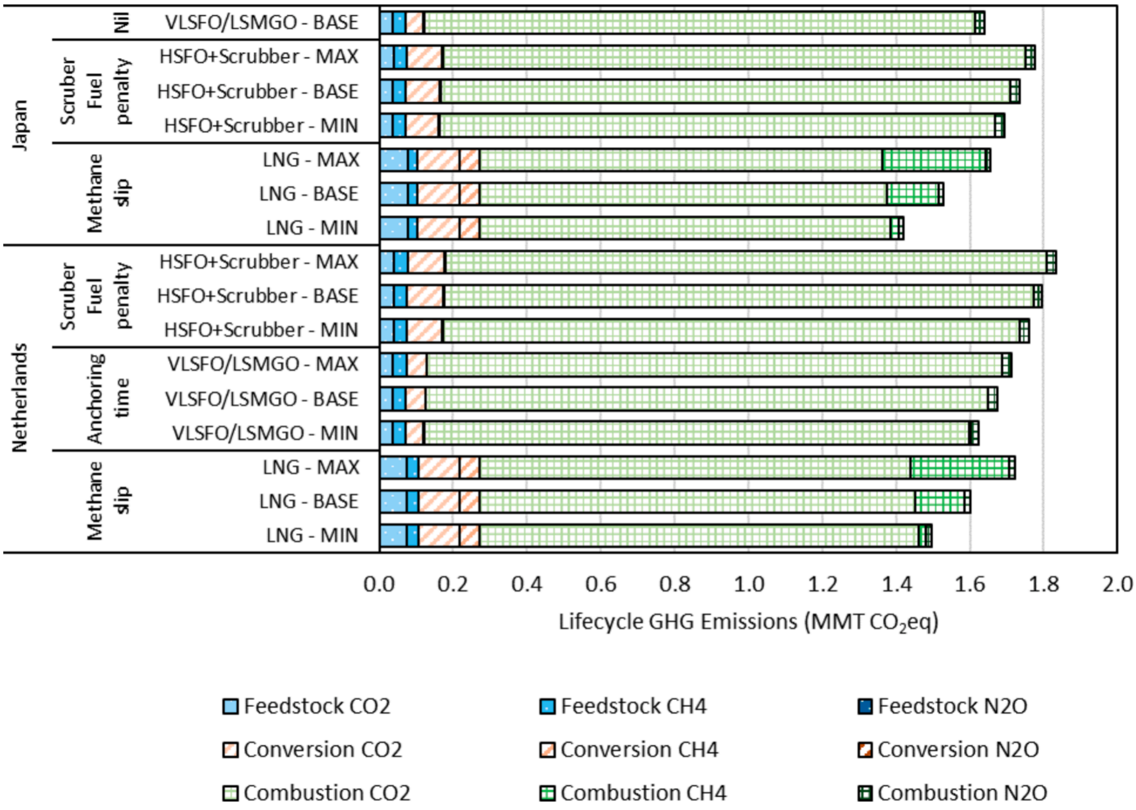

Fig. 3. Lifetime GHG emissions of the different GHGs for each fuel life cycle phase.

LCA results

The LCA results obtained for the two different trips are shown in Fig. 3 for the lifetime GHG emissions in million metric ton (MMT) of CO_2 equivalent (CO_2eq) for the fuel life cycle, showing the contribution of CO_2, CH_4 and N_2O, individually. For the LNG vessel it can be observed that despite it being the lowest GHG emitting vessel in all cases, its feedstock and conversion emissions were higher than the fuel oil vessels. This was mainly due to the upstream methane leakage of LNG production. Because the GWP of methane is 30 times of CO2, the overall GHG emissions were 4 % and 7 % less than the VLSFO vessel for the trips to the Netherlands and Japan, respectively. Further, the change in the methane slip considered in the sensitivity analysis had a significant impact to the life cycle GHG emissions, compared to the base case VLSFO vessel. In the best case (min) scenario, the LCA results were 11 % and 13 % higher, while in the worst case (max) scenario, it was 3 % and 1 % higher for the trip to the Netherlands and Japan, respectively. Regarding the VLSFO vessel, since there was no anchoring time for the trip to Japan, no parameter is used to perform any sensitivity analysis and is referred as “Nil” in the y-axis of Fig. 3.

For the HSFO vessel, by changing the scrubber fuel penalty, a difference of less than 5 % was observed for both the trips. Thus, it can be said that the scrubber fuel penalty was quite small and thus was not considered for the LCC as the effect will be quite insignificant. Moreover, the anchoring time for the trip to the Netherlands was found to be the main contributor towards higher fuel consumption and life cycle GHG emissions. In terms of LCA, it was observed to have a more significant impact as the GHGs varied by more than 5 % between the max and min anchoring times for all the vessels. Thus, methane slip and anchoring time had a larger effect on the LCA results than scrubber fuel penalty.

Fig. 4 shows the GHG emission variation based on the trip segments, such as cruise, anchoring, RSZ, etc., for both the trips. This was calculated in g CO_2eq/t-km, which is the standard unit of comparison for cargo carrying vessels. It was calculated by dividing the lifetime GHG emissions with the lifetime distance travelled and the cargo capacity of the vessel. For the trip to the Netherlands, it can be clearly seen that due to the large anchoring time the GHG emissions were slightly higher than the trip to Japan. In fact, if there would have been no anchoring, the trip to the Netherlands would have lower life cycle GHG for each vessel type than for the trip to Japan. This was due to the RSZs during the trip to the Netherlands, since slow speed reduces fuel consumption from the main propulsion engines. Overall, the VLSFO and LNG vessel had about 7 % and 11 % lower lifetime GHG emissions on a per ton-km basis than the baseline HSFO vessel for the trip to the Netherlands, while 6 % and 12 % less for the trip to Japan, respectively. Thus, in the base case the LNG vessel had higher GHG reduction than VLSFO vessel.

LCC results

The LCC includes the CAPEX, OPEX and the interest associated with SUEZMAX tankers for a lifetime of 30 years. The cost contribution calculated for each of the components taken for CAPEX and OPEX calculations are shown in Fig. 5 for both the trips in million United States dollars (MUSD). It was observed that the major share of the CAPEX was associated with the base CAPEX, while for the OPEX it was associated with the port and canal fees. The LNG vessel has the lowest LCC due to the lower fuel OPEX, primarily from the lower specific cost of LNG (USD/MJ) in KSA. In terms of CAPEX alone, the LNG vessel has the highest total due to the cost associated with the storage of LNG. While the VLSFO/LSMGO vessel has the lowest CAPEX, as it does not need to be equipped with scrubber systems to ensure low SO_x emissions, unlike the HSFO vessel. Thus, the lower annual OPEX offsets the higher CAPEX of the LNG vessel, making its LCC the lowest for a 30-year lifetime, except for the max LNG cost scenario where the cost of LNG is almost ten times higher.

Generally speaking, the trip to the Netherlands had higher LCC than the trip to the Japan mainly because of the higher fuel consumption caused while anchoring. Thus, the higher anchoring times observed for the trip to the Netherlands played an important factor in the LCC evaluation. Also, it was observed that despite the HSFO vessel being equipped with scrubber systems, that added to its CAPEX and OPEX, it still had similar LCC as the VLSFO/LSMGO vessel. This is due to the high cost of the VLSFO and LSMGO that makes its LCC the highest, despite having less primary fuel consumption. In the case of scrubbers for the HSFO vessel, its OPEX is higher than its CAPEX, due to the added fuel consumption to run the scrubber system over the lifetime of the vessel, i.e., for thirty years. This added fuel penalty was to run the pump, that ensures the recirculation of the seawater, with or without added alkaline chemical, that washes off the SO_x emissions from the exhaust of the vessel. [19].

In the worst-case scenario (max), when the cost of LNG becomes as high as its current cost at the port of Rotterdam, the LCC of the LNG vessel will be about 4 % higher than the HSFO vessel for both the trips. However, when LNG from Saudi Arabia is used, the LCC of the LNG vessel will be about 9–10 % lower than the HSFO vessel. Therefore, it can be said that when using LNG from Saudi Arabia, the LNG ship will have lower LCC than the conventional vessel.

While the trip to the Netherlands had about 217 h of anchoring time,

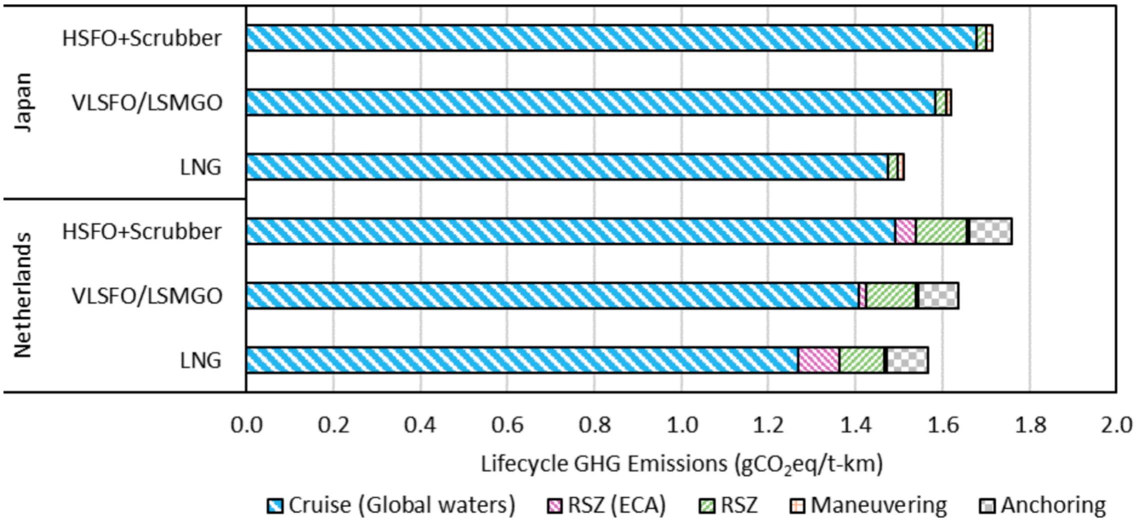

Fig. 4. Life cycle GHG emissions in the base case for the different segments of the trips to Japan and the Netherlands with the three different fuels.

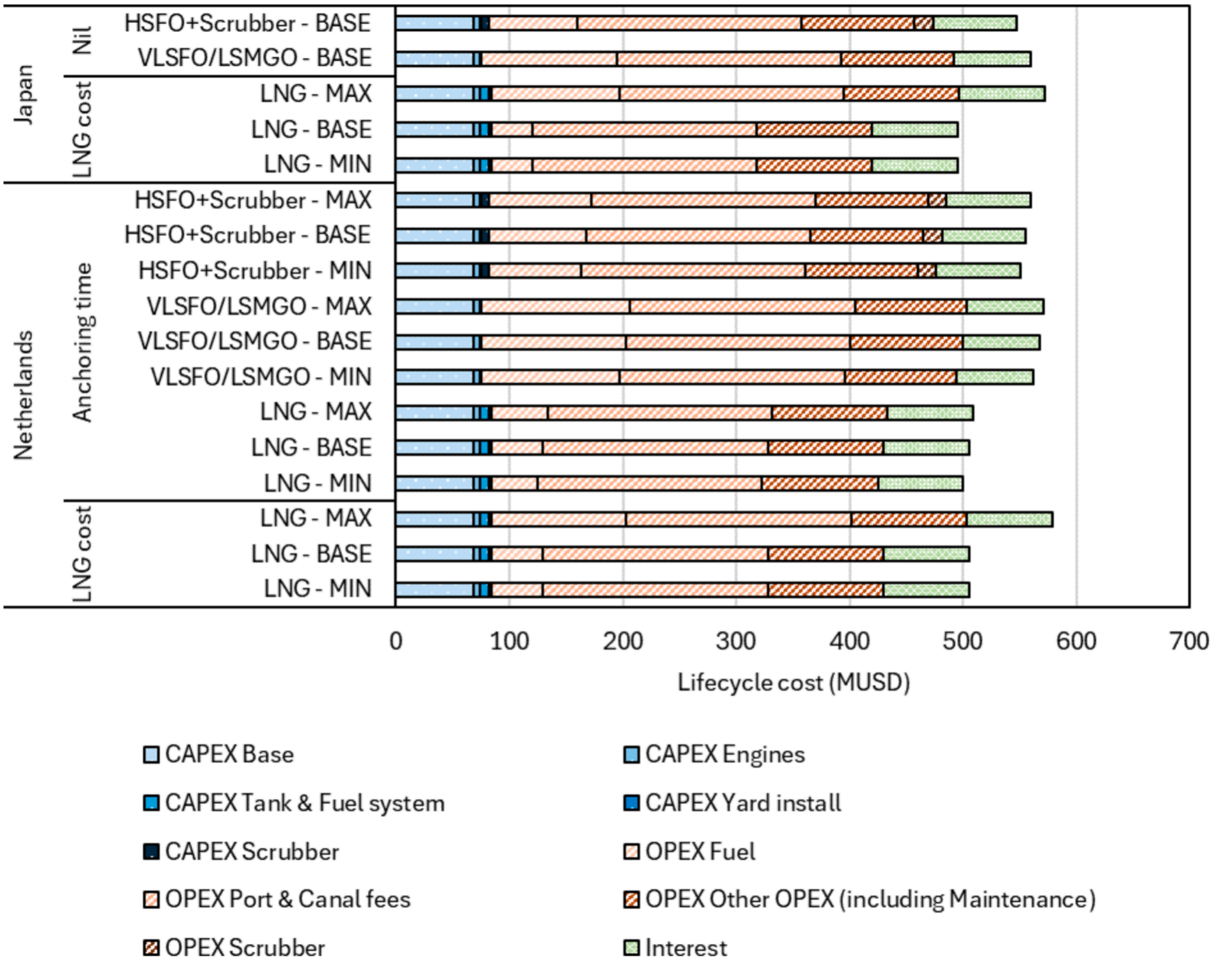

Fig. 5. LCC results (excluding interest) for Japan and the Netherlands.

for the trip to Japan there was none. For the best-case scenario (min), with a decrease of 47 % of the anchoring time from the base case, there was a decrease of 1 % of the total LCC results and about 4 % decrease in the OPEX. While in the worst-case scenario (max), by increasing the anchoring time by 40 %, an increase of 1 % in LCC and 3 % in OPEX. Thus, showing that the variation in anchoring time doesn't have much effect on the LCC results as compared to the LCA results.

CCA results

The sensitivity analysis showed that based on the variation in different parameters, the results can change significantly. From the LCA GHG results, it was observed that the LNG vessel with high methane slip had similar GHG emissions to the HSFO vessel. Similarly, from the LCC results, it was observed that if the future LNG cost in KSA became as high as currently in the Netherlands, the LNG vessel becomes the most expensive vessel. Thus, it is important to consider the maximum and

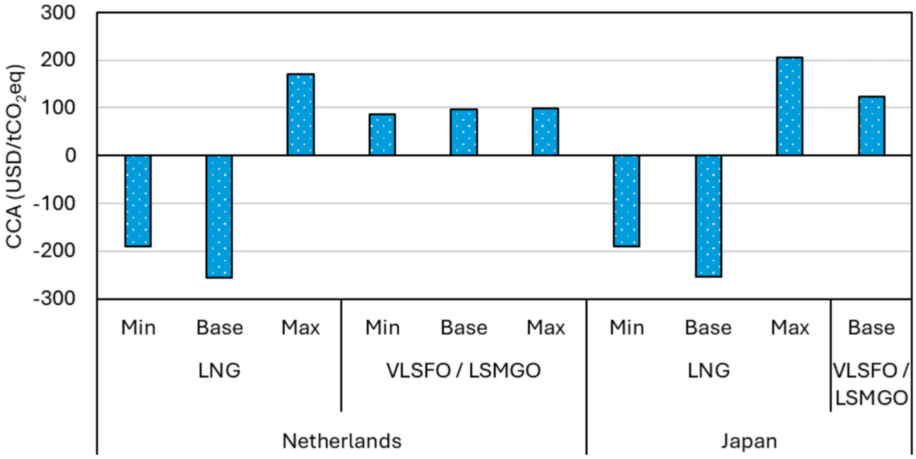

Fig. 6. Cost of carbon abatement for the VLSFO and LNG vessels compared to the baseline HSFO vessel.

minimum values of the combined LCA and LCC results and perform a sensitivity analysis of Cost of Carbon Abatement (CCA). For this, the best-case and worst-case results from the combined LCA and LCC results obtained from their sensitivity analyses were used to calculate a base, min (best-case), and max (worst-case) CCA. The cost of CO_2 abatement was calculated as explained earlier in the corresponding methodology section and is presented here in Fig. 6 for both trips. The CCA of the VLSFO and LNG vessels was calculated with respect to the HSFO vessel.

It was observed that the LNG vessels had a negative CCA in the base case and the best case (min) but it was positive for both trips in the worst case (max), for both the trips. Moreover, the VLSFO vessel had positive CCA based on the evaluated cases for both the trips. Although the VLSFO vessel provides LCA GHG savings, it does have higher LCC in each of the evaluated scenarios. While the LNG vessel in the base and best case (min) scenario provides LCC reduction, along with LCA GHG reductions. Although, in the worst case (max) scenario, the LNG vessel has the highest LCC and therefore in that case the CCA becomes positive. The CCA results for the LNG vessel in the worst-case (max) scenario were observed to be higher by about 2–3 times than the base-case, during both the trips. Moreover, it was observed that the base case CCA for the LNG vessel were slightly more negative than the best case (min) results. Since the price of LNG in Saudi Arabia is the lowest price at which LNG is available among the three regions considered in this study, the same LNG cost was considered for the base and the best cases. Since the CCA is calculated by dividing the increase in life cycle cost by the reduction in life cycle emissions, the best case (min) had no change in LCC but only a larger reduction in LCA GHG emissions, making the CCA less negative than the base case.

Further, the CCA of the VLSFO and LSMGO relative to the HSFO operation was observed to be higher for the trip to Japan than the Netherlands. This was mainly due to a higher increase in LCC for the trip to Japan while higher LCA GHG emissions reduction for the trip to the Netherlands, compared to HSFO operation. It is important to note that these differences are due to the parameters considered for the sensitivity analysis. Anchoring time is considered only for the trip to the Netherlands, which showed a variation less than 5 % for LCA GHG emissions but less than 2 % for LCC. Similarly, for HSFO operation no LCC sensitivity analysis was performed for the trip to Japan, while variation in the anchoring time is considered for the trip to the Netherlands, which shows a variation of slightly lower than 2 %. But for the LCA GHG emissions, sensitivity analysis for HSFO operation is done by considering a variation in scrubber fuel penalty which showed a higher variation of up to 5 % for both the trips.

However, for the LNG operation, there was higher increase in LCC for the trip to the Netherlands, while higher LCA GHG emissions reduction for the trip to Japan. This too depends on the parameters selected for the sensitivity analysis, as the LCA GHG emissions were evaluated for varied methane slip, resulting in significant variation of 13–14 %. While LCC were evaluated by varying LNG cost that showed a variation of 13 % as well for both the trips. Thus, due to this variation in the numerator and the denominator for different scenarios, the CCA for LNG operation were higher for the trip to Japan than to the Netherlands. Further, parameters such as methane leakage, specific cost of LNG and anchoring time needs to be controlled to ensure negative CCA (cost saving) from LNG vessels. However, considering the long-term targets set by the IMO for decarbonization by the years 2030, 2040 and 2050, simply operating vessels on LNG alone will not provide enough decarbonization, since it only reduces life cycle GHG emissions by 11–12 %.

Conclusions

This study of life cycle GHG emissions and cost for a SUEZMAX tanker, operating with three different fueling options, on two different routes, and highlights several important findings. Despite the distance being similar for both the routes, the speed profile varied significantly due to the anchoring and reduced speed zone segments experienced for the trip to the Netherlands. Thus, the GHG emissions and cost associated with energy transport from Saudi Arabia is not only dependent on the shipping distance but is also very much dependent on the route characteristics. Since the operating profile of the vessels for each shipping route will be different, the fuel consumption from each energy converter needs to be calculated for each trip segment individually. This must be done based on the load factor associated with each trip segment as the specific fuel consumption and emissions of each energy converter varies with the load factor. In terms of total fuel consumed during the trip, the relative consumption of primary fuels (i.e., HSFO, VLSFO and LNG), have similar trends for both the trips. However, in terms of secondary fuel (LSMGO) consumption, the trip to the Netherlands had almost double that of the trip to Japan. This is primarily due to the large amount of time spent anchoring for the trip to the Netherlands, which only involved the operation of auxiliary engines and boilers.

In the case of LNG, a large portion of the life cycle GHG emissions came from the methane emissions during the fuel life cycle (i.e., feedstock, conversion, and combustion) and had a significant impact on the sensitivity analysis results. Across all primary fuels, the trip to the Netherlands had about 1–5 % higher life cycle GHG emissions than the trip to Japan, where HSFO had the highest and LNG had the lowest GHG emissions. Despite the lowest GHG emissions from the LNG vessels among the three, the maximum possible reduction was only up to 13 % and therefore could not help meeting the 2030 IMO indicative checkpoint target of 20 % reduction in life cycle GHG emissions. Thus, other fuels such as renewable natural gas, biofuels, methanol, ammonia, etc., produced from cleaner sources and onboard carbon capture needs to be investigated to meet the future IMO GHG emission reduction targets.

In terms of life cycle cost, the VLSFO vessel had the highest cost, and the LNG vessel had the lowest cost, except for the worst-case (highest methane slip) scenario. Overall, the trip to the Netherlands had about 2–3 % higher life cycle cost than the trip to Japan. Further, based on the sensitivity analysis, the LCA results are sensitive to methane slip and anchoring time, while the LCC results are sensitive to LNG cost and anchoring time as well. However, it was found that the LCA GHG emissions were much more sensitive to anchoring time than life cycle cost. The sensitivity analysis for the cost of CO_2 abatement showed that in the best-case scenario the LNG vessel can provide cost savings while reducing GHG emissions. However in the worst-case scenario, there will be an added cost investment for the same level of CO_2 abatement.

Hence, it can be said that the anchoring time observed during the trip to the Netherlands is the main difference between the characteristic of the two trips effecting the LCA results accordingly. However, for the LCC results there is very less impact the fuel consumption effects only the fuel cost which doesn’t have very significant contribution on the overall LCC of the vessels, unlike the LCA. Therefore, for any trip that includes high anchoring time, the results will be like the Netherlands trip while for a trip with almost no anchoring time, will be like the results for Japan, especially on a per metric ton-km basis as shown in Fig. 4. The possibility of on-board carbon capture and storage systems should be investigated for these vessels to estimate where it could be applied. Especially in the case of low-cost LNG where methane slip is properly managed using technologies such as HPDF main propulsion engines and LSMGO for low load operating conditions, as considered in this study.

CRediT authorship contribution statement

Shashwat Tripathi: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation. **Christopher P. Kolodziej:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Zifeng Lu:** Writing – review & editing, Validation, Supervision, Resources, Project administration, Methodology, Funding acquisition, Data curation, Conceptualization. **Daniel De Castro Gomez:** Supervision, Resources, Project administration, Investigation, Funding acquisition, Data curation, Conceptualization. **Xin He:** Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Data curation, Conceptualization. **Jessey Bouchard:** Supervision, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Farhad Masum:** Writing – review & editing, Validation, Methodology, Investigation, Data curation. **Troy Hawkins:** Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, Conceptualization. **Michael Wang:** Writing – review & editing, Supervision, Software, Resources, Project administration, Methodology, Funding acquisition, Conceptualization.

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.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecmx.2024.100747.

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