



Techno-economic assessment of low-carbon ammonia as fuel for the maritime sector

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ABSTRACT

Low-carbon ammonia has recently received interest as alternative fuel for the maritime sector. This paper presents a techno-economic analysis of the total cost of ownership (TCO) of a Post-Panamax vessel powered by low-carbon ammonia. We also calculate the annual increase in carbon tax needed to compensate for the increment in TCO compared to a vessel powered by very low sulfur fuel oil. The increment in TCO is calculated as function of propulsion efficiency to account for uncertainties in the thermodynamics of ammonia combustion for three different cost scenarios of low-carbon ammonia. We evaluate the benefits and drawbacks of hydrogen and diesel as dual fuel for three types of propulsion systems: a compression ignition engine, a spark-ignition engine, and a combination of a solid oxide fuel cell (SOFC) system and a spark-ignition engine. We incorporate three different cost levels for ammonia and a variable engine efficiency ranging from 35 % to 55 %. If the ammonia engine has the efficiency of a conventional marine engine, the increment in TCO is 25 % in the most optimistic cost scenario. SOFCs can reach a better efficiency and yield no pollutant emissions, but the reduction in fuel expenses in comparison to conventional combustion engines only offsets their high investment costs at either low engine efficiency or high fuel prices. The increment in TCO and reduction in GHG emissions depend on whether high combustion efficiencies, small dual fuel fractions, and low NO_x, N₂O, and NH₃ emissions can be simultaneously achieved.

Introduction

The Paris Agreement aims to limit global warming to <2 °C compared to pre-industrial levels. This can only be achieved by a drastic reduction in greenhouse gas (GHG) emissions, and requires a rapid transition to zero-emission energy sources in all sectors. The maritime sector currently accounts for nearly 3 % of global GHG emissions and the International Maritime Organization (IMO) has recently tightened its GHG reduction goals to at least 20 % by 2030 and 70 % by 2040 (both compared to 2008 levels), while net-zero emissions need to be achieved by 2050 [1]. Currently, 99 % of energy demand of the international shipping sector is delivered by fossil fuels [2]. Since the general lifespan

of cargo ships is 25 years [3], there is an urgent need to have the first commercial vessels powered by low-carbon energy sources in operation as soon as possible.

Since at present the gravimetric density of batteries is too low to be useful for international shipping [4], full decarbonization of the maritime industry requires a transition to zero-emission fuels. Over the past years, the sector has shown an increasing interest in the use of ammonia (NH₃) as alternative fuel for cargo shipping. Ammonia is a zero-carbon fuel, it is easy to store and transport in comparison to liquid hydrogen, has a relatively high energy density, and it is already produced commercially in large quantities for its use in fertilizers.

Among the challenges with ammonia as fuel are its high toxicity and

Abbreviations: AICT, Annual Increase in Carbon Tax; AOG, Anode Off-Gas; CAPEX, CAPital EXpenditures; CI, Compressed Ignition; CR, Compression Ratio; CTI, Carbon Tax Increase expenses; ECA, Emission Control Area; EEC, Effective Energy Cost; FUELEX, FUEL EXpenditures; HFO, Heavy Fuel Oil; ICE, Internal Combustion Engine; IMO, International Maritime Organization; ITE, Indicated Thermal Efficiency; GHG, GreenHouse Gas; HPDF, High Pressure Dual Fuel; NO_x, Nitrogen Oxides; OPEX, OPERational EXpenditures; RPM, Rotation Per Minute; SI, Spark-Ignition; SOFC, Solid Oxide Fuel Cell; TCO, Total Cost of Ownership; TEU, Twenty-foot Equivalent Unit; TRL, Technology Readiness Level; VLSFO, Very Low Sulfur Fuel Oil.

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poor combustion properties. It has a slow burning velocity, a high auto-ignition temperature, and a narrow flammability (see Table 1). Ammonia concentrations of 300 ppm can be immediately lethal, while 25 ppm can be dangerous over a longer period of exposure. Preventing any spillage or leakage is thus of great importance. The thermodynamically most favorable combustion products are water and nitrogen, which pose no threat to the environment. However, due to poor combustion characteristics, exhaust gasses also contain high levels of nitrogen oxides (NO_x), nitrous oxide (N₂O) and traces of unburned ammonia, that can inflict environmental damage. Compression ignition of ammonia without dual fuel is challenging, since compression ratios as high as 1:35 are required [5].

The use of dual fuels can mitigate these shortcomings. Methane, dimethyl ether, gasoline, diesel, and hydrogen are among the dual fuels proposed to enhance ammonia combustion, of which the latter two are the most well studied. Kumar et al. [6] estimate the technology readiness level (TRL) of marine internal combustion engines (ICEs) fueled by ammonia-hydrogen at 7–8, while those suited for ammonia-diesel at 9. Previous studies on the combustion characteristics of ammonia mixed with small portions of hydrogen or diesel show promising results in both reducing GHG and NO_x emissions, as well as diminishing ammonia concentrations in exhaust gasses [7–10,4,11–14].

Liu et al. [7] undertook a simulation study on ammonia-diesel combustion in a two-stroke marine compressed ignition (CI) ICE with diesel fractions of 1 %, 5 %, and 10 %. Their results showed that at 1 % diesel, GHG emissions could be reduced by 94 % while the engines indicated thermal efficiency (ITE) was 50 %, NO_x emissions were able to meet TIER III regulations (see Table 2), and ammonia slip was below 150 ppm. Similar simulation studies performed by Li et al. [11] and Zhou et al. [4] reported both that at a 3 % diesel ratio, 97 % reduction in GHG emissions could be achieved at an ITE of respectively 45 % and 51 %, while keeping NO_x emissions equal to those in pure diesel mode and ammonia slip at roughly 100 ppm. These promising results largely depended on the high-pressure dual fuel (HPDF) injection strategy used in both studies.

Despite the promising results of these simulation studies and ammonia being one of the most prominent alternative fuels to replace oil, there is an absence in literature of experimental studies on ammonia-diesel combustion in low-speed, two-stroke, large-bore marine engines. Experimental studies on ammonia combustion generally focus on high-speed, small-bore engines typically used in cars. The ammonia fraction has less time to combust at high speed and thus needs a larger dual fuel fraction, which results in smaller GHG reductions. Wang et al. [8] experimentally found that at an 80 % ammonia fraction in a 1000 rotation per minute (rpm) CI engine the GHG emissions decrease by 55 %, at an engine efficiency decreasing from 47 % down to 34 %.

Table 1
Fuel Properties.

Property	Ammonia	Gasoline	Diesel	Natural Gas	Hydrogen
Chemical Formula	NH ₃	C ₈ H ₁₈	C ₁₂ H ₂₃	CH ₄	H ₂
Lower Heating Value (LHV) (MJ/kg)	18.6	44.4	42.5	50.0	120.0
Stoichiometric Air-Fuel Ratio (kg air/kg fuel)	6.05	14.7	14.5	17.2	34.3
Auto-ignition Temperature (°C)	651	246	210	540	585
Flame Temperature (°C)	1800	2470	2100	1950	2045
Flammability Limits in Air (vol. %)	15–28	1.4–7.6	0.6–7.5	5–15	4–75
Boiling Point (°C)	–33	35	180–360	–162	–252

Table 2

NO_x emission limits IMO [15].

TIER:	Ship construction date on or after:	NO _x emission limit (g/kWh) of engine <i>n</i> = engine's rated speed (rpm)		
		<i>n</i> < 130	<i>n</i> = 130 - 1999	<i>n</i> > 2000
I	01–01–2000	17.0	45 * <i>n</i> ^{–0.2}	9.8
II	01–01–2011	14.4	44 * <i>n</i> ^{–0.2}	7.7
III ¹	01–01–2016	3.4	9 * <i>n</i> ^{–0.2}	2.0

1) TIER III regulations only apply when navigating in emissions control areas (ECAs). Outside these regions TIER II limits apply.

Studies on ammonia combustion with hydrogen as dual fuel are nearly all dedicated to SI engines with small bores, medium to high speed, and a compression ratio (CR) below 14. Qi et al. [9] provide a comprehensive review on this topic. In general, all studies find an optimal energy share for hydrogen, above which the engine efficiency decreases. The optimal energy share varies between 7.5 % and 20 %, depending on engine characteristics. Increasing the energy share of hydrogen beyond this optimum can also lead to an increase in NO_x emissions. This is due to the engine temperature increasing beyond 1800 K, after which thermal NO_x formation occurs.

It is unsure to what extent results of ammonia-hydrogen combustion studies are applicable to marine engines used in cargo shipping. These engines typically have large bores, a low speed, and a CR of 12–18. This design is beneficial for the ITE, but might be problematic for ammonia-hydrogen combustion. Combustion chambers with large volumes (i.e. large bores and high CR) in spark-ignition (SI) engines require a high flame propagation speed for the complete combustion of ammonia. Conventional SI of ammonia at the scale of a marine engine might lead to high ammonia slip due to its low reactivity.

This problem might be circumvented by jet ignition [14], in which the spark plug is placed in a pre-combustion chamber connected to the main combustion chamber via holes. When the hydrogen ignites in the pre-combustion chamber, the flames eject under high pressure through the holes into the main combustion chamber, essentially serving as a flame thrower. This ignition strategy is already applied for other low reactivity fuels, but studies on ammonia-hydrogen combustion are so far limited to simulations.

Pochet et al. [13] published a few studies on ammonia-hydrogen combustion via CI engines. Key findings are that the equivalence ratio needs to be around 0.3, and that the combustion efficiency of ammonia falls below 80 %. In [12] they find an engine efficiency of 37 %, which is similar to efficiencies found in studies on SI engines.

Research departments of maritime companies seem to be ahead of academia in the development of an ammonia-diesel fueled marine engine. For example, Wärtsilä [16] has a medium speed 4-stroke ammonia-diesel fueled marine engine commercially available, which claims to achieve a 70 % reduction in GHG emissions. MAN [17] aims to develop a two-stroke marine engine that is 95 % fueled by ammonia.

GHG emissions are not completely eliminated with diesel as dual fuel, although we can still reach net-zero emissions with biodiesel. Also, ammonia production from fossil fuels complemented with carbon capture, utilization and storage (CCUS), also known as blue ammonia, can be a way forward to reduce GHG emissions. Net-zero does therefor not necessarily imply zero GHG emissions or complete abandoning of fossil fuels.

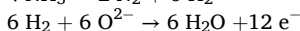
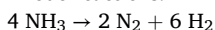
Diesel has the advantage that it is easy to store compared to liquid hydrogen. However, ammonia can be decomposed into hydrogen and nitrogen, so there is no need for hydrogen storage tanks for dual fuel supply. This can be done either via a cracker or a solid oxide fuel cell (SOFC).

A cracker endothermically splits ammonia into hydrogen and nitrogen with a catalyst, which can reach an efficiency of 83 % on small scale [18]. Ru-based catalysts show the best thermodynamical

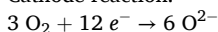
performance with decomposition efficiencies of 95–99 % at 450 °C but are due to their scarcity and costs not necessarily the best choice for industry [19]. Catalysts without rare earth metals require operating temperatures of ≥ 600 °C for near-full conversion, but can achieve around 50 % conversion at 500 °C [20]. Within the context of dual fuel supply for ammonia-hydrogen combustion, the amount of produced hydrogen is far more important than its purity. It thus might be favorable to operate at low temperatures to increase efficiency.

This decomposition on ammonia on a metal catalyst also occurs at the anode of an SOFC, but part of the hydrogen gets exothermically oxidized into steam. This results in a current from the anode to the cathode, at which oxygen gets reduced to oxide ions. The diffusion of the O^{2-} ions through the interconnecting electrolyte requires operating temperatures between 600 °C to 800 °C, which simultaneously catalyzes the cracking of ammonia.

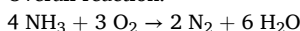
Anode reactions:



Cathode reaction:



Overall reaction:



The oxidation from hydrogen to water is the rate-determining step, so part of the exhaust gas at the anode (anode off-gas, AOG) consists of hydrogen gas. This can be extracted and used as dual fuel for ammonia combustion in an ICE. In this so-called SOFC-ICE combination the power supply is thus divided between an SOFC system and an ICE.

The prospects for the manufacturing costs of SOFCs have been extensively studied by [21–23], and [24]. There is a notable gap between the 2025–2030 target of 900\$/kW set by the US Department of Energy (DoE) [25] and the actual market prices. Modelling studies [24] provide promising prospects based on assumed cost reductions resulting from scaled-up manufacturing, but this cost reduction is not yet observable in actual market data. Whiston et al. [22] perform an expert elicitation, in which experts would assess the manufacturing costs of large-scale SOFC systems at 2400 USD\$/kW, 1909 USD\$/kW, and 841 \$/kW, for respectively 2020, 2035, and 2050. Although analyses of market data show some degree of cost reductions over time [23,21], we are currently not close to the target of the DoE. Large-scale SOFC systems that were part of the self-generation incentive program [26] in California were delivered at a minimum of 5000\$/kW, and the lifespan of these systems is unsure. Herbinet et al. [10] estimates the TRL of ammonia-fed SOFCs at 3–4.

Previous techno-economic assessments of ammonia as alternative fuel in the maritime industry mostly ignore the use of dual fuels. Wu et al. [27] compare the total cost of ownership (TCO) for a 20,182 twenty-foot equivalent unit (TEU) container vessel for LNG, heavy fuel oil (HFO) and ammonia in an ICE and SOFC. They conclude that an ammonia-fed SOFC propulsion system has equal TCO over a 20-year lifetime to an HFO-fueled ICE. Kim et al. [28] study the economic potential of an ammonia-fueled SOFC, PEMFC, and an ICE for a 2500 TEU vessel. They find that the TCO of ammonia-powered vessels is 3.5 to 5.2 times higher than for HFO-powered vessels. Kanchiralla et al. [29] evaluate how ship operation impacts the techno-economic feasibility of carbon-neutral fuels and find that ammonia and methanol have the lowest lifecycle costs for all ship types. Micco et al. [30] provide a modeling study on fuel cell applications in shipping, and find that a SOFC power system reduces the cargo capacity of a small container vessel by 4.8 %.

Uncertainties around engine efficiency and future green ammonia production costs make it difficult to properly estimate fuel expenditures (FUELEX). The price of green ammonia is currently 700 USD\$/t but is expected to significantly decrease up to 2050 as a result of cost reductions in green hydrogen production. However, it is highly uncertain how steep this decline in costs will be. The price of grey ammonia depends for roughly 80 % on the feedstock costs for natural gas and ranges

from 350 to 550 USD\$/t [31].

The novelty of the present work is that we estimate the increment in TCO for one of the most commonly used cargo vessels as function of both the power system efficiency and the future production costs of green ammonia. To our best knowledge, no comprehensive techno-economic evaluation has yet been made in which both variations of the power system efficiency and fuel prices have been taken into account. We compare an ICE and a SOFC-ICE combination fueled with ammonia to a conventional marine engine powered by very low sulfur fuel oil (VLSFO). Although a large part of the international cargo fleet is still powered by HFO, new regulations from the IMO regarding the sulfur content will likely cause shipping companies to shift soon to VLSFO.

The remainder of this article is structured as follows. Section 2 describes the methodology of our techno-economic evaluation. Our test case and cost assumptions are described in section 3. We report and discuss our results in section 4 and in section 5 we summarize our main findings and overall conclusions.

Methodology

A maritime power system fueled by low-carbon ammonia is only competitive when the TCO is less or equal to that of a conventional marine engine powered by VLSFO. This comparison requires quantifying the cost difference of the capital expenditures (CAPEX), FUELEX and operational expenditures (OPEX) over the lifespan of the vessel.

The share of FUELEX in the TCO tends to positively correlate with the carrying capacity of the vessel [32,27,33,34]. The main reason for this is that OPEX and CAPEX do not necessarily scale with the size of the vessel, whereas the fuel consumption is obviously related to the size. Rodrigue et al. [32] estimate that FUELEX are equal to OPEX for Post-Panamax vessels (see Fig. 1). The largest share in OPEX are port charges (21 %), followed by insurance (12.5 %), repair & maintenance (8.5 %), manning (4 %), stores & lubes (2.5 %), and administration (1.5 %).

The high toxicity and environmental risks associated with ammonia will likely lead to higher insurance and repair & maintenance costs. It is important to note that the repair and maintenance costs shown in Fig. 1 applies to the entire ship, not merely the propulsion system. Kim et al. [28] estimates that the repair and maintenance cost for both ICEs and SOFCs fueled by ammonia scale with 1 % of their CAPEX per year; similar to those of conventional marine engines. However, due to a lack of empirical data, these estimations are uncertain. Although the increment in repair and maintenance costs originating from the propulsion system is unsure, it is arguably insignificant compared to the other cost components. We therefore expect that the vast majority of the difference in TCO results from differences in CAPEX and FUELEX. This justifies the approximation:

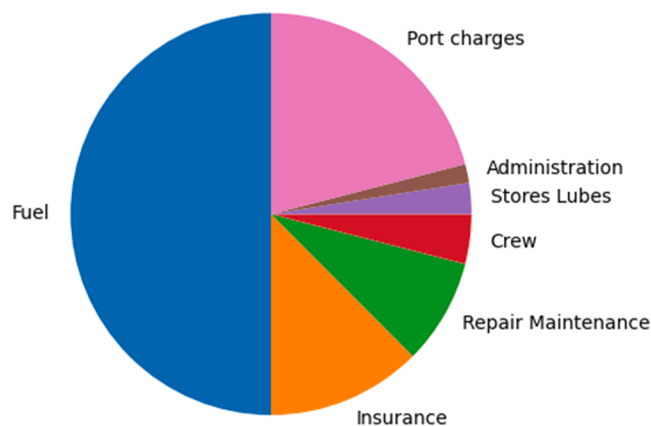


Fig. 1. FUELEX and OPEX of a Post-Panamax vessel.

$$\Delta TCO = \Delta CAPEX + \Delta FUELEX \quad (1)$$

in which FUELEX is calculated per fuel and power system as:

$$FUELEX_f = \sum_{i=1}^t FC_i \times C_{f,i} \times E_{share} \quad (2)$$

In this equation t denotes the lifespan of the ship in years, FC_i the annual fuel consumption in kg/year, $C_{f,i}$ the (estimated) cost of fuel in USD\$/kg per year, and E_{share} the ratio of the primary and dual fuel in terms of mass (for VLSFO this is equal to 1). The annual fuel consumption depends on the efficiency of the power system, and can be expressed as:

$$FC_i = \frac{EC_i}{\eta_{PS} \times LHV_f} \quad (3)$$

in which η_{PS} is the energy efficiency of the power system, LHV_f denotes the lower heating value per fuel in MJ/kg, and EC_i is the annual energy consumption in MJ/year.

We assume that the $\Delta CAPEX$ in eq. (1) is equal to the sum of the cost differences of the power system and the fuel tank:

$$\Delta CAPEX = \Delta CAPEX_{PS} + \Delta CAPEX_T \quad (4)$$

where the $CAPEX_T$ can be calculated as:

$$CAPEX_T = V \times C_{f,T} \quad (5)$$

in which V is the tank capacity in kg, and $C_{f,T}$ the fuel tank costs in USD \$/kg.

The CAPEX of the power system is calculated as:

$$CAPEX_{PS} = P_{ship} \times C_{PS} \times S_{PS} \quad (6)$$

where P_{ship} is the power capacity of the ship in MW, C_{PS} is the cost of the power system in USD\$/MW, and S_{PS} is the share of the power-system in the power capacity of the ship. This is trivially 1 for each scenario in which the power system only consists of an ICE, but is less straightforward for the SOFC-ICE combination. For the SOFC-ICE combination, the S_{SOFC} of the SOFC can be calculated as function of the overall efficiency as:

$$S_{SOFC} = \frac{(\eta_{SOFC-ICE} - \eta_{ICE})}{(\eta_{SOFC} - \eta_{ICE})} \quad (7)$$

from which the S_{ICE} of the ICE can be simply derived as:

$$S_{ICE} = 1 - S_{SOFC} \quad (8)$$

With the above-mentioned cost factors, we can make our approximation of the ΔTCO . When we divide this cost difference by the summation of the ship's lifespan in years, we have the absolute amount at which the carbon tax needs to increase annually in order to make ammonia fueled power systems competitive to VLSFO ones:

$$CTI = \frac{\Delta TCO}{\sum_{y=1}^t \mathcal{Y}} \quad (9)$$

Where CTI is the annual increase in carbon tax expenses in USD\$. This can be converted into USD\$/tCO₂/year via:

$$\Delta AICT = \frac{CTI}{FC_i \times 0.003415 \text{ tCO}_2/\text{kg}} \quad (10)$$

Where 0.003415 tCO₂/kg is the emission factor associated with VLSFO [35], and $\Delta AICT$ the annual increase in carbon tax in USD \$/tCO₂/year.

In our evaluation of the economic competitiveness of the different ammonia driven power systems, we use the cost estimates listed in Table 2. The assumptions of size and power of different components for our case study in Table 3 (see below) are based on the technical

Table 3

Assumed costs, efficiencies, and power of power system and tank.

	CAPEX	Assumed size/ power	Efficiency
Ammonia tank (\$/kg)	0.7 [36]	32.000 ton	–
Diesel tank (\$/kg)	0,144[4]	5 % x 15.000 ton	–
Dual fuel CI ICE (\$/kW)	870 [37]	50 MW [38]	35 % – 50 %
Dual fuel SI ICE (\$/kW)	870 [37]	0 - 50 MW *	35 % – 50 %
VLSFO CI ICE (\$/kW)	600 [37]	50 MW	50 %
SCR (\$/kW)	43.4 [39]	–	–
Ammonia cracker (\$/kW)	8521 x kW ^{0.252} [18]	–	83 % [18]
SOFC (\$/kW)	5000 – 10,000 [40]	0 - 50 MW *	63 % [41]
VLSFO tank (\$/kg)	0,144 [4]	15.000	–

specifications of Post-Panamax vessels, which will be further outlined in section 4.

For the SOFC-ICE case we estimate the FUELEX and CAPEX as function of the power system efficiency, which depends on both the engine efficiency and the power distribution between the ICE and SOFC. We assume the efficiency of the SOFC to be $\eta = 63\%$, and calculate the TCO, FUELEX, and CAPEX as function of the overall efficiency for SI ICE efficiencies of 35 %, 40 %, 45 %, and 50 %. An overall efficiency of 63 % thus represents a power distribution in which all the power is delivered by the SOFC, while an overall efficiency of 35 % represents a scenario in which the ship is entirely powered by an SI ICE of 35 %.

The price data (see Table 4) for VLSFO, blue- and green ammonia are retrieved from respectively Ship & Bunker, [42], and [43]. For green ammonia, we perform our analysis with both the upper and the lower bound of the price forecasts. The green ammonia price forecasts span from 2030 to 2050, while the lifetime of the ship spans from 2025 to 2050. We therefore assume that green ammonia prices from 2025 to 2030 equal the price forecasts of 2030. For 2030 to 2050, we calculate the price per year via:

$$C_{green \text{ ammonia, year, LB}} = 0.475 - \frac{0.475 - 0.310}{20} \times \text{years} \quad (11)$$

$$C_{green \text{ ammonia, year, UB}} = 0.950 - \frac{0.950 - 0.610}{20} \times \text{years} \quad (12)$$

Based on the studies undertaken by Li et al. [11], Zhou et al. [4], and Liu et al. [7] we assume an energy share of 5 % of diesel for dual fuel combustion with ammonia. The optimum energy share for hydrogen is somewhere between 7.5 % and 20 %. Hydrogen can be produced from ammonia with an efficiency of 83 % and its combustion produces no pollutant emissions, so the actual optimum has little impact. The division of the LHV by the fuel price is for diesel, hydrogen and blue ammonia close to 30 MJ/\$. We therefor assume that the dual fuel energy share in the combustion engine has no impact on the fuel price.

Especially for ammonia-hydrogen combustion in SI engines, it is unsure whether this can meet the ITE of conventional marine engines (~50 %) without yielding unacceptable high NO_x, N₂O and NH₃ emissions. We therefor calculated the TCO as function of the engine efficiency.

To give a more general perspective on the economic competitiveness

Table 4

Cost projections of different fuels (USD\$/kg).

	VLSFO *	Blue Ammonia	Green Ammonia**	Diesel (5 %)	Hydrogen***
2025	0.63	0.6	0.950 – 0.475	1.25	4
2050	0.63	0.6	0.610 – 0.310	1.25	4

* Average of 20 biggest ports.

** Green ammonia forecasts for 2030 – 2050.

*** Based on [18].

of low-carbon ammonia, we also calculate the effective energy costs (EEC):

$$EEC_{f,PS} = \frac{LHV_f \times \eta_{PS}}{C_f} \quad (13)$$

This variable is an expression for the amount of power delivered for each dollar spent on fuel. The EEC is independent of CAPEX and fuel consumption, and therefor provides a more general insight into the economic competitiveness of ammonia.

Case study

We choose a cargo vessel for our case study since cargo shipping accounts for the vast majority of GHG emissions in the maritime sector [44]. Post-Panamax vessels have been the most popular type of cargo vessel in the past decade [45], so our choice of size and power of the different components (see Table 2) and assumed fuel consumption resembles averages for Post-Panamax vessels found in literature.

Hua et al. quantified the average fuel oil consumption of Post-Panamax vessels at 26.000.000 kg per year [45]. Other research by Wu et al. [27] estimated the ammonia tank volume for a 20.182 TEU vessel with a 56 MW engine as 32.760 m³, equivalent to a 15.000 m³ fuel oil tank while Kim et al. [28] estimated the oil tank capacity of a 2500 TEU cargo ship with a 13.5 MW engine at 1800 m³. The tank capacity for fuel oil in m³ seems to scale as roughly ~0.75 times the TEU capacity.

De Melo Rodrigues et al. estimate the propulsion power of a Post-Panamax vessel at 27 MW to 77 MW [38]. We therefor assume a power system capacity of 50 MW for our case study.

A study by Zhang et al. [33] found that the average construction costs for >100.000 deadweight tonnage (dwt) cargo- and bulk carriers were respectively 108 and 77 million USD\$. We therefor estimate the construction costs of the VLSFO powered ship to be 92.5 million USD\$.

Results & discussion

Fig. 2 shows the cost structure of the 912 M USD\$ TCO of a conventional Post-Panamax container vessel. The black bar corresponds to the construction costs of 92.5 M USD\$, the grey bar to the FUELEX for 26.000.000 kg/year at 0.63 USD\$/kg, and the red bar to the OPEX.

Fig. 3 shows the TCO for the same vessel when powered by an ammonia fueled ICE as function of the engine efficiency for three cost levels of low-carbon ammonia. Each bar represents the increment in either CAPEX or FUELEX compared to the TCO in Fig. 2. The right y-axis shows the annual increase in carbon tax at which the TCO of a VLSFO powered vessel would be equal to an ammonia powered ship.

The orange bar represents the additional CAPEX for an ammonia-powered ship, that mainly arise from increased storage costs. The light green, blue, and dark green bars represent the increment in FUELEX for respectively the lower bound of green ammonia price forecasts, the current global average price of blue ammonia, and the upper bound of

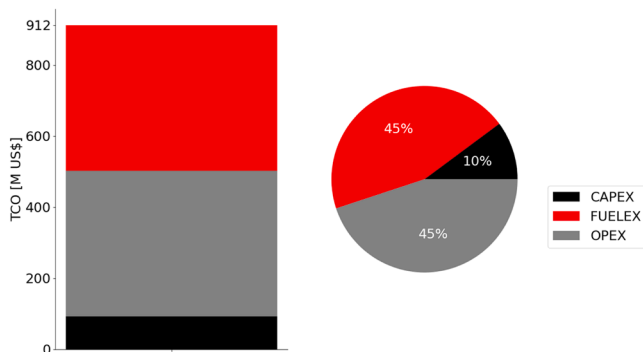


Fig. 2. TCO of Post-Panamax container vessel.

green ammonia price forecasts (see Table 3).

The three dotted lines indicate the annual increase in carbon tax required to make the three cost scenarios competitive to VLSFO.

The annual increase of 18,8 USD\$/tCO₂ for blue ammonia combustion at 50 % efficiency would thus over a 25-year period result in a carbon tax of 470 USD\$/tCO₂.

Even in the most optimistic case, in which green ammonia prices follow the lower bound of the forecasts and the efficiency of the dual fuel engine reaches 55 %, there would still be an increment in TCO of approximately 19 %. It is remarkable that the rise in CAPEX is negligibly small over the lifespan of the vessel.

Effective energy costs

Fig. 4 shows the price ratio of VLSFO to ammonia at which an ammonia fueled power system has equal EEC to a VLSFO powered engine with 50 % efficiency. The black solid line denotes the current price ratio between VLSFO (0.63 USD\$/kg) and blue ammonia (0.60 USD\$/kg). Even at 100 % efficiency, ammonia would still not be able to compete with VLSFO in terms of EEC. Increasing propulsion efficiency would thus not be enough to make ammonia competitive with VLSFO.

Figs. 5 and 6 compare the EEC of VLSFO and ammonia for three different ammonia propulsion efficiencies, while we estimate the efficiency for the VLSFO ICE to be 50 %. Fig. 6 considers the constant ammonia price of 0.60 USD\$/kg and a variable VLSFO price, whereas Fig. 5 assumes a constant VLSFO price of 0.63 USD\$/kg with a variable ammonia price.

When the cost of low-carbon ammonia stays at 0.60 USD\$/kg and is combusted with equal efficiency as VLSFO, the cost of VLSFO would need to increase to 1.42 USD\$/kg. This would correspond to a carbon tax of 231 USD\$/tCO₂, which requires ambitious climate policy.

If the VLSFO costs stay constant and the efficiency of the ammonia engine would be equal to a conventional marine engine, the ammonia costs should drop below 0.28 USD\$/kg to reach an equal EEC. This is below the lower bound of the green ammonia cost projections for 2050.

The only realistic pathway for low-carbon ammonia to economically compete with VLSFO would thus be a simultaneously decreasing low-carbon ammonia costs, increasing carbon tax, and development of efficient ammonia power systems.

SOFC-ICE

Whether the high efficiency of SOFCs is worth their investment costs, depends on the fuel price and efficiency of the ICE. Tables 5 and 6 show whether an ICE, a SOFC, or an SOFC-ICE combination is the economically most favorable power system for SOFCs with an efficiency of 63% and a combined CAPEX and OPEX of respectively 5000 USD\$/kW and 10.000 USD\$/kW over the vessel lifetime. The columns denote the efficiencies of the ICE, while the rows represent the three different cost levels of low-carbon ammonia. The graphs for the optimal power distribution of each option can be found in Appendix A.

Table 5 shows that at high combustion efficiencies and low ammonia prices, the cheapest option would be to leave out the SOFC and just use a combustion engine. The optimal power distribution between the SOFC and ICE shifts towards the SOFC as the ammonia price increases or the combustion efficiency decreases. This can be understood as that the increment in CAPEX of the SOFC compared to the ICE is mitigated by a reduction in FUELEX thanks to its better efficiency.

The same trends observed in Table 5 can also be seen in Table 6, although the SOFCs would never be favorable without an ICE. Both tables clearly show that the cost of low-carbon ammonia is a more important factor for the TCO than engine efficiency or SOFC CAPEX & OPEX.

In nearly every case where SOFC or SOFC-ICE configurations are the cheapest propulsion options, the increment in TCO is still above 50 %. The SOFC configurations listed in the first row of Table 5 do show

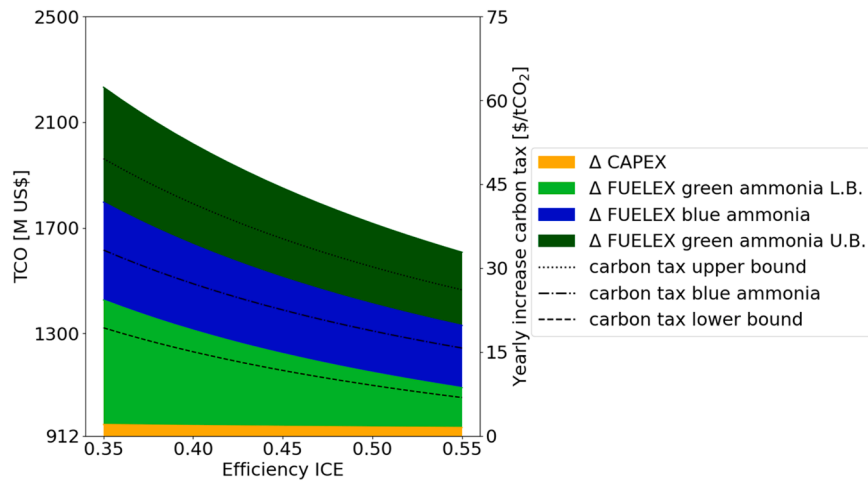


Fig. 3. TCO as function of ICE efficiency.

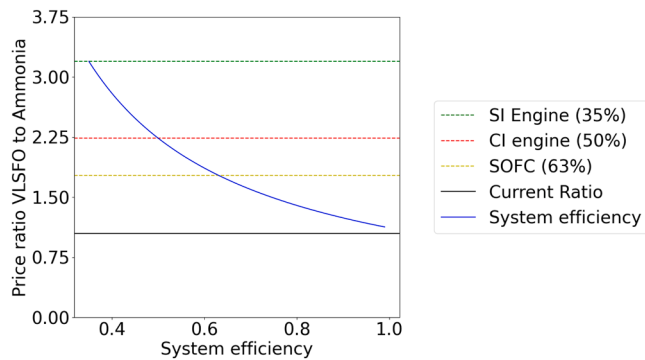
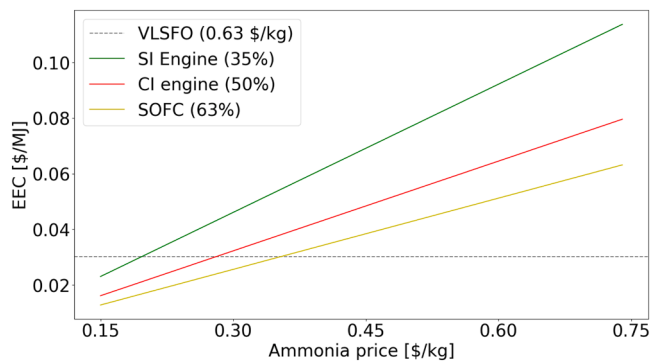
Fig. 4. Price ratio at which ammonia-fueled power systems reach parity in FUELEX to a VLSFO powered engine with $\eta = 50\%$ as function of power system efficiency.

Fig. 5. Effective energy costs of VLSFO as function of oil price with three ammonia fueled power systems as benchmark.

smaller TCO increases, but the corresponding TCO-graphs in the Appendix show that the TCO difference between the ICE-only configuration (i.e. left part of the graph) and the optimum is minimal. It is also not known whether the AOG of SOFCs would contain enough hydrogen for the dual fuel supply of the ICE. Given that 5000 USD\$/kW over a 25-year period is already an optimistic estimate it is unlikely, even when the maritime sector transitions to low-carbon ammonia, that SOFC-systems will be used for ship propulsion.

At low ICE efficiency and SOFC CAPEX & OPEX of 5000 USD\$/kW, the SOFCs save enough fuel to return their investment costs. But since low fuel prices are regardless of the SOFCs CAPEX a necessity for

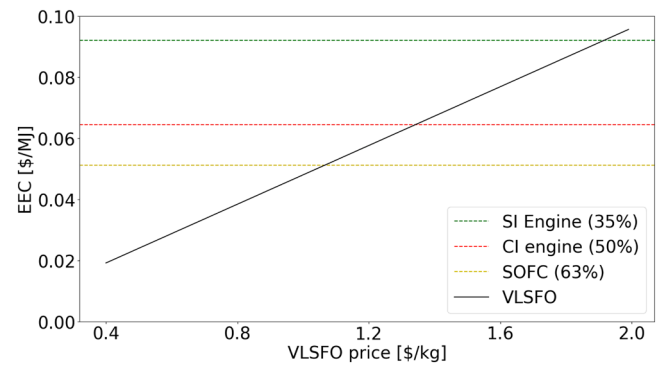


Fig. 6. Effective energy cost as function of VLSFO price.

Table 5

Power system with smallest increment in TCO for SOFC CAPEX & OPEX of 5000 USD\$/kW.

ICE η	35 %	40 %	45 %	50 %
Green LB	SOFC (33 %)	SOFC-ICE (33 %)	SOFC-ICE (31 %)	ICE (25 %)
Blue	SOFC (57 %)	SOFC (57 %)	SOFC (57 %)	SOFC-ICE (54 %)
Green UB	SOFC (85 %)	SOFC (85 %)	SOFC (85 %)	SOFC (85 %)

N.B.: percentages in the column header denote the ICE efficiency for ammonia-hydrogen combustion, and the percentages in brackets in the cells denote the increment in TCO compared to a VLSFO powered vessel.

Table 6

Power system with smallest increment in TCO for SOFC CAPEX & OPEX of 10.000 USD\$/kW.

ICE η	35 %	40 %	45 %	50 %
Green LB	SOFC-ICE (50 %)	ICE (42 %)	ICE (32 %)	ICE (25 %)
Blue	SOFC-ICE (81 %)	SOFC-ICE (76 %)	ICE (65 %)	ICE (55 %)
Green UB	SOFC-ICE (112 %)	SOFC-ICE (110 %)	SOFC-ICE (104 %)	ICE (90 %)

N.B.: percentages in the column header denote the ICE efficiency for ammonia-hydrogen combustion, and the percentages in brackets in the cells denote the increment in TCO compared to a VLSFO powered vessel.

ammonia to compete with VLSFO, the increase in TCO would still be high. These power distributions would thus be the cheapest of expensive options.

Repeating the same analyses for SOFCs at 10.000 USD\$/kW shows that SOFCs only become favorable at engine efficiencies below 45 %, although there is a slight decrease in the TCO at a very small SOFC contribution for the upper bound of green ammonia price forecasts. However, due to the thermodynamics of SOFCs, it is unlikely that a SOFC operating at 63 % efficiency would yield enough hydrogen dual fuel for the ICE at such a disproportionate power distribution. The needed amount of hydrogen would most likely require decreasing the fuel utilization of the SOFC, which would require decreasing the operating voltage of the SOFC and thereby its efficiency.

Although there is a wide range in the fuel price forecasts, combustion efficiency, and the SOFC CAPEX, it is probable that the most favorable power distribution between the SOFC and ICE is heavily shifted towards the ICE. SOFCs are only favored by high ammonia prices and low combustion efficiencies for the ICE, which would greatly limit the potential of ammonia with respect to other alternative fuels such as methanol. The cases in which a fully SOFC-powered ship is the cheapest option, are only relatively expensive scenarios.

In order to produce enough hydrogen dual fuel for combustion, it is likely that the voltage of the SOFC is reduced to a level where an efficiency of over 60 % is no longer achievable. The SOFC would in this case thus serve more as a cracker that has as benefit that it also produces power, rather than as a fuel cell that has as benefit that it also produces hydrogen.

There is currently a gap in literature regarding to what extent it is possible to increase the hydrogen content in the anode off gas without lowering cell voltage. The optimal energy share of hydrogen for ammonia combustion is another degree of uncertainty, but based on values found in literature it is most likely in the range of 7.5 % to 20 %. This optimal energy share is a tradeoff between engine efficiency and emission of NO_x, N₂O, and unburned NH₃. It is thus unsure if the economically most favorable configuration is also thermodynamically desirable.

With respect to the question whether hydrogen or diesel is more favorable as dual fuel, there is no conclusive answer from our analyses. The ratios between the fuel prices and their LHV are close to each other, and since the dual fuel will only comprise a small energy fraction, it will thus not have a significant impact on FUELEX. The impact of the CAPEX of an ammonia cracker on the TCO seems to be negligibly small, so the primary factors that determine the increment in TCO are combustion efficiencies and low-carbon ammonia costs.

The impact of the dual fuel on the TCO depends on what engine efficiency can be achieved while keeping emissions at acceptable low levels. Spark ignited ammonia-hydrogen engines seem to be disadvantaged in a maritime context but have the benefit that the size of the dual fuel fraction does not impact CO₂ emissions. Ammonia-diesel combustion poses less engineering challenges but inevitably emits CO₂. A high dual fuel fraction would either create a large demand for biodiesel or make it impossible to reach net-zero emissions.

Conclusion

We performed a techno-economic evaluation of the impact of using low-carbon ammonia as fuel for either an ICE or an SOFC-ICE combination for large international cargo shipping on the TCO. We incorporated hydrogen and diesel as dual fuel for combustion.

The results show for an ICE powered vessel that the increment in the TCO is primarily determined by the fuel prices and combustion efficiency of the ICE. Although there are additional CAPEX due to the costs of onboard ammonia storage, these costs are significantly lower than the increment in FUELEX.

The question whether hydrogen or diesel is preferable as dual fuel does not depend on their fuel prices, but on the combustion efficiency and the content of NO_x, N₂O, unburned NH₃, and in case of diesel CO₂ in exhaust gasses. Experimental validation of the promising results of simulation studies on ammonia-diesel combustion in low-speed marine engines would remove important uncertainties around the use of ammonia as alternative fuel for cargo shipping.

We found that the TCO increments by at least 25 %, assuming 50 % engine efficiency and low green ammonia prices. SOFCs or SOFC-ICE combinations only significantly decrease the TCO compared to an ICE in cases in which the increment in TCO for any power system is 50 % or more compared to a VLSFO-powered vessel. We therefore conclude that it is unlikely that ammonia-fed SOFCs will become an economically feasible option for cargo shipping in the near future.

This study only accounts for additional costs in FUELEX and CAPEX, where the evaluation of the latter is restricted to the power system and the tank. The use of ammonia will most likely also lead to additional costs related to exhaust gas cleaning, safety measures, reduced cargo capacity, insurance, and crew training, but these are assumed to be significantly lower than the increment in CAPEX and FUELEX. The increment costs related to exhaust gas cleaning and reduced cargo capacity differ for each case based on fuel composition, engine type, ship capacity, while FUELEX is for each cargo ship a major cost component. Our results should nevertheless be interpreted as a conservative estimation.

The current price ratio between low-carbon ammonia and VLSFO makes it impossible for ammonia fueled power systems to compete in terms of FUELEX with VLSFO-powered marine engines. Without carbon tax, ammonia costs should drop to 0.28 USD\$/kg to reach equal EEC. Without decreasing ammonia costs, VLSFO costs should increase to 1.37 USD\$/kg, implying a carbon tax of 217 USD\$/tCO₂. The most realistic pathway for low-carbon ammonia to reach parity with VLSFO in EEC would thus be a simultaneously decreasing low-carbon ammonia costs and increasing carbon tax.

CRedit authorship contribution statement

Wouter Schreuder: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **J. Chris Slootweg:** Supervision. **Bob van der Zwaan:** Supervision.

Declaration of competing interest

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

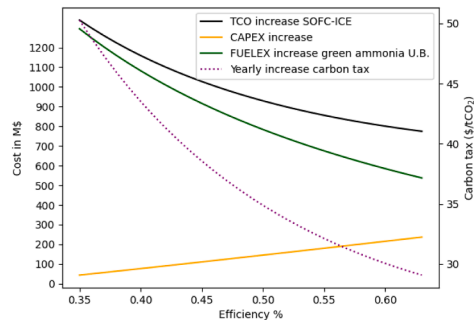
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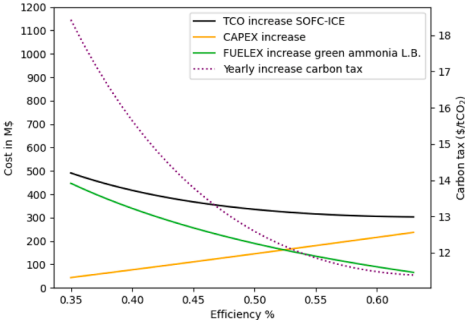
Appendix A

Table A1
SOFC CAPEX & OPEX 5.000 USD\$.

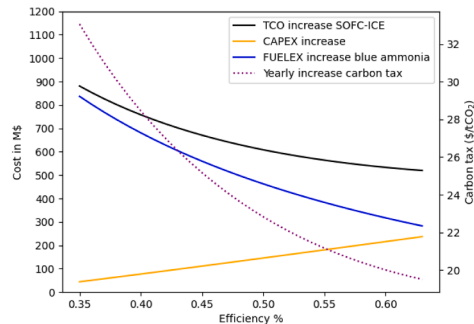
ICE η = 35%, GREEN UB



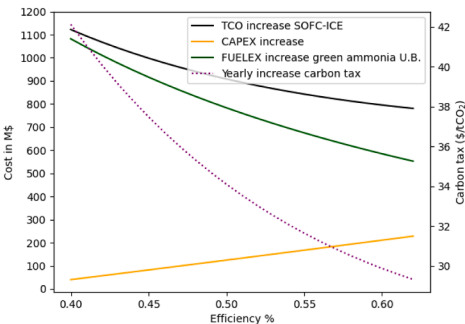
ICE η = 35%, GREEN LB



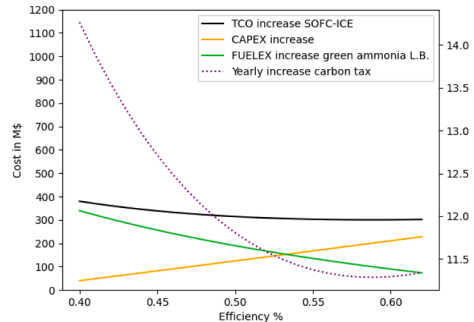
ICE η = 35%, BLUE



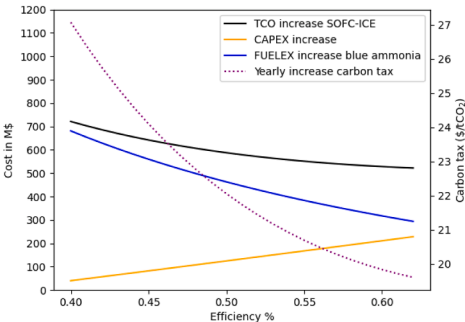
ICE η = 40%, GREEN UB



ICE η = 40%, GREEN LB



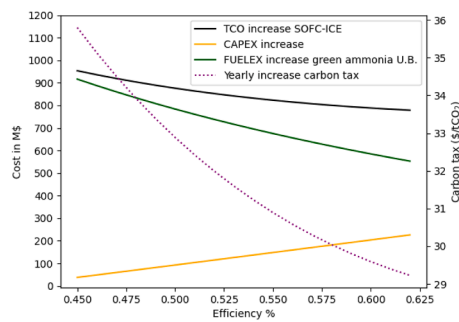
ICE η = 40%, BLUE



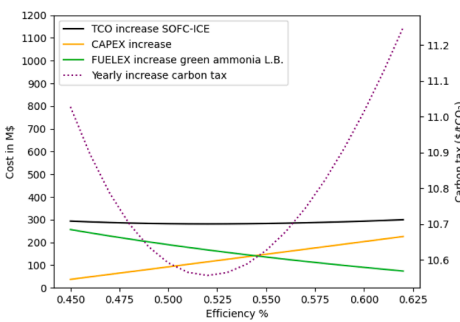
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Table A1 (continued)

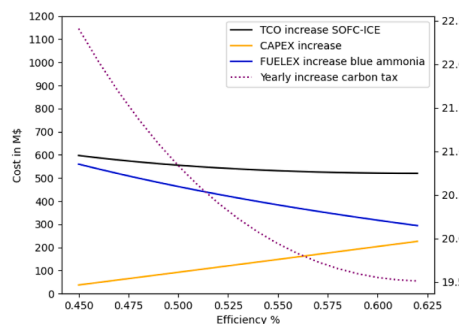
ICE $\eta = 45\%$, GREEN UB



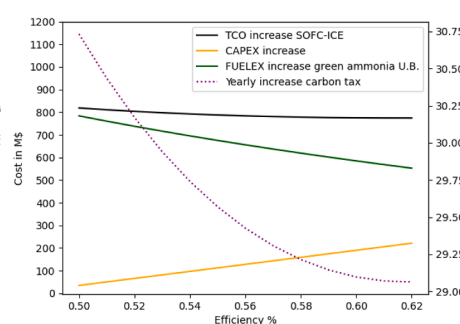
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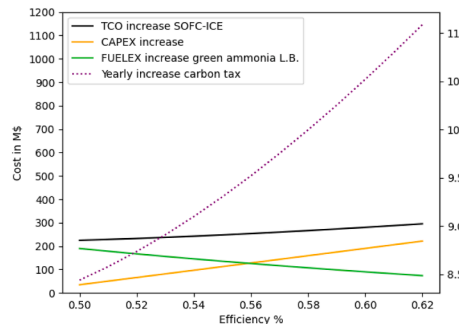
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ICE $\eta = 50\%$, GREEN UB



ICE $\eta = 50\%$, GREEN LB



ICE $\eta = 50\%$, BLUE

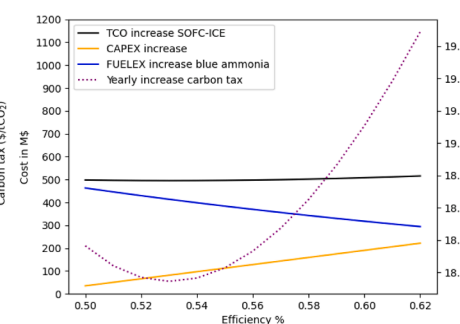
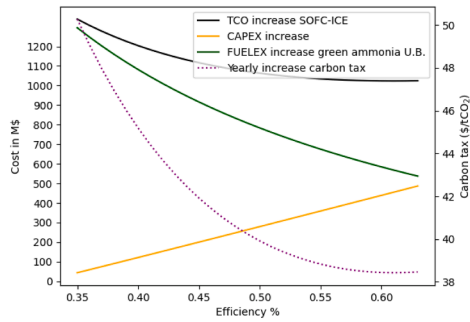
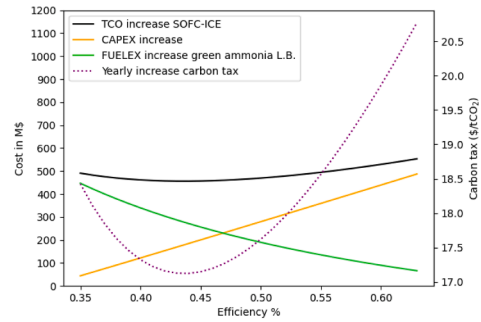


Table A2
SOFC CAPEX & OPEX 10.000 USD\$.

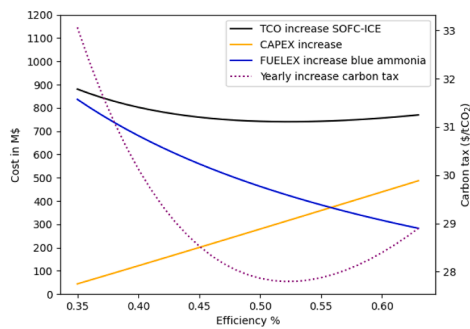
ICE $\eta = 35\%$, GREEN UB



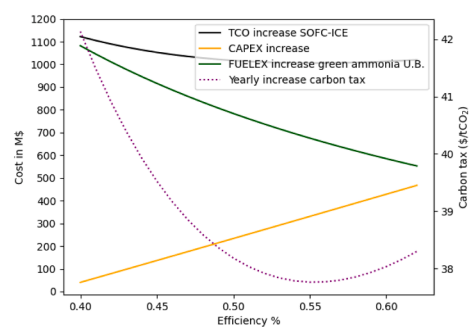
ICE $\eta = 35\%$, GREEN LB



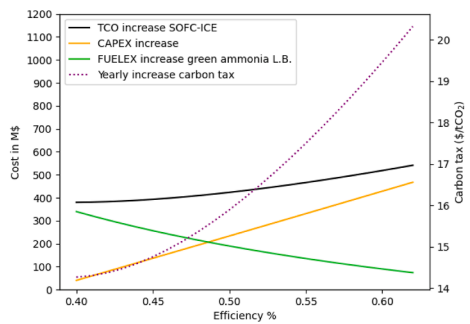
ICE $\eta = 35\%$, BLUE



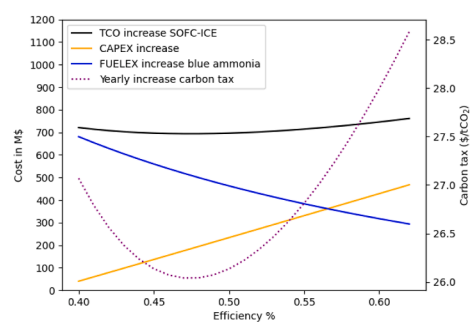
ICE $\eta = 40\%$, GREEN UB



ICE $\eta = 40\%$, GREEN LB

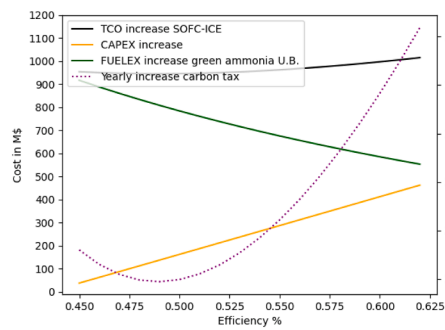
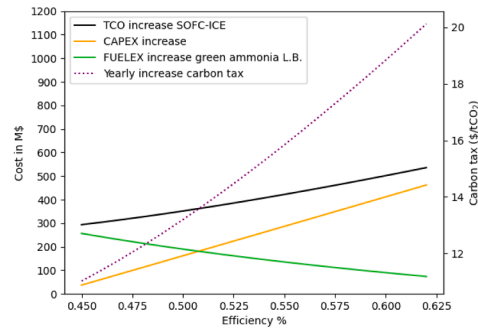
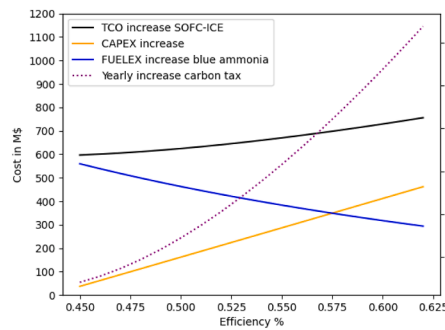
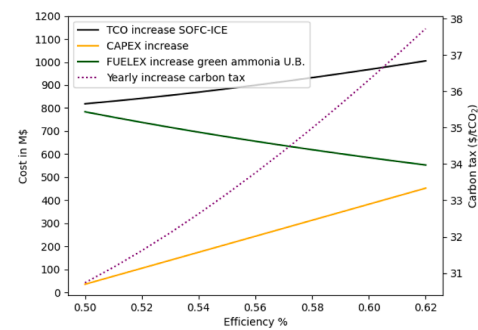
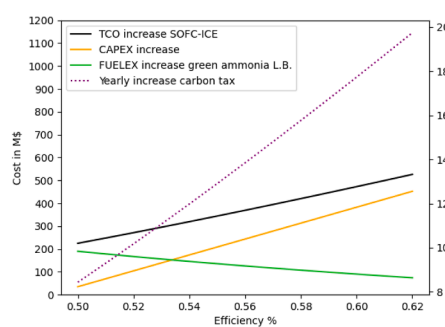
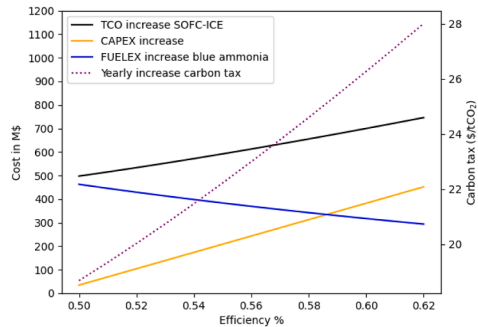


ICE $\eta = 40\%$, BLUE



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Table A2 (continued)

ICE $\eta = 45\%$, GREEN UBICE $\eta = 45\%$, GREEN LBICE $\eta = 45\%$, BLUEICE $\eta = 50\%$, GREEN UBICE $\eta = 50\%$, GREEN LBICE $\eta = 50\%$, BLUE

Data availability

Data will be made available on request.

References

- [1] R. MEPC, "2023 IMO strategy on reduction of GHG emissions from ships," 2023.
- [2] M. Stefanides, "A pathways to decarbonise the shipping sector by 2050 presenter," IRENA: international renewable energy agency, 2022.
- [3] O. Dinu I.A. Maritime vessel obsolescence, life cycle cost and design service life. In: IOP conference series: materials science and engineering. 1st ed.95. IOP Publishing; 2015.
- [4] Zhou X, Li T, Wang N, Wang X, Chen R, Li S. Pilot diesel-ignited ammonia dual fuel low-speed marine engines: a comparative analysis of ammonia premixed and high-pressure spray combustion modes with CFD simulation. *Renew. Sustain. Ener. Rev* 2023;173:113108.
- [5] W. and H. L.W. and M.H.R. Cornelius, "Ammonia as an engine fuel," SAE Transactions, pp. 300–326, 1966.
- [6] Kumar L, Sleiti AK. Systematic review on ammonia as a sustainable fuel for combustion. *Renew. Sustain. Ener. Rev. Sep. 2024;202:114699*. <https://doi.org/10.1016/j.rser.2024.114699>.
- [7] Liu L, Wu J, Liu H, Wu Y, Wang Y. Study on marine engine combustion and emissions characteristics under multi-parameter coupling of ammonia-diesel stratified injection mode. *Int J Hydrogen Energy* 2023;48(26):9881–94.
- [8] Wang X, et al. Exploring the GHG reduction potential of pilot diesel-ignited ammonia engines - effects of diesel injection timing and ammonia energetic ratio. *Appl Energy Mar. 2024;357:122437*. <https://doi.org/10.1016/j.apenergy.2023.122437>.
- [9] Qi Y, Liu W, Liu S, Wang W, Peng Y, Wang Z. A review on ammonia-hydrogen fueled internal combustion engines. *eTransportation* 2023;100288.
- [10] Herbinet O, Bartocci P, Dana AGrinberg. On the use of ammonia as a fuel – A perspective. *Fuel Communications Jun. 2022;11:100064*. <https://doi.org/10.1016/j.fueco.2022.100064>.
- [11] Li T, et al. A comparison between low-and high-pressure injection dual-fuel modes of diesel-pilot-ignition ammonia combustion engines. *J. Ener. Instit.* 2022;102: 362–73.
- [12] Pochet M, Jeanmart H, Contino F. A 22:1 compression ratio ammonia-hydrogen HCCI engine: combustion, load, and emission performances. *Front Mech Eng Jun. 2020;6*. <https://doi.org/10.3389/fmech.2020.00043>.
- [13] M. Pochet, I. Truedsson, F. Foucher, H. Jeanmart, and F. Contino, "Ammonia-hydrogen blends in homogeneous-charge compression-ignition engine," Sep. 2017. doi: 10.4271/2017-24-0087.

- [14] Wang Y, Zhou X, Liu L. Feasibility study of hydrogen jet flame ignition of ammonia fuel in marine low speed engine. *Int J Hydrogen Energy* Jan. 2023;48(1):327–36. <https://doi.org/10.1016/j.ijhydene.2022.09.198>.
- [15] International Maritime Organization, “[https://www.imo.org/en/OurWork/Environment/Pages/Nitrogen-oxides-\(NOx\)-%E2%80%93Regulation-13.aspx](https://www.imo.org/en/OurWork/Environment/Pages/Nitrogen-oxides-(NOx)-%E2%80%93Regulation-13.aspx)”.
- [16] Wartsilla, “<https://www.wartsila.com/media/news/15-11-2023-wartsila-continues-to-set-the-pace-for-marine-decarbonisation-with-launch-of-world-first-4-stroke-engine-based-ammonia-solution-3357985>”.
- [17] MAN Energy Solutions, “<https://www.man-es.com/marine/products/two-stroke-engines/ammonia-engine?592380e5-7b22-42aa-bf83-f8dd18223552%5B%5D=1>”.
- [18] Cha J, et al. An efficient process for sustainable and scalable hydrogen production from green ammonia. *Renew. Sustain. Ener. Rev.* 2021;152:111562.
- [19] Asif M, et al. Recent advances in green hydrogen production, storage and commercial-scale use via catalytic ammonia cracking. *Chemical Engineering Journal* Oct. 2023;473:145381. <https://doi.org/10.1016/j.cej.2023.145381>.
- [20] Mukherjee S, Devaguptapu SV, Sviripa A, Lund CRF, Wu G. Low-temperature ammonia decomposition catalysts for hydrogen generation. *Appl Catal B Jun.* 2018;226:162–81. <https://doi.org/10.1016/j.apcatb.2017.12.039>.
- [21] Rivera-Tinoco R, Schoots K, van der Zwaan B. Learning curves for solid oxide fuel cells. *Energy Convers Manag* May 2012;57:86–96. <https://doi.org/10.1016/J.ENCONMAN.2011.11.018>.
- [22] Whiston MM, Lima Azevedo IM, Litster S, Samaras C, Whitefoot KS, Whitacre JF. Paths to market for stationary solid oxide fuel cells: expert elicitation and a cost of electricity model. *Appl Energy Dec.* 2021;304:117641. <https://doi.org/10.1016/J.APENERGY.2021.117641>.
- [23] Wei M, Smith SJ, Sohn MD. Experience curve development and cost reduction disaggregation for fuel cell markets in Japan and the US. *Appl Energy Apr.* 2017;191:346–57. <https://doi.org/10.1016/j.apenergy.2017.01.056>.
- [24] Scataglini R, Wei M, Mayyas A, Chan SH, Lipman T, Santarelli M. A direct manufacturing cost model for solid-oxide fuel cell stacks. *Fuel Cells Dec.* 2017;17(6):825–42. <https://doi.org/10.1002/fuce.201700012>.
- [25] Whiston MM, Azevedo IML, Litster S, Samaras C, Whitefoot KS, Whitacre JF. Meeting U.S. Solid oxide fuel cell targets. *Joule Sep.* 2019;3(9):2060–5. <https://doi.org/10.1016/j.joule.2019.07.018>.
- [26] California Public Utilities Commission, “<https://sgipsd.org/statistics>”.
- [27] Wu S, Miao B, Chan SH. Feasibility assessment of a container ship applying ammonia cracker-integrated solid oxide fuel cell technology. *Int J Hydrogen Energy* 2022;47(63):27166–76.
- [28] Kim K, Roh G, Kim W, Chun K. A preliminary study on an alternative ship propulsion system fueled by ammonia: environmental and economic assessments. *J Mar Sci Eng* 2020;8(3):183.
- [29] Kanchiralla FM, Brynolf S, Olsson T, Ellis J, Hansson J, Grahn M. How do variations in ship operation impact the techno-economic feasibility and environmental performance of fossil-free fuels? A life cycle study. *Appl Ener. Nov.* 2023;350:121773. <https://doi.org/10.1016/j.apenergy.2023.121773>.
- [30] Di Micco S, Cigolotti V, Mastropasqua L, Brouwer J, Minutillo M. Ammonia-powered ships: concept design and feasibility assessment of powertrain systems for a sustainable approach in maritime industry. *Ener. Convers. Manag.: X Apr.* 2024;22:100539. <https://doi.org/10.1016/j.ecmx.2024.100539>.
- [31] “<https://businessanalytiq.com/procurementanalytics/index/ammonia-price-index/>”.
- [32] Rodrigue J-P. *The Geog. Transport Syst.* 2024.
- [33] Zhang Y, Chang Y, Wang C, Fung JCH, Lau AKH. Life-cycle energy and environmental emissions of cargo ships. *J Ind Ecol* 2022;26(6):2057–68.
- [34] Kjær LL, Pagoropoulos A, Hauschild M, Birkved M, Schmidt JH, McAloon TC. From LCC to LCA using a hybrid input output model – A maritime case study. *Procedia CIRP* 2015;29:474–9. <https://doi.org/10.1016/j.procir.2015.02.004>.
- [35] Comer B, Osipova L. A review on life cycle assessments of maritime systems combined with an analysis of the THETIS-MRV portal quantifying Emissions in the European Maritime Sector. *INT. COUNCIL ON CLEAN TRANSPORT.* 2021. <https://doi.org/10.2760/496363>.
- [36] Lloyd’s Register U. Techno-economic assessment of zero-carbon fuels. *Table B9* 2020:49.
- [37] Taljegard M, Brynolf S, Grahn M, Andersson K, Johnson H. Cost-effective choices of marine fuels in a carbon-constrained world: results from a global energy model. *Environ Sci Technol* 2014;48(21):12986–93.
- [38] G. de Melo Rodriguez and I. Echevarrieta Sazatornil, “Resizing study of main and auxiliary engines of the container vessels and their contribution to the reduction of fuel consumption and GHG,” in *IAMU AGA15*, 2014, pp. 441–452.
- [39] Issa M, Ilinca A, Ibrahim H. A review and economic analysis of different emission reduction techniques for marine diesel engines. *Open J. Marine Sci.* May 2019;09. <https://doi.org/10.4236/ojms.2019.93012>.
- [40] Kiang Yen. Solid oxide fuel cell (SOFC) module pricing. *ENVIRONMENT ENERGY NOTES* 2025.
- [41] Quach T-Q, Giap V-T, Keun Lee D, Pineda Israel T, Young Ahn K. High-efficiency ammonia-fed solid oxide fuel cell systems for distributed power generation. *Appl Energy Oct.* 2022;324:119718. <https://doi.org/10.1016/j.apenergy.2022.119718>.
- [42] Saygin D, et al. Ammonia production from clean hydrogen and the implications for global natural gas demand. *Sustainability Jan.* 2023;15(2):1623. <https://doi.org/10.3390/su15021623>.
- [43] IRENA and AEA. Innovation outlook: renewable Ammonia. Abu Dhabi: Int. Renew. Ener. Agency 2022.
- [44] UNCTAD, “Review of maritime transport 2020,” 2020.
- [45] Hua J, Cheng C-W, Hwang D-S. Total life cycle emissions of post-Panamax containerships powered by conventional fuel or natural gas. *J Air Waste Manage Assoc* 2019;69(2):131–44.