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Towards Green Ferry Corridors in the Adriatic Sea – Integrating Monte Carlo Simulations into Life Cycle Costing Scheme for Methanol

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ABSTRACT: The maritime transport sector is essential to global trade, handling a large share of international trade volume, but its reliance on fossil fuels raises significant environmental and economic concerns. The transition to greener options is slow, with 98.8% of the fleet still using fossil fuel, while the research into economic performance of this transition often overlooks fuel price volatility, a critical factor influenced by global events which have caused significant fuel price fluctuations. This paper introduces a model which incorporates fuel price volatility into lifecycle cost assessments (LCCA) on an example of a ferry connecting the Croatian and Italian shores of the Adriatic Sea. A comparison of diesel- and methanol-powered systems is provided, using Monte Carlo simulations to evaluate economic sustainability under volatile fuel prices. Diesel prices showed a consistently symmetrical and normal distribution across all simulations, indicating a stable price range, while methanol prices demonstrated more volatility. The LCCA results, which included the simulated fuel prices, showed that methanol-powered systems despite greater price volatility, show lower overall costs through different carbon taxation scenarios.

1 INTRODUCTION

The shipping sector presents the backbone of global trade, as maritime transport makes up over 50% of the value of trade and 70% of the volume of international trade [1]. Due to the possibility of transporting large quantities of goods over long distances, at a reasonable price, maritime transport takes the leading place in global transport, compared to land and air, and a moderate growth in maritime trade volume is expected by 2028 [2]. The problems arise, both in an environmental and economic sense, when the fact that the maritime fleet is almost entirely powered by fossil fuels, is considered. As stated by van Leeuwen and Monios [3], 79% of maritime transport is powered by Heavy Fuel oil (HFO), while the rest is powered by marine diesel oil, marine gas oil or Liquified Natural Gas (LNG). Consequently, the level of Greenhouse Gases (GHGs) caused by maritime fleets is assessed at 3% of global GHG emissions caused by human activity, with an increase of 20% over the last decade [2].

From an environmental viewpoint, the use of fossil fuels tends to be reduced as much as possible and in the shortest possible time. Decarbonization measures set by the Paris Agreement [4] aim to limit the global average temperature to well below 2°C above pre-industrial levels, with efforts to keep it to 1.5°C. On its basis, the International Maritime Organization (IMO) advocated for the reduction of GHG emissions in international shipping, applying various technical, operational and market measures. Starting with technical measures such as the Energy Efficiency Design Index (EEDI) mandatory for new ships, and operational the Ship Energy Efficiency Management Plan (SEEMP), IMO continues to develop new strategies and expand them to an ever-increasing share of the fleet [5]. An example is the Energy Efficiency Existing Ship Index (EEXI) and the annual operational Carbon Intensity Indicator (CII), which entered into force in January 2023 and are mandatory for ships of 5000 GT and above [6]. Next to technical and operational measures, marked-based ones such as carbon taxation, proved to be an effective means of controlling emissions [7], [8] and policy changes are recommended for emerging countries working on supporting environmentally friendly, sustainable economic growth [9], [10].

1.1 *Transition to cleaner fuels*

Decarbonization policies and climate regulations are significantly transforming the marine fuel landscape and have led to increased investment in alternative fuels, such as methanol, ammonia, LNG, biofuels, hydrogen, and electro-fuels, and in cleaner propulsion technologies, including fuel cells and hybrid-electric systems [11], [12], [13]. The introduction of carbon pricing, efficiency measures (like EEXI and CII), and fuel-specific emission limits has made conventional fossil fuels more expensive, while simultaneously encouraging the development of low-carbon alternatives [14], [15].

An overview of current and emerging options aimed at reducing GHG emissions in the marine sector are given in [13]. Alternative fuels are categorized into low-carbon, carbon-neutral, zero-carbon, and electro-fuels, each with distinct characteristics, benefits, and challenges. Low-carbon fuels, such as natural gas (CNG/LNG) or methanol, offer lower carbon content compared to conventional fuels and it can be easily applied in dual-fuel engines. LNG presents a fossil fuel-based alternative which is widely adopted, primarily due to its significant environmental advantages over conventional marine diesel fuels. It emits approx. 25% less CO2, produces only trace amounts of SO_x and particulate matter, and can reduce NO_x emissions by up to 91.4% [16]. Carbon-neutral fuels, predominantly biofuels like Liquefied Biogas (LBG) and biodiesel blends, reduce GHG emissions significantly by offsetting combustion-related CO_2 with biomass absorption. Methanol stands out as a flexible option due to its liquid state at normal conditions, compatibility with existing infrastructure, and relatively straightforward storage and handling. While it reduces emissions compared to conventional fuels, its energy density is significantly lower, requiring larger storage volumes [17]. Its high oxygen content promotes more efficient combustion in engine systems, resulting in nearly zero SOX emissions and significant reductions in CO2. Additionally, methanol contributes to lower NOX emissions compared to conventional marine fuels [16]. The potential of implementing methanol in dual-fuel engine is demonstrated in [18], which showed that combined with a slow steaming technique, the configuration can significantly reduce exhaust emissions by up to 90%. Zero-carbon fuels, including full electrification, hydrogen, and ammonia, eliminate CO_2 emissions during use and are viewed as long-term solutions. Hydrogen can be classified in several types, depending on the production method. Currently, most hydrogen is produced via methane reforming, typically from natural gas, although oil and coal are also used [16]. According to [19], 99.5% of the LCA emissions of hydrogen powered systems arises from electricity usage. Further research found that emissions in case of non-renewable hydrogen are significantly higher than compared to renewable. Renewable hydrogen can reduce GHG emissions by 75.8% compared to diesel-powered ferries [20]. Electro-fuels produced using renewable electricity, hydrogen, and captured carbon (e.g., e-methanol, e-methane), present another pathway to decarbonization but are currently expensive and dependent on subsidies and pilot projects for wider adoption [13].

However, the widespread adoption of these alternatives remains limited due to high capital costs, technological uncertainty, retrofitting challenges, and underdeveloped global bunkering infrastructure [21], [22]. Life-cycle assessments (LCA) consistently highlight the emissions-reduction potential of cleaner fuels [23], [24], while life-cycle cost assessments (LCCA) often reveal that these options are not yet economically viable without substantial subsidies or high carbon taxes [25], [26]. Probabilistic methods such as Monte Carlo simulations have been increasingly used to evaluate investment risk under fluctuating fuel and carbon prices, often showing LNG as a favourable near-term option due to its balance of cost and emissions [27], [28]. These challenges are exacerbated by global disruptions, such as the COVID-19 pandemic and the Russia–Ukraine conflict, which have destabilized energy markets, disrupted supply chains, and caused extreme volatility in fuel prices [22]. These conditions underscore the need for more resilient, efficient, and economically feasible marine energy systems, supported by consistent policy, adaptive regulation, and integrated techno-economic-environmental evaluation methods. The variation of crude oil prices (expressed in $ per barrel) in period 2018-2024 is plotted in Figure 1 where the effects of COVID-19 pandemic and start of Russia-Ukraine war are evident.

Figure 1. Fluctuations of crude oil prices 2018-2024 [29]

1.2 *Research gap and aim of paper*

The literature survey indicates large number of studies dealing with the economic analysis of alternative fuels in the maritime sector, but fuel price modelling is done in a rather simplified manner. While LCCA is widely used to evaluate the economic feasibility of alternative fuels and technologies, most existing studies do not account for the volatility of fuel prices and, thus, the long-term economic impacts of transitioning to alternative fuels under volatile market conditions are not well understood. The following research gaps are identified from the literature review:

- Current economic feasibility studies of alternative fuels in shipping often overlook the impact of fuel price volatility, which significantly affects operational costs and investment decisions;
- Many studies fail to consider the effects of global events, such as the COVID-19 pandemic and the Russia-Ukraine war, which disrupt energy market supply and demand, affecting the fuel prices;
- Incorporating probabilistic methods, such as Monte Carlo simulations, into LCCA can provide a more detailed understanding of risks and uncertainties compared to traditional approaches.

This paper addresses these gaps by developing a model that incorporates fuel price volatility into economic assessments, providing a clearer picture of the financial risks and benefits associated with different decarbonization strategies. Using historical fuel price databases, Monte Carlo simulations are conducted, and the probability of price changes is given. The values obtained are further used in the LCCA to provide insight into the impact of fuel prices on the total operating costs. Furthermore, few analyses have been adapted to the operational characteristics of ferries, which differ significantly from deep-sea shipping in terms of voyage duration, port frequency and fuel consumption. In addition, most models do not include life-cycle emission costs or variables related to fuel production and use. This results in a limited understanding of the long-term economic viability of alternative fuels under changing future conditions. Addressing these shortcomings through comprehensive Monte Carlo frameworks, that consider cost variability over time and ferry-specific operational parameters, is essential to guide investment and regulatory decision-making in the transition to low-carbon shipping.

2 METHODOLOGY

2.1 *Monte Carlo Simulations*

Monte Carlo simulation is a widely used statistical technique for analysing systems influenced by uncertainty, enabling more robust and informed decision-making. By running a large number of simulations, the probability distribution of possible outcomes in processes driven by random variables is estimated. The inputs are selected from chosen probability distributions (normal, uniform, binominal) which describe the probability of different outcomes [30]. Monte Carlo simulation is widely used in various fields, and they are commonly performed using software such as MATLAB, Minitab, @Risk, etc. The process begins with defining a mathematical model of the process that clearly defines the relationships between inputs and outputs, along with the appropriate probability distributions. Random samples are then generated using random number generators, and the simulation is executed repeatedly to produce a range of possible outcomes. These outcomes are analysed to extract key statistical indicators such as means, variances, and percentiles, and are often visualized using histograms or cumulative probability curves. This method is especially valuable in fields like finance, engineering, and energy systems, where decision-making under uncertainty is critical.

In this paper, the normal distribution is chosen due to its characteristic symmetry where most data cluster towards the middle of the range. This distribution effectively captures the behaviour of fuel prices [31] in the maritime sector, where fluctuations generally remain around a central value, and larger deviations become less frequent. Therefore, the assumption of normality serves as a reasonable approximation for modelling price volatility.

In mathematical form, the normal distribution $N(\mu,\sigma^2)$ can be expressed as:

$$N\left(\mu,\sigma^2\right)=\frac{1}{\sqrt{2\pi\sigma^2}}\cdot e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2}, \quad (1)$$

where μ marks the arithmetic mean and σ marks the standard deviation. The arithmetic mean is the mathematical average of a data set, found by dividing the sum of all values x by the number of values, while standard deviation describes how spread-out values are from its mean value [32]. In a normal distribution, 68.2% of results fall within the first standard deviation, 95.4% within two standard deviations and 99.7% within three standard deviations.

Even though Monte Carlo simulation offers several advantages, such as handling complex problems and providing a range of possible outcomes and their probabilities, it can be computationally intensive, especially considering multiple simulations. Moreover, the results depend on the quality of the input data and the accuracy of the probability distributions, thus the interpretation and validation of results require expertise [32]. Monte Carlo simulations are often used in maritime research to account for uncertainty in emissions reductions, fuel life-cycle analysis, and regulatory compliance costs. For instance, in [33] Monte Carlo is used to model the cumulative distributions of the Net Present Value (NPV) for different fuel cases—ammonia, LNG, and low sulfur fuel oil —under two scenarios of Emissions Trading Systems (ETS) from the EU and the IMO. In the evaluation of alternative marine fuels, Taljegard et al. [34] used Monte Carlo to analyse the robustness of the results which included parameters such the availability of primary energy resources, the adoption of carbon capture and storage (CCS) technologies, and the costs associated with different technologies and fuels. In a similar research [25], Monte Carlo has been used to model the variability in electricity prices by employing a uniform distribution, along with other production costs. In this paper, the Monte Carlo simulation is conducted to model fuel price volatility. For each fuel type, a number of simulations of fuel prices are conducted, all with the same statistical properties (mean and standard deviation). The historical data on fuel prices were used to calculate the mean, standard deviation, variance, and skewness.

2.2 *LCCA*

Life-cycle Cost Assessment (LCCA) is an economic mechanism for predicting the total costs of a product and simplifying the improvement of its cost-effectiveness [35]. The method includes total costs that occurred during the product's lifetime, from the investment to operative costs up to the recycling stage. In recent years, LCCA often includes the cost of externalities associated with directives, such as carbon taxation [36]. It is widely adopted in the industrial sector, and it has gained significant attention in maritime research for assessing various economic options. This paper considers the investment, fuel and maintenance costs of two different power systems (diesel and methanol) over the selected vessel's lifetime (20 years).

The investment costs $LCCA_{inv}$ refer to the installation of the power system and the calculation multiplies the power of the engine P_{eng} with its cost PR_{eng} [37]. The investment costs are calculated equally for the diesel-power system as well as the methanol one, with a difference in engine price of 250 €/kW for the diesel engine [13]. The retrofitting costs for methanol dual-fuel engines range from approximately 250–350 up to 650 €/kW, and in this paper an average cost of 450 €/kW is considered [38].

The operating costs $LCCA_{op}$ include the fuel and maintenance costs. In the case of a diesel-powered system, the costs can be calculated as:

$$LCCA_{op,D} = FC_D \cdot PR_D \cdot t + EC \cdot PR_{D\_main} \cdot t. \tag{2}$$

Input on fuel consumption FC_D, in kg, depends on the vessel type and is further detailed in the following section presenting the case study. The price of diesel fuel, PR_D (€/kg), is collected from statistical databases [39], based on which Monte Carlo simulations are performed and possible future values are determined. The equation also includes the number of years t for which the costs are calculated, in this case 20 years. The maintenance costs of the vessel are calculated by multiplying the annual EC with a conversion factor of 0.014 €/kWh [13], both in the case of a diesel- and methanol-diesel dual-fuel driven vessel. The operating costs of a methanol-diesel dual-fuel driven vessel are calculated similarly:

$$LCCA_{op,\,M} = FC_M \cdot PR_M \cdot t + FC_{P-D} \cdot PR_D \cdot t + EC \cdot PR_{M\_main} \cdot t. \tag{3}$$

The main difference compared to a diesel-powered system is the use of a dual-fuel engine which requires a combination of fuel - 5% diesel as pilot fuel and 95% of methanol [40]. Thus, the fuel consumption of methanol FC_M and pilot fuel $FC_{P\text{-}D}$ are calculated as

$$FC_M = 0.95 \cdot EC \cdot SFC_M \tag{4}$$

$$FC_D = 0.05 \cdot EC \cdot SFC_{P-D} \tag{5}$$

with a specific fuel consumption of methanol SFC_M of 327.2 g/kWh and a specific consumption of pilot fuel $SFC_{P\text{-}D}$ of 10.1 g/kWh [13]. The price of methanol is gathered from [41] and Monte Carlo simulations are performed the same as in the case of diesel.

2.3 *Carbon taxation*

Carbon taxation is a marked-based measure designed to mitigate carbon dioxide (CO_2) emissions, a primary GHG contributing significantly to global warming. The main objective of this measure is to impose a tax on the carbon content of fossil fuel, thereby incentivizing the reduction of fossil fuel use and encouraging a shift towards greener alternatives [42]. Currently, the carbon tax is estimated at 85 €/t CO_2 and it is projected to rise to as much as 238 €/t CO_2 [43]. There are various scenarios for carbon taxation that progressively tighten regulations to accelerate the achievement of net-zero emissions. This paper focuses on the Net Zero Emission Scenario (NZES), the strictest scenario with the goal of reaching net-zero emissions in advanced economies by 2050 at the latest [44].

The carbon tax is calculated by multiplying the CO_2 emissions released due to fuel combustion TTW, in kg CO_2, with the considered carbon allowance CA, in €/kg CO_2, of a particular year. The tailpipe emissions TTW are calculated as follows:

$$TTW = EF \cdot FC \tag{6}$$

where EF marks the emission factor in kg gas/kg fuel. The EF of CO_2 emissions for marine diesel equals 3.206 kg gas/kg fuel and 1.375 kg gas/kg fuel for methanol [5].

The value fluctuations according to the given scenarios are shown in Figure 2, and the carbon taxes for the following years were obtained by interpolation.

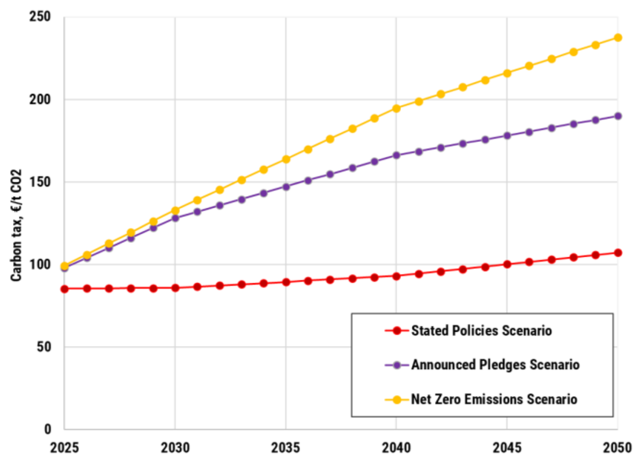

Figure 2. Carbon taxation scenarios [44]

3 CASE STUDY

The case study focuses on a Croatian ferry operating on the international route between Ancona, Italy, and Split (Spalato), Croatia. This route covers a distance of approximately 245 kilometres, with each crossing taking around 9.5 hours to complete. The ferry performs a total of 116 trips annually, serving as a vital connection across the Adriatic Sea [45]. Regarding technical characteristics, the vessel is equipped with four main engines, which provide the primary propulsion power, complemented by four auxiliary engines that support onboard electrical and operational systems. The configuration is typical for a medium-sized ferry, making it an appropriate subject for analysing fuel consumption, emissions, and the economic viability of alternative fuels under real operational conditions. More ferry details are provided in Figure 4.

Ship name	Marko Polo
Lenght, m	128.1
Breadth, m	19.6
Draught, m	5.7
Engine power - main, kW	4 x Stork-Werspoor Diesel 8TM410 each 3754 kW
Engine power - auxiliary, kW	4 x Nohab Polar SF 16 RS each 771 kW
Design speed, kn	19.5

Figure 3. Technical characteristics of ferry “Marko Polo” [45]

In real-world operation, a vessel’s service speed often deviates from its design speed due to factors such as meteorological conditions, weather routing, fixed timetables, and other operational limitations. Thus, at the design operating speed, the average power demand of the main engines $P_{ME,ave}$ (kW) is estimated as 90% of the engine’s maximum design output P_{ME} (kW):

$$P_{ME,ave} = 0.9 \cdot P_{ME} \tag{7}$$

The auxiliary engines are assumed to operate at an average load of 50% and the total average ship power P_{ave} (kW), is obtained by summing the average main engine power and average auxiliary engine power. For a diesel-powered ferry, the energy consumption per unit distance, EC (kWh/km), is determined using the following equation:

$$EC = \frac{P_{ave}}{v_{ave}} . \tag{8}$$

The average speed v_{ave} (kn) is calculated by dividing the total route length by the average trip duration. In this study, it is assumed that all alternative power systems have the same energy requirements as the reference diesel-powered ferry.

There is a wide selection of alternative fuels that provide the possibility of reducing GHG emissions while at the same time ensuring that operational requirements are met. The literature provides countless studies on different fuels, and methanol has proven to be the optimal solution in terms of both environmental friendliness and economic sustainability [46], [47]. Despite the advantages, the current production methods for methanol, including natural gas reforming and coal gasification, are carbon-intensive, limiting its potential as a truly low-carbon fuel. Although alternative feedstocks are being explored, the production of methanol still relies heavily on fossil-based sources. Additionally, methanol's toxicity, volatility, and flammability pose safety concerns, and the infrastructure for large-scale production and distribution remains under development [23]. Methanol fuel prices experience considerable fluctuations driven by various factors, much like other energy commodities, as seen in Figure 4. They are influenced by multiple, interconnected factors, from global supply and demand dynamics to crude oil prices, regulatory changes, and geopolitical events. The total cost of methanol is affected by its production process. Since methanol is mainly derived from natural gas, the changes in natural gas prices have a direct impact on methanol production costs and, therefore, on methanol prices [48], [49]. Chronologically speaking, before the COVID-19 pandemic methanol prices were relatively stable with fluctuations mainly driven by changes in production prices and demand dynamics, but during the pandemic a significant drop is visible due to reduced demand across various industries. After the pandemic, there was a rapid increase in prices similar to crude oil, but there was volatility influenced by the Russia-Ukraine war [41], [50]. Currently, the methanol prices experience fluctuations influenced by regulatory changes, incentives for the application of green technologies and varying production costs. For instance, FuelEU Maritime Regulation aims to achieve a more sustainable, low-carbon maritime sector by encouraging the use of cleaner fuels. Thus, the initiative provides support for the development and deployment of innovative technologies and fuels that can lower the carbon footprint of shipping, such as ammonia, hydrogen, and methanol [51]. Since its application is more and more recommended in the shipping sector, price volatility must be considered as it affects the cost-effectiveness of methanol as a cleaner alternative to traditional marine fuels.

Figure 4. Methanol price fluctuations, 2014-2024 [41]

4 RESULTS

After collecting the necessary data and creating a database on marine diesel and methanol prices, several Monte Carlo simulations of fuel prices were carried out. For each fuel separately, each histogram illustrates the distribution of 10 000 simulated fuel prices. These simulations are based on random number generation, ensuring that each run provides a different set of fuel prices, yet all share the same statistical properties, such as mean and standard deviation, derived from the historical data, as presented in Table 1. Figures 6 and 7 show the histograms of 6 such simulations. Thus, the key difference between the six scenarios lies in the random number generation process, which allows for the modelling of fuel price volatility under varying conditions. This offers the possibility to assess the potential future costs for each fuel type across different time periods (2030, 2040, and 2050), and to compare the economic impact of using diesel versus methanol in the LCCA.

Each histogram is overlaid with a red line representing a normal distribution curve with the same mean and standard deviation, providing a visual reference for how closely the simulated data approximates a normal distribution. The choice of normal distribution helps the study to model fuel price volatility in a way that is both practical for real-life application and simplifies the calculation [31]. Then, the LCCA is conducted using the fuel prices obtained by Monte Carlo simulations, as presented in Figures 8, 9 and 10. LCCA results were compared for diesel and methanol in order to gain insight not only into the difference in total costs but also into price movements and their stability. By adding carbon taxes, the trends of total costs for 2030, 2040 and 2050 were compared. Considering that the validity of the investment is to be considered in the worst case (i.e. when the total costs are the highest), carbon taxes are calculated for the most expensive scenario, the Net Zero Emission scenario.

Table 1. Statistical results of diesel and methanol prices

	Mean, €/kg	Variance, €/kg	Standard deviation, €/kg	Skewness, €/kg
Diesel (D)	0.86	0.003	0.06	0.48
Methanol (M)	0.34	0.009	0.09	0.38

The results of Monte Carlo simulations for diesel prices, Figure 5, are calculated for a mean of 0.86 €/kg and a standard deviation of 0.06 €/kg. The x-axis represents the diesel price, ranging from 0.66 to 1.08 €/kg, while the y-axis indicates the frequency, showing how often each diesel price range appeared in the simulations. The standard deviation of 0.06 €/kg indicates a relatively narrow spread around the mean. In D-1, the distribution is symmetrical and centred around the mean, with the highest frequency bar observed between 0.84 and 0.88 €/kg. D-2 exhibits a similar centred distribution, with a more pronounced peak occurring in the same range, indicating a higher concentration of diesel prices near the mean. Graph D-3 also demonstrates a well-centred distribution closely following the normal curve, with limited deviations at the tails. D-4 shows a slightly wider spread compared to the others, with minor flattening around the mean, indicating slightly lower peak frequencies and a marginal increase in tail occurrences. Histogram D-5 demonstrates the sharpest peak among the six, concentrated around 0.84 to 0.88 €/kg, while D-6 displays a balanced distribution, symmetrical and well-aligned with the expected normal pattern. Overall, all histograms indicate that the simulated diesel prices are predominantly centred around 0.86 €/kg, with frequencies decreasing gradually as values of the prices deviate from the mean. Extreme price values are rare, and the overall pattern remains consistent.

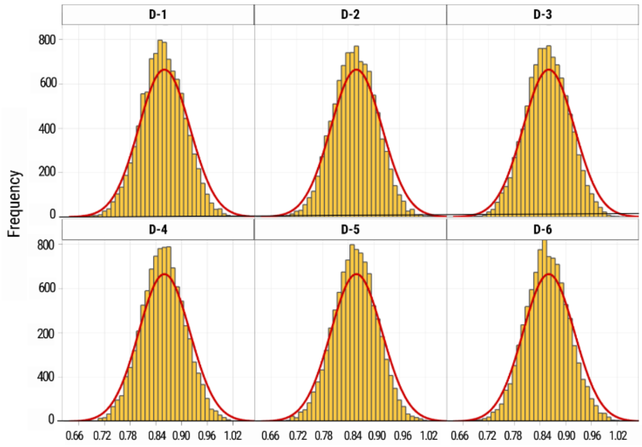

Figure 5. Monte Carlo simulations of diesel prices

The results of Monte Carlo simulations for methanol prices, Figure 6, are calculated for a mean of 0.34 €/kg and a standard deviation of 0.09 €/kg. The higher standard deviation compared to diesel indicates moderate variability, causing the prices to occasionally deviate more significantly from the mean. The x-axis represents the methanol price, ranging from 0 to 0.75 €/kg, and the y-axis shows the frequency. The graph M-1 displays a roughly symmetrical distribution centred around the mean, with the highest frequency observed between 0.33 and 0.39 €/kg. M-2 follows a similar pattern but with a slightly sharper peak at the mean, indicating a stronger central clustering of prices. Minor deviations are observed in the tails of both histograms, reflecting slight skewness. In M-3 there is a noticeable peak around 0.33 to 0.37 €/kg, but also a minor bimodal tendency is observed. Although the results of skewness based on previous methanol price data showed that fairly symmetrical values can be expected, variations due to the random generation process are obvious in the histograms. Graph M-4 presents a broader peak with more pronounced tails, indicating a higher frequency of extreme price values. As the prices cluster into two distinct ranges rather than forming a single dominant peak, this suggests that methanol prices may experience variations influenced by market fluctuations or other external factors. Histogram M-5 shows similar results as M-4, while histogram M-6 maintains a symmetrical shape with frequencies gradually declining towards both tails. Overall, the methanol price distributions show a noticeable difference in skewness, tail thickness, and spread, particularly in M-4 and M-5. These deviations suggest that while methanol prices remain relatively stable around the mean of 0.34 €/kg, occasional wider fluctuations and market-driven subgroups may emerge.

The limitation of this model can be observed in some deviations, even though the majority of histograms follow a normal distribution curve. The presence of this bimodal shape and slight skewness suggest that the assumption of a normal distribution may not fully capture the underlying price behaviour. The deviations may reflect the randomness inherent in Monte Carlo simulations or incorrect assumption of distribution in the model. If the fuel price distribution is indeed bimodal or influenced by different market conditions or price regimes, it may lead to incorrect cost projections. Thus, future research, with a greater number of simulations, is necessary to understand the reasons for the bimodal distribution and to determine whether it is a result of specific market events, pricing models, or other external factors.

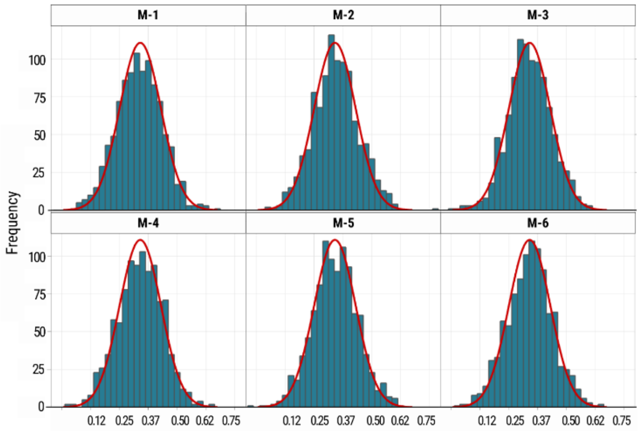

Figure 6. Monte Carlo simulations of methanol prices

The LCCA is usually calculated based on a fixed fuel value, which is why the results for a vessel (or product in general) with the same technical and operational characteristics can vary significantly depending on the trend in the observed fuel prices. In Figure 8, the LCCA costs, calculated based on the mean values of diesel and methanol fuel, for a ferry lifetime of 20 years, are presented to show the breakdown of costs. Diesel power-system shows higher total costs than the methanol one, primarily due to higher fuel costs and carbon taxes based on NZES scenario. Although the investment cost for methanol is approximately 1.8 times higher than that of diesel, maintenance costs remain comparable for both fuels. The most significant cost differences arise from fuel expenses, where diesel results in substantially higher expenditures due to its fuel price, around 1.5 times higher than methanol dual-fuel engine.

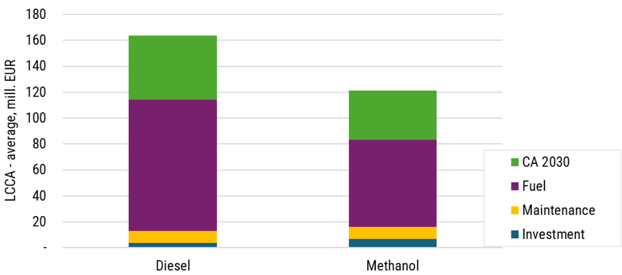

Figure 7. LCCA results based on mean values of fuel prices

To get a deeper insight into lifecycle costs, carbon tax fluctuations are taken into account in this calculation, which gives a direct insight into the LCCA trends, assuming a lifetime of 20 years. The carbon tax prices, according to the NZES scenario, are obtained according to Figure 3. The results are given in Figures 9 and 10. Figure 9 shows the influence of carbon taxation over time and compares it in the case of a diesel- and methanol-diesel dual fuel driven ferry. Both fuels show an increase in costs over time, reflecting the anticipated rise in carbon taxation. However, diesel consistently shows higher values compared to methanol over the years, indicating higher expected costs under the given conditions. Even during a cost increase and variable cost projections, methanol remains to show lower expenses than diesel, making it a more cost-effective alternative under stringent carbon tax regulations.

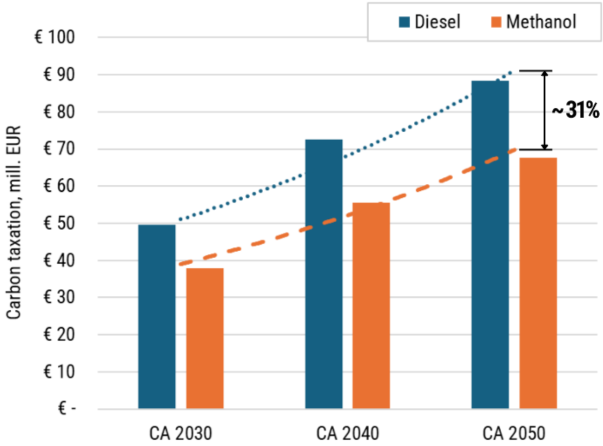

Figure 8. Carbon taxation cost for NZES scenarios

In Figure 10, the histograms illustrate the LCCA for both diesel-powered and methanol-powered ferry under three carbon tax NZES scenarios: CA 2030, CA 2040, and CA 2050. The x-axis, ranging from 0 to 180 million EUR, is kept constant across all scenarios to clearly visualize the shift in costs as carbon taxes increase through the years. The y-axis represents the frequency of occurrence for each cost range.

For the CA 2030 scenario, the diesel-powered ferry shows a narrow and sharply peaked distribution cantered around approximately 160 mill. EUR, indicating low variability and high predictability of costs. In contrast, the methanol-powered ferry displays a broader distribution centred around 115–140 million EUR, reflecting slightly higher variability but overall lower costs compared to diesel. In the CA 2040 scenario, there is a discrete shift to the right in both cases, reflecting higher expected costs due to increased carbon taxation. Diesel centres around 180–195 mill. EUR with a narrow peak, while methanol ranges from roughly 135 to 160 mill. EUR with a wider spread. By CA 2050, the rightward shift becomes more pronounced for both fuels. Diesel is centred around 202 million. EUR, showing the highest expected costs among the scenarios but still maintaining a relatively narrow distribution. Methanol, on the other hand, clusters around 158 million EUR with a wider spread, indicating increased uncertainty in long-term cost projections. As seen before, the graphs demonstrate a clear upward trend in LCCA for both fuels as carbon taxes increase over time. Methanol consistently offers lower average costs compared to diesel but exhibits greater variability. Diesel remains more predictable in terms of distribution shape, but at the expense of higher projected costs.

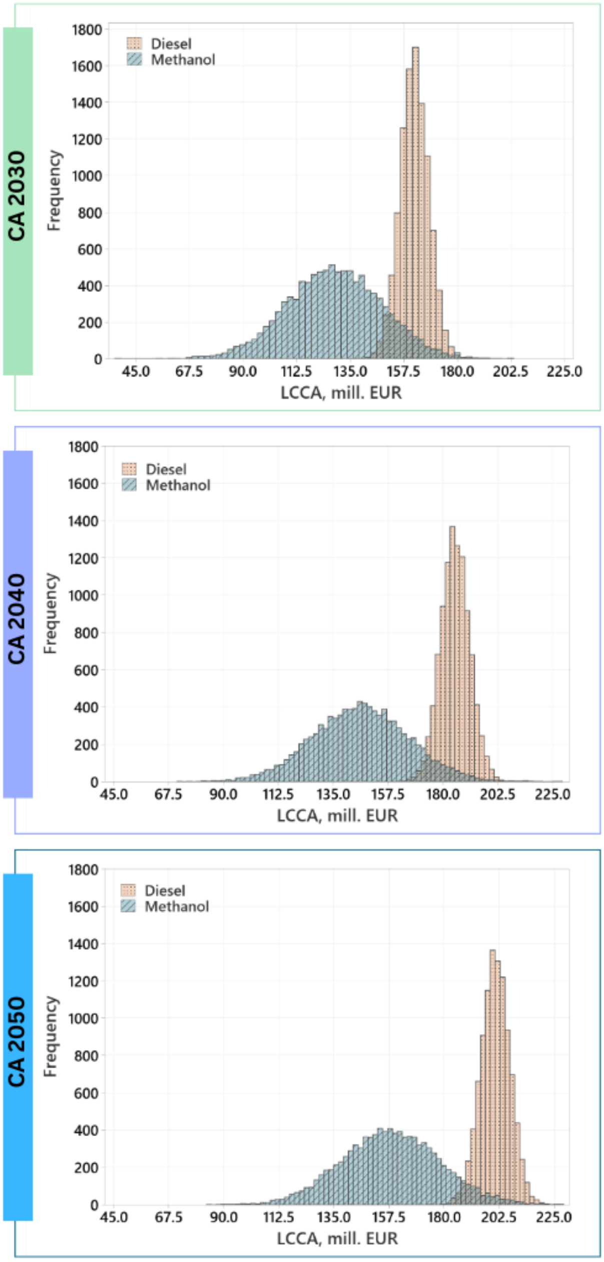

Figure 9. Comparison of LCCA simulations of a diesel- and methanol-powered ferry under different carbon taxes

Both fuels show increasing total costs over time, reflecting the impact of rising carbon taxes. Diesel consistently has higher mean costs with less variability, exhibiting tightly grouped distributions that align well with normal curves, indicating low uncertainty and predictable costs. In contrast, methanol shows lower average costs but with broader spreads and greater variability, suggesting higher uncertainty and more dispersed results. Overall, while diesel presents a stable and predictable cost profile, methanol offers potential cost reductions but with increased long-term unpredictability.

5 CONCLUSIONS

The shipping sector, despite its important role in global trade and transportation, faces significant challenges related to environmental friendliness and economic sustainability. Since the sector is a major consumer of fossil fuels, it highly contributes to global GHG emissions and an increase in the share is expected. Efforts to reduce the environmental impact of shipping are based on the decarbonization goals set by the Paris Agreement, and technical, operational and market measures are set to reduce the use of fossil fuels and improve its efficiency. These measures, while crucial for environmental protection, have also influenced the economic aspect of marine fuels, influencing the volatility of their prices. Innovations in the maritime sector are crucial for improving energy efficiency and reducing dependence on fossil fuels. While research into alternative fuels and electrification shows promise, the economic feasibility of these technologies is heavily influenced by fluctuating fuel prices.

The LCCA and Monte Carlo simulations have been conducted to provide insights into the financial risks and benefits associated with different decarbonization strategies, such as alternative fuels and carbon taxation. In the case of a ferry operating in the Adriatic Sea, the transition from a diesel-powered to a methanol-diesel dual-fuel drive is presented. The Monte Carlo simulations for diesel and methanol prices reveal crucial insights into their price volatility and the economic impact on the observed vessel. The simulations show the following:

- Diesel prices, despite some variability, tend to cluster around the mean value of 0.86 €/kg, with a relatively narrow range of fluctuations;
- The resulting stability is crucial for forecasting long-term operational costs for vessels relying on diesel fuel;
- Methanol price simulations, centred around a mean price of 0.34 €/kg, showed a higher standard deviation, reflecting more significant variability compared to diesel;
- The bimodal characteristics and wider spread suggest that methanol prices are more susceptible to market, political and/or other influences, affecting its cost-effectiveness as a marine fuel over time;
- The LCCA results show that diesel configuration result in 1.5 times higher costs due to high fuel costs and carbon taxation;
- With the increase in carbon taxes, the difference in costs could reach 31% by 2050;
- When including carbon taxation, the variability in methanol becomes lower than in the diesel-powered case, suggesting that methanol could be more appropriate for long-term planning and investment.

The LCCA results indicate that the methanol-diesel dual-fuel driven system, despite higher initial investment and more significant fuel price volatility, presents a slightly lower total LCCA compared to the traditional diesel-powered system. Lower emissions and the resulting reduced carbon taxation achieved by using methanol fuel, have an important impact in the overall cost. The economic assessment shows that methanol is a viable alternative despite its price volatility. The reduced carbon footprint aligns with global decarbonization efforts, and the lower total costs, when considering carbon taxation, recognize methanol an economically sustainable option.

Innovations in the maritime sector are essential for enhancing energy efficiency and reducing the use of fossil fuels. Research on alternative fuels, such as methanol, show promise but are economically sensitive to fluctuating fuel prices. This study highlights the importance of considering price volatility in economic assessments of alternative fuels. Future research should expand this approach to other alternative fuels and technologies and research policy frameworks and incentives that could stabilize fuel prices and support the adoption of cleaner technologies.

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