Marginal abatement cost curves (MACCs) for assessing the role of market-based measures (MBMs) in enhancing the adoption of alternative marine fuels

Sotiria Lagouvardou (✉ sotla@dtu.dk)
Technical University of Denmark  https://orcid.org/0000-0002-9380-3720

Benjamin Lagemann (✉ benjamin.lagemann@ntnu.no)
Norwegian University of Science and Technology  https://orcid.org/0000-0002-6106-0280

Harilaos Psaraftis (✉ hnpsar@dtu.dk)
DTU  https://orcid.org/0000-0003-1671-4406

Elizabeth Lindstad (✉ Lindstad@sintef.no)
Sintef Ocean As  https://orcid.org/0000-0003-1015-7135

Stein Ove Erikstad (✉ stein.ove.erikstad@ntnu.no)
Norwegian University of Science and Technology

Additional Declarations: There is NO Competing Interest.
Marginal abatement cost curves (MACCs) for assessing the role of market-based measures (MBMs) in enhancing the adoption of alternative marine fuels

Sotiria Lagouvardou\textsuperscript{a,*}, Benjamin Lagemann\textsuperscript{b}, Harilaos N. Psaraftis\textsuperscript{a}, Elizabeth Lindstad\textsuperscript{c}, Stein Ove Erikstad\textsuperscript{b}

\textsuperscript{a} Department of Technology, Management and Economics, Technical University of Denmark (DTU) \\
\textsuperscript{b} Department of Marine Technology, Norwegian University of Science and Technology (NTNU) \\
\textsuperscript{c} SINTEF Ocean AS \\
* Corresponding author: sotla@dtu.dk

\textbf{Keywords}: Market-Based Measures; Shipping Decarbonization; GHG emissions, IMO, Alternative Marine Fuels, Marginal Abatement Cost

\textbf{Abstract}

Uncertainties on the global availability and affordability of alternative marine fuels are stalling the shipping sector’s decarbonization course. Several candidate measures are proposed at the International Maritime Organization, including market-based measures (MBMs), environmental policies like carbon taxes and emissions trading systems. Their implementation increases the cost of fossil fuel consumption and provides fiscal incentives towards greenhouse gas emissions reductions. MBMs can bridge the price gap between alternative and conventional fuels and generate revenues for funding the up-scaling of alternative fuels’ production, storage and distribution facilities and, thus, enhance their availability. By estimating the fuels’ implementation and operational costs and carbon abatement potential, this study develops their marginal abatement cost curves and estimates the optimal level of carbon pricing needed to render investments into alternative fuels cost-effective. The results can assist policymakers in establishing the fundamental factors and MBM design principles that can make MBMs a robust and effective decarbonization measure.
1 Introduction

In light of the global attention placed on climate change mitigation, the International Maritime Organization (IMO) adopted the Initial IMO Strategy aiming, among others, to reduce the total annual greenhouse gas (GHG) from shipping by at least 50% by 2050 compared with 2008 while pursuing efforts towards phasing them out entirely (IMO, 2018). However, the results of the 4th IMO GHG Study, show that under a Business As Usual (BAU) scenario, CO₂ emissions from shipping in 2050 are expected to be 90-130% of 2008 levels (Faber et al., 2020). In combination with estimates from UNCTAD (2021) on an expected growth in global trade volumes it becomes clear that without any solid regulatory intervention, emissions from shipping will not peak and decline but might instead continue to rise.

To leverage its decarbonization targets, the IMO strategy proposes several candidate measures classified into short-, medium- and long-term measures that are to be agreed upon and implemented by 2023, between 2023 and 2030, and 2030 and 2050, respectively. Market-based measures (MBMs) belong to the medium-term measures and aim to incentivize GHG emissions reductions. MBMs are environmental policies such as carbon taxes and emissions trading schemes that aim to close the price gap between conventional and zero carbon technologies. By increasing the cost of fossil fuels they provide fiscal incentives to stakeholders to reduce consumption and thus GHG emissions. Their implementation gathers revenues that can accelerate a maritime energy transition by funding research and development projects and by subsidizing first movers or green ships that comply with the carbon elimination regimes (Shi, 2016; Tanaka and Okada, 2019; Wang et al., 2019; Lagouvardou et al., 2020).

There is an increasing number of studies advocating that, to harness the decarbonization potentials, technological measures and especially the uptake of alternative marine fuels is unavoidable (Ashrafi et al., 2022; Lindstad et al., 2021a; Korberg et al., 2021; Lagemann et al., 2022; Wang and Wright, 2021; McKinlay et al., 2021; Xing et al., 2021; Nair and Acciaro, 2018). However, the lack of global availability and sufficient supply of these fuels hamper the energy transition. MBMs can accelerate the upscaling of zero-carbon technologies by closing the price gap between conventional and alternative fuels.

This study aims to assess and quantify the potential of MBMs in enhancing the adoption of alternative marine fuels. We utilize the concept of Marginal Abatement Cost Curves (MACCs) - an environmental policy tool - that associate the cost of any carbon mitigation measure with its
abatement potential. The analysis focuses on estimating the net cost of implementing and utilizing alternative marine fuels and their abatement potential for several case studies of newbuilding and existing vessels. The marginal abatement cost of a mitigation measure corresponds to the level of the carbon tax that renders an alternative fuel cost-competitive from a ship owner’s point of view. Our study ranks the alternative fuel solutions to reflect the market’s preference for their adoption and estimates the carbon price needed to close the price gap with the baseline fuel.

The rest of this study is organized as follows. Section 2 performs a literature survey on the alternative marine fuels pathways and the concept of MACCS for assessing carbon prices and cost-efficient carbon reduction measures. Section 3 contains the methodology we followed to develop and construct the MACCs and Section 4 presents the data set used for this analysis. Section 5 demonstrates the results and, finally, Section 6 highlights the conclusions of this study.

2 Literature review

MACCs have been widely applied in assessing the economics of climate change mitigation policies (Kesicki, 2012). Their development allows policy makers to illustrate the relationship between an abatement measure’s emissions reduction potential (measured in tCO$_2$e$^1$) and its associated cost for reducing CO$_2$e emissions by one unit (USD/tCO$_2$e). The prospect of MACCs is manifold. They can provide insights on policy-making guiding principles, assist in realizing the impacts of various mitigation options that may not bear the upfront implementation costs but have the capacity to support the GHG abatement efforts, and compare some mitigation technologies relative to their cost-effectiveness along with their abatement spectrum (Ibrahim and Kennedy, 2016). So far, they have been used in environmental theory and energy economics to indicate in a straightforward way the CO$_2$ tax (= marginal abatement cost) associated with a specific reduction level or the carbon price resulting from an emissions cap in a cap-and-trade system (Newell and Stavins, 2003; Requate, 2005; Kesicki and Ekins, 2012; Huang et al., 2016).

According to Kesicki and Ekins (2012), there are mainly two methods for constructing MACCs. First, the model-based approach generates a linear cost-effectiveness trend-line relative to the abatement potential. In shipping, it has been used to evaluate different carbon mitigation measures (Eide et al., 2009; Franc and Sutto, 2014; Longva et al., 2010; Smith et al., 2016), including operational and technological mitigation measures. IMAREST (2011) developed

---

$^1$CO$_2$e or carbon dioxide equivalent accounts for other GHGs besides CO$_2$ and translates their potency in relation to CO$_2$ on the basis of their global warming potential (GWP). This study considers the 100-year time horizon GWP relative to CO$_2$ (IPCC, 2001).
their own model-based MACCs to investigate the cost-effectiveness and CO₂ emissions reductions of potential technical and operational measures. Both the 2nd and 4th IMO GHG studies involve MACCs on a model-based approach (Buhaug et al., 2009; Faber et al., 2020), and last but not least, CE Delft has published their analysis on model-based MACCs (Faber et al., 2011, 2009). Model-based MACCs tend to demonstrate macroeconomic responses on international trade more precisely and capture the interdependencies between different mitigation measures. However, they often are criticized for lacking transparency, technical detail, and clarity in their findings (Kesicki, 2012).

The second method for producing MACCs is the expert-based method that uses a step-form visualization of the various mitigation measures and ranks them accordingly by demonstrating the economic and technical merits of reducing GHG emissions. The technique provides a MAC comparison of the assessed mitigation measures, transparency on the calculations of the associated costs, and a simpler representation of the relationship between cost-effectiveness and abatement potential. More specifically, the expert-based model is constructed using several mitigation measures from lowest to highest cost-effectiveness forming multiple steps, representing the MAC over the whole lifetime of the mitigation measure. In shipping, it has been used to study various maritime carbon mitigation measures’ interdependencies and propose methods to rank them systematically.

Hu et al. (2019) consider 14 measures and demonstrate the influence of interdependencies between operational and technical standards, highlighting the importance of fuel prices and discount rates on the preference of a mitigation measure. Nepomuceno de Oliveira et al. (2022) gather data on the implementation cost and mitigation potential of 22 measures to assess the applicability of MAC for ships and found that measures with negative MAC are frequently implemented in the sector. The results highlight that MACCs can be an effective tool in forecasting any mitigation measure implementation rate. Lindstad et al. (2021b) calculate the abatement cost of various eFuels and conclude that the most robust path to follow is through dual-fuel engines that ensure flexibility in fuel selection and can set the scene for growing eFuels supplies at lower risks. Kyprianidou et al. (2021) implement the expert-based approach to study several operational and technical measures such as trim and ballast optimization, main engine auto tuning, LNG, and flettner rotors and conclude that the investigated measures with negative abatement cost should only be considered as medium-term solutions as they do not lead to fossil fuel’s independence. Huang et al. (2016) assess the different MAC methodologies and suggest
that MACCs can be a reliable tool to rank the mitigation options relative to a baseline rather than to focus on the absolute value of the individual measures. Last but not least, (DNV, 2009; Eide et al., 2009) published a study on the development of expert-based MACCs for the shipping sector, estimating the abatement potential of various operational and technological measures towards 2030.

The literature review demonstrated that MACCs are a suitable tool for informed policy-making, and to date, there is a gap in estimating MACCs for alternative marine fuels. This study aims to close this gap by utilizing the principle of MACCs to assess the cost effectiveness of alternative marine fuels and their supporting technology. We use the expert-based approach to rank the alternative fuels from the lowest to the highest MAC and identify the required carbon pricing level that renders these fuels’ costs comparable with a baseline fuel. This study assumes that each fuel will be used as the only solution for covering the vessel’s energy requirements and that interactions among the fuels do not compromise the utilization of MACCs. The utilization of MACCs allows for the identification of the required level of carbon pricing for closing the price gap between conventional fuels and alternative fuels and for rendering these fuels cost competitive.

3 Methods

To generate the MACC of an alternative marine fuel, it is necessary to determine each project’s financial details and the expected GHG abatement volume over the project’s lifetime. The analysis follows the five steps below:

1. Conduct a comprehensive survey of the various technologies and their costs required to facilitate the adoption of alternative marine fuels for a case study vessel.
2. Calculate the MAC of these alternatives for various stages of the vessel’s lifetime and different scenarios on the evolution of fuel prices.
3. Develop the MACCs and correlate MAC and the fuels’ abatement potential
4. Prioritize the alternative fuels based on their MAC
5. Estimate the required level of carbon pricing that renders the alternative fuels’ cost-competitive with the baseline fuel.

Table 1 defines the various symbols and variables of this analysis. Both carbon coefficients $C_{fA}$ and $C_{fB}$ and fuel prices $P_{fA}$ and $P_{fB}$ are normalized by unit energy (per kWh) to allow for direct comparison of alternative fuels on a common denominator basis. The common denominator is
the required energy to propel the ship over its lifetime (equivalently, on an annual basis). For our study, we assume that this energy is known and fixed, equal to $F_c$, expressed in kWh. Furthermore, we assume that introducing alternative fuel will not change the pattern of trade or service speed of the vessel over its lifetime. Also, we shall only compare fuels that have $C_{fA} < C_{fB}$, so that they have a (positive) emissions reduction potential and serve the initial goal of reducing the sector’s GHG emissions. $\Delta CAPEX(A)$ represents the difference in the capital costs for implementing the alternative fuel $A$. In the newbuilding scenario, the value represents the difference in newbuilding costs whereas in the retrofit, the cost of retrofitting.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Description/Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Alternative Fuel</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Baseline Fuel</td>
<td></td>
</tr>
<tr>
<td>$R$</td>
<td>Project’s lifetime</td>
<td>\begin{cases} 25, \text{ newbuilding scenario} \ 1 &lt; R &lt; 25, \text{ retrofit scenario} \end{cases}</td>
</tr>
<tr>
<td>$i$</td>
<td>Discount rate, investor’s cost of capital</td>
<td>assumed 3%</td>
</tr>
<tr>
<td>$F_c$</td>
<td>Annual Fuel consumption</td>
<td>in kWh</td>
</tr>
<tr>
<td>$C_{fA}$</td>
<td>Carbon coefficient of fuel A</td>
<td>in g CO$_2$/kWh. See table 3</td>
</tr>
<tr>
<td>$C_{fB}$</td>
<td>Carbon coefficient of fuel B</td>
<td>in g CO$_2$/kWh. See table 3</td>
</tr>
<tr>
<td>$P_{fA}$</td>
<td>Price of fuel A</td>
<td>in USD/kWh. See table 3</td>
</tr>
<tr>
<td>$P_{fB}$</td>
<td>Price of fuel B</td>
<td>in USD/kWh. See table 3</td>
</tr>
<tr>
<td>$MAC(A)$</td>
<td>Marginal abatement cost of fuel A</td>
<td>USD/MT of CO$_2$ See eq. 1</td>
</tr>
<tr>
<td>$\Delta NCOST(A)$</td>
<td>Difference in total net cost over the vessel’s lifetime due to A</td>
<td>See eq. 2</td>
</tr>
<tr>
<td>$\Delta CAPEX(A)$</td>
<td>Additional capital outlay for implementing fuel A</td>
<td>See table 2</td>
</tr>
<tr>
<td>$\Delta OP\text{EX}(A)$</td>
<td>Difference in annual operating costs over the vessel’s lifetime $R$ due to fuel $A$</td>
<td>See eq. 3</td>
</tr>
<tr>
<td>$OppC(A)$</td>
<td>Opportunity cost calculated based on the vessel’s lost cargo capacity to implement $A$</td>
<td>See eq. 3</td>
</tr>
<tr>
<td>$\Delta CO_{2k}$</td>
<td>The total CO$_2k$ averted over the vessel’s lifetime $R$ due to $A$.</td>
<td>See eq. 4</td>
</tr>
<tr>
<td>$MAC'(A)$</td>
<td>Marginal abatement cost of fuel $A$ after the imposition of a tax</td>
<td>USD/MT of CO$_2$ See eq 6</td>
</tr>
<tr>
<td>$\Delta NCOST'(A)$</td>
<td>Difference in total net cost after the imposition of the carbon price</td>
<td>See eq. 7</td>
</tr>
<tr>
<td>$\Delta OP\text{EX}'(A)$</td>
<td>Difference in annual operating costs after the imposition of the carbon price</td>
<td>See eq. 8</td>
</tr>
<tr>
<td>$C_{p0}$</td>
<td>Carbon price for $MAC'(A) = 0$</td>
<td>in USD/MT of CO$_2$ See eq 10</td>
</tr>
</tbody>
</table>

We note that both $P_{fA}$ and $P_{fB}$ are considered exogenous inputs. These are the costs that the ship operator (ship owner or charterer) needs to bear for purchasing the fuel and usually derive as the sum of the fuel production, transportation, and storage cost. Due to the high level of uncertainty regarding future prices of alternative marine fuels, this study performed a literature survey on the various estimations published so far and presents them in Appendix A. The final purchasing cost is also influenced by market parameters that are hard to predict. For instance, the latest rise in LNG prices does not correlate with an increase in the production cost.
of LNG but is attributed to a radical decrease in LNG supply.

The definition of the MAC of alternative fuel A is described in the following formula:

\[
MAC(A) = \frac{\Delta NCOST(A)}{\Delta CO_{2e}(A)}
\]  

(1)

\[
\Delta NCOST(A) = \Delta CAPEX(A) + \sum_{t=1}^{R} \frac{\Delta OPSEX(A) + OppC(A)}{(1 + i)^t}
\]  

(2)

\[
\Delta OPSEX(A) = (P f_A - P f_B) \times F_c
\]  

(3)

\[
\Delta CO_{2e}(A) = (C f_B - C f_A) \times F_c \times R
\]  

(4)

\[
MAC(A) = \frac{\Delta CAPEX(A)}{\Delta CO_{2e}(A)} + \frac{1}{\Delta CO_{2e}(A)} \times \sum_{t=1}^{R} \left(\frac{(P f_A - P f_B) \times F_c + OppC(A)}{(1 + i)^t}\right)
\]  

(5)

The above methodology estimates the MAC of an alternative fuel A vis-à-vis baseline fuel B. Considering that alternative fuel solutions are deemed expensive investments, they are expected to have MAC>0. As mentioned above, in the definition of MAC, investments with MAC<0 are already cost-competitive, and at this point, the carbon abatement option is equally expensive as the baseline scenario from an investor point of view.

To identify the abatement cost turning point that will achieve cost-competitiveness of the alternative fuel, this study identifies the required level of the levy that renders the MAC=0. More specifically, considering the enforcement of carbon pricing at the level of \(C_0\), the following considerations are essential:

The imposition of a carbon price is an additional operational cost for the ship that alters the MAC to MAC’:

\[
MAC'(A) = \frac{\Delta NCOST'(A)}{\Delta CO_{2e}(A)}
\]  

(6)

where \(\Delta CO_{2e}(A)\) is still given by Eq. 4 and \(C_0 > 0\) the carbon price on \(CO_{2e}\) that makes \(MAC'(A) = 0\), expressed in USD/MT \(CO_{2e}\).

The new annual operational costs \(\Delta OPSEX'(A)\), will be reduced by \((C f_B - C f_A) \times F_c \times C_0\) due to the emissions reductions achieved by the alternative fuel A, and therefore:

\[
\Delta NCOST'(A) = \Delta CAPEX(A) + \sum_{t=1}^{R} \frac{\Delta OPSEX'(A) + OppC(A)}{(1 + i)^t}
\]  

(7)

\[
\Delta OPSEX'(A) = (P f_A - P f_B) \times F_c + (C f_B - C f_A) \times F_c \times C_0
\]  

(8)
From eq. 7 and 8 we identify the carbon price $C_{p0}$ for which $MAC'(A) = 0$ or $ΔN\text{COST'}(A) = 0$. Since $ΔCO_{2e} = (Cf_B - Cf_A) \times F_e \times R$ is constant we get the following:

$$\frac{ΔC\text{APEX}(A)}{ΔCO_{2e}(A)} + \frac{1}{ΔCO_{2e}(A)} \times \sum_{t=1}^{R} \left( \frac{P_f_A - P_f_B}{R} \times F_e + (Cf_B - Cf_A) \times F_e \times C_{p0} + OppC(A) \right) = 0$$

Or:

$$MAC(A) - \sum_{t=1}^{R} \frac{C_{p0}}{R \times (1+i)^t} = 0 \quad (9)$$

$$C_{p0} = \frac{R \times MAC(A)}{\sum_{t=1}^{R} \frac{1}{(1+i)^t}} = 0 \quad (10)$$

Eq. 10 is noteworthy as it proves mathematically that the carbon tax is influenced only by the MAC of a mitigation measure and the mean value of the discount rate over the project’s lifetime. It can also be seen that, in this case, a carbon price would preserve the ranking of alternative fuels according to their MAC, since $MAC(A_1) < MAC(A_2)$ would imply that $MAC'(A_1) < MAC'(A_2)$.

4 Data Set

The development of fuel prices depends on various exogenous inputs, such as the price of renewable electricity, the price of carbon capture and storage (CCS), and the global and sufficient availability of these fuels. Given the high level of uncertainty in the evolution of alternative fuel prices, our data set consists of a high and low price expectancy scenario. Fossil fuels, were based on historic trajectories, while the bio-fuel prices depend on the cost of biomass. E-fuel prices rely on the levelized cost of renewable electricity (as well as the cost of CO$_2$). The two different price scenarios are intended to capture the uncertainty with respect to the named exogenous factors. Data on fuel prices are derived from a comprehensive literature survey of academic research papers and reports from relevant institutions and maritime stakeholders. A larger table, showing various estimates of prices for an expanded set of alternative fuels according to various sources is shown in Appendix A.

Our case study focuses on a 63,000 DWT Supramax bulk carrier of 7500 kW maximum brake power. The analysis assumes that the annual energy output of the vessel will remain constant and thus additional fuel storage space will be required to account for the lower energy density of the alternative fuels. For calculating the opportunity cost associated with the revenues lost due to cargo space being used as fuel storage capacity we keep the total displacement of the ship
constant for all power systems and reduce the respective cargo carrying capacity. For the first 58,000 dwt, we assume we assume an average utilization of 90%, and for the next 5,000 dwt, we estimate an average utilization of 25%. According to the aforementioned deadweight ranges’ utilization, we assume a charter rate of 25,000 USD per day, which is distributed proportionally among them (Handybulk, 2022).

Firstly, our analysis focuses on a newbuilding scenario, ranks the alternative marine fuels according to their MAC and evaluates the carbon price needed to render these investments cost-effective. In estimating the newbuilding price over the past years, our Very Low Sulphur Fuel Oil (VLSFO) reference configuration costs roughly 30 mUSD (Hellenic Shipping News, 2022). We deduct the cost of a VLSFO power system and instead use the alternative fuel power systems cost per unit of brake power as estimated by Lindstad et al. (2021b) and derive the alternative fuel vessels’ newbuilding costs as shown in Table 2. Second, this study estimates the MACCs for a retrofit scenario and uses the same system-based cost factors as for newbuilds plus an additional penalty of 3.6 mUSD to account for shipyard costs and lost income during retrofitting. Table 2 summarizes our inputs.

Our next case study involves a newbuilt vessel equipped with a conventional Diesel internal combustion engine (ICE) that seeks to switch to an alternative fuel at its 5th and 10th year of age. We aim to calculate the carbon price that will incentivize the retrofit. The analysis is conducted for two different price scenarios to account for the uncertainty on the evolution of alternative fuel bunker prices. Retrofitting to alternative marine fuels entails various technical modifications onboard. We assume that additional tanks up to 1600m$^3$ can be installed on deck in the aft part of the ship to accommodate the new fuel. The case differs from other shipping segments, and decisions on the installment of the alternative fuel storage tanks depend on the type and initial design of the vessel.

In the case of retrofitting to methanol, we assume that the fuel tanks can be integrated into the ship’s structure. Retrofitting would require modifications to the fuel supply system regardless of the chosen alternative (MZCCb, 2022). On the other hand, in the case of retrofitting to LNG or ammonia, the advanced requirements for main engine modifications and the installation of additional tank capacity will lead to a relatively higher retrofitting cost compared to methanol. For LPG, we shall assume that retrofitting costs are similar to methanol, and for hydrogen, due to its unique properties and relatively low technological readiness retrofitting costs are considered the most expensive.
Moreover, we develop the MACCs for an existing vessel equipped with an LNG ICE. Considering the current record on the orderbook for LNG newbuilding vessels (and 25 years life expectancy), it is very likely that LNG ICE ships will seek to comply with the more stringent forthcoming regulations before 2050, and retrofitting will become a viable solution. According to Comer et al. (2018) and Lindstad et al. (2021a), it is only the LNG dual fuel engine operating on a Diesel cycle that can deliver GHG emissions reductions on a WTW and this study will consider this engine technology.

### Table 3 – Fuel prices and WTW emissions

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Climate Pollutants GWP100 (gCO2p/kWh Fuel)</th>
<th>Fuel Prices (USD/kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GWP WTT</td>
<td>GWP TTTW</td>
</tr>
<tr>
<td>E-Diesel</td>
<td>0.0[1]</td>
<td>4.5[1]</td>
</tr>
<tr>
<td>E-LNG</td>
<td>0.0[1]</td>
<td>6.0[1]</td>
</tr>
<tr>
<td>E-Ammonia</td>
<td>0.0[1]</td>
<td>19.0[1]</td>
</tr>
<tr>
<td>Grey Liq. Hydrogen</td>
<td>393.0[6]</td>
<td>0.0[1]</td>
</tr>
<tr>
<td>Green Liq. Hydrogen</td>
<td>0.0[1]</td>
<td>0.0[1]</td>
</tr>
</tbody>
</table>

Sources and comments:
[1] Lindstad et al., 2021a
[2] Lindstad et al., 2021b
[4] Assuming 80% CCS efficiency
[6] The upper bound is 100% of electricity-based pendants, lower bound is 70% of electricity-based pendants
[7] Al-Aboosi et al., 2021
[8] Atillan et al., 2021
5 Analysis

This section presents the results of the analysis in the form of MACCs for our case studies. Figures 1-5 on the y axis illustrate the estimated MAC or the NPV per MT of CO$_2$ abated, and on the x-axis, the width of each column represents the emission abatement potential of each alternative fuel relative to the baseline. Furthermore, the results in the data tables are ranked from the lowest to the highest MAC and contain the total amount of CO$_2$ averted by implementing the alternative fuel over the vessel’s lifetime, the % of GHG emissions reductions achieved relative to using the baseline fuel and the level of carbon pricing that renders the fuels cost viable. A low and high bound of fuel prices is considered to capture the uncertainty of the expected alternative marine fuel production prices and their dependency on exogenous inputs such as the prices of renewable electricity and CCS. As established in the literature review of this study, MACCs are mainly utilized to facilitate a straightforward interpretation of the relationship between cost-effectiveness and abatement potential and to compare some mitigation technologies with respect to their MAC and abatement spectrum.

Figure 1a shows the MACCs for a newbuilding vessel in a high fuel price scenario, assuming a lifespan of 25 years and a discount rate of 3%. The results indicate that investments into an ICE LNG vessel have a negative MAC and thus constitute cost-effective investment choices under high fuel price expectancy. The results are attributed to LNG prices in the future expected being low (lower than VLSFO). When $P_{fA} < P_{fB}$ then $OPEX_{fA} - OPEX_{fB} < 0$, and the investor benefits from a cheaper fuel. However, when the increase in capital expenditure is not high enough to compensate for the difference in the long-term operational cost savings attributed to the low LNG prices, then $MAC(A)$ will be positive. The LNG ship’s abatement potential is limited to only 8% of GHG emissions reductions for a WTW scope and GWP100. This insufficient reduction in absolute emissions could be complemented with other operational measures, such as speed reduction, to reach the desired emissions levels. Furthermore, Figure 1a shows that investments into Bio-Methanol can become cost-effective after imposing a tax of around 40 USD/MT CO$_2$e and CAN achieve 65% GHG reductions. The same rationale is followed for all other fuel choices within the scope.
Figure 1 – (a) MACCs of a newbuilding vessel in a high fuel price scenario based on 100 USD/kg of CO₂ cost of CCS and 100 USD/MWh cost of electricity [IEA (2019)]. (b) As for (a) but over a low fuel price scenario of 20 USD/MWh cost of electricity.
Figure 1b shows the MACCs of a newbuilding vessel assuming a lifespan of 25 years and a discount rate of 3% for a low fuel price scenario. In this case, investments into LPG vessels have the lowest MAC and would require a carbon tax of approximately 65 USD/MT of CO$_2$e to become economically viable. The results differ from the high price scenario for various reasons, such as the lower marginal difference in the relevant fuel cost between LPG and Diesel and LNG and Diesel, the higher abatement potential of LPG versus LNG, and the marginal difference in the capital cost of a newbuilding LPG vessel and a conventional Diesel vessel. However, the emissions reduction potential of an LPG vessel is approximately 20% - not enough to reach the 50% target without additional logistic-based practices to complement the fuel choice. Blue-Ammonia, on the other hand, that follows LPG in the MACC figure, can achieve emissions reductions up around 60%, and, from a financial perspective, would require a carbon price of 100 USD/MT CO$_2$e to become financially attractive.

Figures 2-5 contain our results for the retrofitting case. We consider the same Supramax bulk carrier retrofitted after 5 or 10 years, respectively for two fuel price development scenarios. The results show that on the one hand, the ranking of the preferred fuels considered is not influenced significantly by the vessel’s age but the derived MAC increases with the vessel’s age. This is expected as it shows that retrofitting a relatively younger vessel with alternative fuels has a greater return on investment potential and higher total abatement capabilities. In terms of the MBMs, lower MACCs are translated to lower levels of carbon taxation.

Figures 2 and 3 show the MACCs for our first retrofit case study of a vessel equipped with a Diesel ICE. Bio-Methanol appears to be the most preferred solution due to the low retrofitting costs for upgrading the engine to burn methanol, the expected low-price differential of Bio-Methanol and VLSFO, and the large emissions abatement potential that Bio-Methanol can achieve. However if ammonia production costs come down to approx. 56 USD/kWh, then to incentivize retrofits a carbon price of 200 USD/MT CO$_2$e would be sufficient.ent potential that Bio-Methanol can achieve.

Compared with the newbuilding scenario, the reduced lifespan and the lower price range between LNG and Diesel, do not result in high enough operational cost savings to cover the retrofitting costs. Thus, LNG appears to be further down in the ranking of preference for alternative fuels. A switch to E-Diesel is the most cost-intensive choice, whereas for Green Liq. Hydrogen a levy of 600 USD/MT CO$_2$e is required.

13
Figure 2 – (a) MACCs of a retrofit of a 5-year-old Diesel ICE vessel in a high fuel price scenario. Upper bound based on 200 USD/kg of CO$_2$ cost of CCS and 100 USD/MWh cost of electricity. *IEA (2019)* (b) As for (a) but over low fuel price scenario of 20 USD/MWh cost of electricity.
Figure 3 – (a) MACCs of a retrofit of a 10-year-old Diesel ICE vessel in a high fuel price scenario. Upper bound based on 200 USD/kg of CO$_2$ cost of CCS and 100 USD/MWh cost of electricity. IEA (2019) (b) As for (a) but over low fuel price scenario of 20 USD/MWh cost of electricity.
Figure 4 – (a) MACCs of a retrofit of a 5-year-old LNG ICE vessel in a high fuel price scenario. Upper bound based on 200 USD/kg of CO\textsubscript{2} cost of CCS and 100 USD/MWh cost of electricity.\textit{IEA (2019)} (b) As for (a) but over low fuel price scenario of 20 USD/MWh cost of electricity.
Figure 5 – (a) MACCs of a retrofit of a 10-year-old LNG ICE vessel in a high fuel price scenario. Upper bound based on 200 USD/kg of CO$_2$ cost of CCS and 100 USD/MWh cost of electricity IEA (2019) (b) As for (a) but over low fuel price scenario of 20 USD/MWh cost of electricity.
Figures 4 and 5 contain our results for our Supramax bulk carrier case study that is built with a dual fuel LNG ICE running on a Diesel cycle. We highlight that in this analysis, LNG constitutes the baseline fuel, and due to the engine’s dual fuel technology, calculations on retrofitting to Diesel are not examined. The model runs for two distinct vessel age stages and both high and low bounds of alternative fuel price expectancies. Figure 4a shows that in a high-price scenario, a switch to bio-LNG would require a carbon tax of 130 USD/MT CO$_{2e}$ to become cost-effective slightly less than the carbon tax required for incentivizing the same fuel for an older vessel shown in Figure 5a. Green-Ammonia has higher MAC but larger emissions reductions potential. Overall, in high fuel price expectancy, it is mainly the OPEX and the fuel’s abatement potential that have the most significant effects on MACCs and only for investments in Hydrogen systems, the high initial capital outlay, has a greater influence on cost viability.

Figures 4b and 5b show that in a low fuel price expectancy scenario where investments in Ammonia ICE seem to become more financially appealing. There are only marginal changes on the fuels’ MAC ranking accounting for their age at the time of the retrofit. Green-Liq. Hydrogen that can achieve 100% GHG emissions reduction can become cost-competitive with LNG after a carbon price of 300 USD/MT CO$_{2e}$.

6 Conclusions

This study focused on the developments of MACCs in order to rank the alternative marine fuels solutions according to their cost effectiveness and calculate the level of carbon pricing needed to close the price gap between alternative and conventional marine fuels. We first considered the capital costs arising from the installation onboard of the relevant power and fuel storage systems for facilitating the alternative fuels both for a newbuilding and a retrofit scenario. Second we estimated the operational costs from the utilization of these fuels during the vessel’s lifetime including bunkering and opportunity costs. Our MACCs demonstrated our case study vessel in a newbuilding/design stage and in existing stage were the ship is built with either a Diesel or an LNG Dual Fuel ICE.

Our findings show that biofuels demonstrate high technical potentials for being used as zero-carbon bunker fuels as their future cost projections are relatively lower than their blue or green competitors. For newbuilding vessels, investments into bio-Methanol can achieve 65% of GHG emissions reductions and will become financially attractive after a carbon price of 50 USD/MT
CO$_2$e. However, ensuring their large-scale supply is likely to be constrained by the limited availability of biomass as well as the competing demands from other transportation sectors (The World Bank, 2021). To reach full maritime decarbonization fuels such as green liquid Hydrogen and their supporting technology would require a carbon price of 600 USD/MT CO$_2$e to become cost-competitive. With a projected levelized cost of electricity as low as 20 USD/MWh, investments in ammonia systems will become attractive for a carbon price of 150 USD/MT CO$_2$e and have significant emissions reductions potential.

For existing ships equipped with a Diesel ICE, investments into biofuels can be a promising solution in a high fuel price scenario, whereas in a low fuel price scenario the retrofitting costs to ammonia systems do not influence the resulting MAC significantly more than the operational costs and the abatement potential of the fuel in the denominator. Overall, the fuel choice will depend on its emissions abatement potential and the respective compliance with the regulations, which is the primary goal of retrofitting. For an existing vessel with a Dual Fuel LNG engine, retrofitting to ammonia seems to be a more profound solution regardless of the fuel price expectancy, mainly because ammonia shares some of the technical design specifications of LNG and requires fewer modifications during the retrofit. To incentivize the adoption of ammonia, a carbon price of 250 USD/MT CO$_2$e appears to be able to close the price gap with the baseline LNG power system. The results show that from a policy perspective, any choice on the level of carbon pricing should consider the average age of the global fleet at the time of enforcement and higher carbon levies are required for larger volumes of older vessels.

From a policy perspective, any choice on the level of carbon pricing in the case of a global fixed fuel levy regime should consider the average age of the global fleet at the time of enforcement. Early investments have greater potential for returns in a new building or retrofit case. As we have mentioned above, our results involve assumptions for fuel prices to capture the volatility of the bunker price and the uncertainty of the overall demand for these fuels.

Last but not least, and even though our study used a Supramax bulk carrier as a case study, the methodology can be applied to any ship type. Each ship has its distinct features and special constraints, thus one would expect the numerical values of the MACCs and required levies to differ across ship types. However, we conjecture that the main thrust of our results will remain the same as the one outlined in this study.
References


Table 4 – Alternative marine fuel production costs

<table>
<thead>
<tr>
<th>Alternative</th>
<th>Source</th>
<th>2020</th>
<th>2021</th>
<th>2021b</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
<th>2025</th>
<th>2026</th>
<th>2027</th>
<th>2028</th>
<th>2029</th>
<th>2030</th>
<th>2031</th>
<th>2032</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLSFO</td>
<td>Lloyd's Register &amp; UMAS</td>
<td>626</td>
<td>18.8</td>
<td>16444</td>
<td>1056</td>
<td>791</td>
<td>15425</td>
<td>19.5</td>
<td>11644</td>
<td>19.5</td>
<td>15425</td>
<td>19.5</td>
<td>11644</td>
<td>19.5</td>
<td>15425</td>
</tr>
<tr>
<td>E-Meth.</td>
<td>Lloyd's Register &amp; UMAS</td>
<td>626</td>
<td>18.8</td>
<td>16444</td>
<td>1056</td>
<td>791</td>
<td>15425</td>
<td>19.5</td>
<td>11644</td>
<td>19.5</td>
<td>15425</td>
<td>19.5</td>
<td>11644</td>
<td>19.5</td>
<td>15425</td>
</tr>
<tr>
<td>LNG</td>
<td>Lloyd's Register &amp; UMAS</td>
<td>626</td>
<td>18.8</td>
<td>16444</td>
<td>1056</td>
<td>791</td>
<td>15425</td>
<td>19.5</td>
<td>11644</td>
<td>19.5</td>
<td>15425</td>
<td>19.5</td>
<td>11644</td>
<td>19.5</td>
<td>15425</td>
</tr>
<tr>
<td>LPG</td>
<td>Lloyd's Register &amp; UMAS</td>
<td>626</td>
<td>18.8</td>
<td>16444</td>
<td>1056</td>
<td>791</td>
<td>15425</td>
<td>19.5</td>
<td>11644</td>
<td>19.5</td>
<td>15425</td>
<td>19.5</td>
<td>11644</td>
<td>19.5</td>
<td>15425</td>
</tr>
<tr>
<td>Green-Liq.H</td>
<td>Lloyd's Register &amp; UMAS</td>
<td>626</td>
<td>18.8</td>
<td>16444</td>
<td>1056</td>
<td>791</td>
<td>15425</td>
<td>19.5</td>
<td>11644</td>
<td>19.5</td>
<td>15425</td>
<td>19.5</td>
<td>11644</td>
<td>19.5</td>
<td>15425</td>
</tr>
<tr>
<td>E-LNG</td>
<td>Lloyd's Register &amp; UMAS</td>
<td>626</td>
<td>18.8</td>
<td>16444</td>
<td>1056</td>
<td>791</td>
<td>15425</td>
<td>19.5</td>
<td>11644</td>
<td>19.5</td>
<td>15425</td>
<td>19.5</td>
<td>11644</td>
<td>19.5</td>
<td>15425</td>
</tr>
<tr>
<td>E-Diesel</td>
<td>Lloyd's Register &amp; UMAS</td>
<td>626</td>
<td>18.8</td>
<td>16444</td>
<td>1056</td>
<td>791</td>
<td>15425</td>
<td>19.5</td>
<td>11644</td>
<td>19.5</td>
<td>15425</td>
<td>19.5</td>
<td>11644</td>
<td>19.5</td>
<td>15425</td>
</tr>
<tr>
<td>BioDiesel</td>
<td>Lloyd's Register &amp; UMAS</td>
<td>626</td>
<td>18.8</td>
<td>16444</td>
<td>1056</td>
<td>791</td>
<td>15425</td>
<td>19.5</td>
<td>11644</td>
<td>19.5</td>
<td>15425</td>
<td>19.5</td>
<td>11644</td>
<td>19.5</td>
<td>15425</td>
</tr>
<tr>
<td>Grey Amm.</td>
<td>Lloyd's Register &amp; UMAS</td>
<td>626</td>
<td>18.8</td>
<td>16444</td>
<td>1056</td>
<td>791</td>
<td>15425</td>
<td>19.5</td>
<td>11644</td>
<td>19.5</td>
<td>15425</td>
<td>19.5</td>
<td>11644</td>
<td>19.5</td>
<td>15425</td>
</tr>
<tr>
<td>Blue Amm.</td>
<td>Lloyd's Register &amp; UMAS</td>
<td>626</td>
<td>18.8</td>
<td>16444</td>
<td>1056</td>
<td>791</td>
<td>15425</td>
<td>19.5</td>
<td>11644</td>
<td>19.5</td>
<td>15425</td>
<td>19.5</td>
<td>11644</td>
<td>19.5</td>
<td>15425</td>
</tr>
<tr>
<td>A Appendix</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>