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Optimal ship lifetime fuel and power system selection

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ABSTRACT

Alternative fuels and fuel-flexible ships are often seen as promising solutions for achieving significant greenhouse gas reductions in shipping. We formulate the selection of alternative fuels and corresponding ship power systems as a bi-objective integer optimization problem. We apply our model to a Supramax Dry-bulker and solve it for a lower bound price scenario including a carbon tax. Within this setting, the question whether bio-fuels will be available to shipping has significant effect on the lifetime costs. For the given scenario and case study ship, our model identifies LNG as a robust power system choice today for a broad range of GHG reduction ambitions. For high GHG reduction ambitions, a retrofit to ammonia, produced from renewable electricity, appears to be the most cost-effective option. While these findings are case-specific, the model may be applied to a broad range of cargo ships.

1. Introduction

In April 2018, the International Maritime Organization (IMO, 2018) adopted a strategic plan to align with the Paris Agreement (United Nations, 2015) temperature goals to reduce annual greenhouse gas (GHG) emissions from international shipping. This strategy can be summarized in three points. First, to reduce the carbon intensity of ships through further reductions of the energy efficiency design index (EEDI) for new ships. Second, to reduce CO_2 emissions per transport work by at least 40% by 2030 and pursue efforts for reducing them by 70% by 2050 compared with 2008. Third, to peak international shipping's GHG emissions as soon as possible and to reduce annual GHG emissions by at least 50% by 2050 compared to 2008.

These global preliminary ambitions however are not without debate. Single states or unions may set out additional goals, such as the EU aiming to achieve carbon-neutrality by 2050 (European Commission, 2019; European Community Shipowners' Association). The translation of shipping's global ambition levels into single ship requirements is an ongoing discussion (IMO MEPC, 2021). Consensus on both fleet and ship emission ambitions is dependent not only on technical issues, but further complicated by political debates (Psaraftis and Kontovas, 2020; Psaraftis and Kontovas, 2021). Moreover, there are different pathways conceivable for how shipping's energy demand can be met in the future (Vergara et al., 2012; Smith, 2012; Lindstad and Eskeland, 2016). The uncertainties with respect to both ambitions and energy pathways are exemplified by DNV GL's various scenarios in its Maritime Forecast to 2050 (DNV GL, 2020) or future price range predictions for alternative fuels (Lloyd's Register and UMAS, 2020).

For a ship designer, aiming to develop a competitive ship, there is hence a large uncertainty associated with exogenous and time-

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dependent factors. These factors can be directly linked to the contextual and temporal aspects of ship design, respectively (Gaspar et al., 2012). The exogenous uncertainties need to be handled in addition to the simultaneously increasing structural and behavioral complexities that stem from new, emission-reducing onboard technologies.

Calleya (2014) presents a 'ship impact model' to assess the impact of technical and operational carbon-reducing measures. The model can be applied to a fully developed ship design and represents a leap forward in tackling the behavioral complexities, i.e. the performance assessment of emissions-reducing technologies. Lindstad and Bø (2018) investigate combinations of different engine setups, batteries, alternative fuels, and hull forms to identify EEDI-compliant solutions. The model provides a full evaluation of costs and emissions as functions of vessel operation, abatement option and fuel prices.

Solem et al. (2015), Balland et al. (2013) and Gaspar et al. (2015) present several decision support models for air emission reductions. These models consider the uncertainty and time-dependency of target emission levels, but do not include GHG reduction measures to the extend required by neither IMO nor EU ambitions. In turn, Korberg et al. (2021) investigate a large number of low-emission options, but without explicitly considering retrofits.

Rehn (2018) investigates ways for considering uncertainty in ship design. Generally, this can be done deterministically or stochastically (Erikstad and Rehn, 2015). For ship design, retrofittability has shown to be a promising strategy for mitigating the consequences of uncertainty. This has been shown for both merchant (Buxton and Stephenson, 2001) and naval ships (Andrews, 2001). Choi et al. (2018) find that a modular design can significantly ease system adaptability and retrofittability. However, retrofittability and modularity both come at a cost. Their trade-offs need to be carefully considered (Erikstad, 2019). DNV GL's Maritime Forecast to 2050 (DNV GL, 2020) takes a scenario-based approach to the alternative fuel selection problem. The model's focus is on a global fleet perspective. Similarly, Nair and Acciaro (2018) present a model for optimized fleet composition under economic and environmental constraints. The decisions and recommendations for a specific ship may thus differ. Moreover, only minor retrofits (switch between similar fuels) are considered.

To sum up, studies so far have focused on technical assessment of emission reduction measures (Calleya, 2014; DNV GL, 2019), the timing of air emission abatement options (Solem et al., 2015; Balland et al., 2013; Gaspar et al., 2015; Korberg et al., 2021) or alternative fuels on a fleet perspective (DNV GL, 2020; Vergara et al., 2012; Smith 2012, Nair and Acciaro, 2018). There seems to be a gap when it comes to analyzing a wide range of alternative fuel options from a ship perspective, considering contextual and temporal complexities in combination with changeability. Even though alternative fuels only represent a subset of the emission reduction options for shipping, they are estimated to have high abatement potential (up to 85% CO_2 reduction potential according to Bouman et al., 2017) and thus are of significant interest to ship designers today. This interest, particularly in power system retrofits, is backed by industry examples: The Spirit of British Columbia's retrofit (MarineLink, 2018) from very low sulphur fuel poil (VLSFO) to liquified natural gas (LNG) or the conversion of the Stena Germanica from heavy fuel oil (HFO) to Methanol (Naval Architect, 2015). Further, Maersk (2021) has recently announced to build dual-fuel ships running on both VLSFO and Methanol and ColorLine investigates conversions towards ammonia (Ammonia Energy Association, 2020).

The motivation for this study is to contribute to an individual ship's lifetime perspective on alternative fuel selection, taking into account potential retrofits. We see a gap when it comes to identifying such cost-efficient and robust solutions in a transparent manner. By assuming a certain lifetime that involves a fundamental change of the favored primary energy source from fossil-based to renewable electricity-based, we aim to answer the questions:

1. How would a transition from cheap fossil to cheap electric energy influence the optimal ship power system choice?
2. How do our here-and-now decision, i.e. what power system to invest in, change when considering a large variety of power systems, including retrofits, fuel options and different emission reduction ambitions?
3. Are retrofits included in the optimal solution?

We outline the problem in more detail in Section 2. Section 3 presents a mathematical bi-objective optimization model that shall provide decision support to the problem at hand. Section 4 describes the application and use of the same model to a case study. We conclude and highlight our findings in Section 5.

2. Problem description

Selecting among alternative fuels under uncertain ambitions and cost scenarios is not an easy endeavor. Not only do the exogenous uncertainties obscure a straight-forward solution. Even under known, but changing exogenous conditions, the decision problem is complex due to the ship's long lifetime and hence exposure to potentially very different exogenous conditions. The problem addressed in this paper is thus: "Given a known fuel price scenario, what are the best power system and fuel choices throughout the ship's lifetime with respect to costs and GHG emissions?". We refer to this problem as 'ship fuel and power system selection under certainty'. By certainty, we mean an assumed, known exogenous future fuel price scenario as well as carbon tax development. Approaching this as a compromise selection problem between emissions and costs over time, uncertain long-term ambition levels as seen by an individual ship can be accounted for when selecting compromises.

Our goal is to provide decision support for the selection among a wide range of alternative fuel options and power system options in the early ship design phase, while considering potential switches between power system options (retrofits). These options all come with different emissions and different costs, which change over time. A ship power system option here denotes all required onboard systems for the combustion of VLSFO or LNG for example. That is, machinery, tanks, piping and processing equipment where necessary shall be included in our definition of power system option. Compatibilities between fuel and power system options must be considered as well as their impact on the ship's payload carrying capacity. For a given power system option, switching between compatible fuels, e.g. from fossil LNG to electric LNG (e-LNG), represents an action with no switch cost. Retrofits, e.g. from VLSFO to Methanol, can be accounted for as switching between power system options, which comes at a certain cost. Note that we here refer to 'option' as the choice of fuel and power system at a discrete point in time. This definition is not far away from the term 'recourse options' (King and Wallace, 2012), apart from that we assume a single, deterministic future instead of a stochastic one. The potentially reduced cargo-carrying capacity compared to a baseline vessel, due to additional weight of lower density fuels and power systems, can lead to a loss in income. This potential loss needs to be taken into account, e.g. by means of a lost opportunity cost.

Our goal is to provide decision support for the initial ship investment as well as the choice of fuel, considering potential retrofits in response to changing exogenous conditions. Knowing that a specific retrofit would be worthwhile, a ship designer could design a vessel such that it is prepared for the later retrofit. For our problem, we assume a ship without any further retrofit preparations such as modular machinery or preparations for elongation. Such measures could reduce retrofit costs significantly. In order to evaluate, select and implement such technical options however, it is necessary to know what to prepare for in the first place, which shall be the focus of this study.

3. Model formulation

We start our model formulation by defining the notation and then describe our mathematical model.

Sets

Set	Description	Modeling comment
$\mathbb{T}$	set of discrete ***time periods***, indexed by t	discretization into 10 year periods for example, as for this study
$\mathbb{F}$	set of ***fuel options***, indexed by f	refers to main chemical composition and physical state
$\mathbb{S}$	set of pre-generated ***ship power system options*** for energy storage and power conversion, indexed by s	refers to a ship with an energy storage of a certain type and size, and a power converter of certain type and size

Parameters

Parameter	Description	Modeling comment
C^N_s	***newbuild cost*** of a ship with power system option s	
$C^R_{s'st}$	***retrofit cost*** from option s' to option s in time period t	
C^F_{ft}	***cost of fuel*** f in time period t	
C^{LO}_{st}	***lost opportunity cost*** of a ship with power system s per time period t	
B	***energy consumption*** per time period	assuming the fuel conversion efficiencies do not change over time, equidistant time periods
E^{WTT}_f	***well-to-tank emissions*** of fuel f per time unit	
E^{TTW}_f	***tank-to-wake emissions*** of fuel f per time unit	assuming tank-to-wake emissions do not change over time.
K_{fs}	1 if fuel f and power system s are ***compatible***, 0 otherwise	

Decision variables

x_{ft}	1 if ***fuel*** f is chosen at time t, 0 otherwise
y_{st}	1 if ***power system option*** s is chosen at time t, 0 otherwise

Auxiliary variables (implicit, required for linearization)

$r_{s'st}$	1 if retrofit is to be made from power system option s' to power system option s after period t, 0 otherwise

Objectives

We define our first objective of minimizing the total cost of ownership (TCO) as:

$$minTCO = \sum_{s\in\mathbb{S}}\left[\underbrace{C^N_s\cdot y_{s0}}_{building\ cost} + \sum_{t\in\mathbb{T}}\left(\underbrace{C^{LO}_{st}\cdot y_{st}}_{lost\ \ opportunity\ \ costs} + \sum_{f\in\mathbb{F}}\underbrace{B\cdot C^F_{ft}\cdot x_{ft}}_{fuel\ cost} + \sum_{s'\in\mathbb{S}}\underbrace{C^R_{s'st}\cdot r_{s'st}}_{retrofit\ cost}\right)\right] \tag{1}$$

A carbon tax could be included either explicitly in the cost function or be included in the fuel prices. We have chosen the latter for simplicity. The retrofit cost is generally dependent on the power system choice between to two consecutive periods. The purpose of the model identifying differences between solutions. Hence, we have not included pure operational expenditures (OPEX), such as manning, that would apply to all solutions. Within our model, we apply a linear formulation with help of the auxiliary variable r_{ist}

which is constrained by constraints (6)–(8).

Our second objective to be minimized is the global warming potential (GWP) accumulated throughout the entire ship lifetime:

$$minGWP = \sum_{t\in\mathbb{T}}\sum_{f\in\mathbb{F}} Bx_{ft}\left(E_f^{WTT} + E_f^{TTW}\right) \tag{2}$$

The energy consumption per time period can be estimated similar to Ji and El-Halwagi (2020).

subject to:

Constraints (3) and (4) ensure that precisely one fuel and one ship power system option are selected at any time:

$$\sum_{f\in\mathbb{F}} x_{ft} = 1 \quad \forall t \in \mathbb{T} \tag{3}$$

$$\sum_{s\in\mathbb{S}} y_{st} = 1 \quad \forall t \in \mathbb{T} \tag{4}$$

Constraints (5) make sure that fuel f and power system s can only be selected if they are compatible with each other:

$$x_{ft} + y_{st} \leq 1 + K_{fs} \quad \forall t \in \mathbb{T},\ f \in \mathbb{F},\ s \in \mathbb{S} \tag{5}$$

Switching from a power system s' to another power system s in consecutive periods implies a retrofit. Our auxiliary retrofit variable r_{ist} are hence constrained by constraints (6)-(8).

$$y_{s'(t-1)} + y_{st} - 1 \leq r_{s'st} \quad \forall s', s \in \mathbb{S},\ t \in \mathbb{T}\backslash\{0\} \tag{6}$$

$$y_{s'(t-1)} + y_{st} \geq 2r_{s'st} \quad \forall s', s \in \mathbb{S},\ t \in \mathbb{T}\backslash\{0\} \tag{7}$$

$$r_{s'st} = 0 \quad \forall s', s \in \mathbb{S},\ t = 0 \tag{8}$$

Constraints (9) and (10) ensure that our decision variables are binary variables.

$$x_{ft} \in \{0, 1\} \quad \forall f \in \mathbb{F},\ t \in \mathbb{T} \tag{9}$$

$$y_{st} \in \{0, 1\} \quad \forall s \in \mathbb{S},\ t \in \mathbb{T} \tag{10}$$

Additional constraints for allowed emissions, e.g. an energy efficiency existing ship index (EEXI), could be added to the problem. For this paper, we have deliberately not included such constraints for the sake of clarity and transparency of the model and its results.

The resulting model is a bi-objective binary programming model, which allows using a commercial solver for integer programming problems, such as Gurobi. In order to obtain a Pareto set of solutions, i.e. non-dominated solutions that represent a compromise between the two objectives, constraint (11) applies the epsilon-constraint method to the GWP objective:

$$GWP \leq \varepsilon$$

The parameter ε is iteratively increased to the GWP of the cheapest solution found in the last iteration.

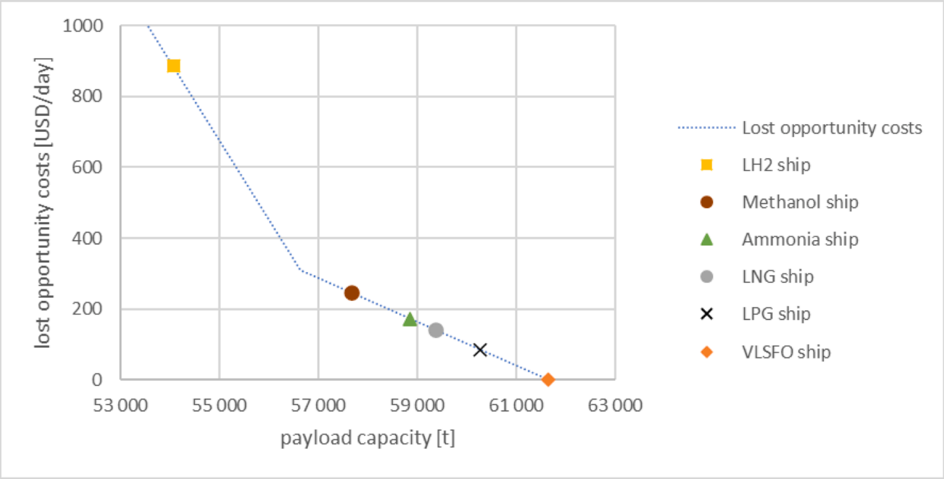

Fig. 1. Daily lost opportunity costs..
Source: own calculation

4. Case study

To test our model proposed in Section 3, we use as a case study a generic dry bulk Supramax vessel for which the ship power system and fuel selection is to be determined throughout the lifetime. A traditional Supramax vessel is designed for maximum cargo-carrying capacity within a maximum length of 200 m, a beam of 32.3 m (the old Panama Canal locks) and a draught of around 13.5 m. This generally yields a cargo capacity between 58,000–65,000 tons. The dry bulk cargo is typically transported in five cargo holds with four slewing cranes for independence of port loading facilities. Supramax bulk carriers constitute approximately 24% of the global dry bulk fleet (Bengtsson, 2018) and perform about 10% percent of the global transport work, measured in ton-miles. The following table shows the data of an exemplary vessel in the Supramax segment, which we use as our reference ship.

We start with a VLSFO ship as a reference and derive alternative ship power system options by replacing the diesel tanks by LNG, liquid hydrogen (LH2), as well as ammonia (NH3), methanol and liquified petrol gas (LPG). We account for the influence of additional fuel tank weight by means of relative factors derived from (Mestemaker, et al., 2020). That is, potential weight in excess of the baseline VLSFO tank configuration is accounted for as a loss of payload capacity (PLC). The loss of payload capacity is consequently converted into a lost opportunity cost C_{st}^{LO} by means of formula (12). Fig. 1 depicts the function values for each of the ship power options.

$$C_{st}^{LO} = \begin{cases} 10y \cdot 300d/y \cdot 13,000USD/d \cdot \dfrac{PLC_s - PLC_{VLSFO} \cdot 25\%}{5000t \cdot 25\% + PLC_{VLSFO} \cdot 90\%}, & PLC_s - PLC_{VLSFO} < 5000t \\ 10y \cdot 300d/y \cdot 13,000USD/d \cdot \dfrac{5000t \cdot 25\% + (PLC_s - PLC_{VLSFO} - 5000t) \cdot 90\%}{5000t \cdot 25\% + PLC_{VLSFO} \cdot 90\%}, & PLC_s - PLC_{VLSFO} \geq 5000t \end{cases} \tag{12}$$

The reasoning behind the lost opportunity cost is as follows: we assume an average utilization of 90% for the first 58,000 dwt and 25% utilization for the last 5,000 dwt. The charter rate of 13,000 USD/day is split proportionally and we assume a piecewise linear contribution to the charter rate. Any loss in charter rate due to additional tank weight contributes to the lost opportunity cost. For a fair comparison we keep speed and endurance constant for all options. In applying this rationale we neglect the influence of lower volumetric density of alternative fuel options. Bulk carriers are traditionally weight-driven ships and hence the designer may have a certain freedom when integrating larger volumes into the arrangement.

The key differences between the ship power system options s and their respective compatibilities K_{fs} to fuels f are listed in Table 2. As for the energy consumption B per time period, we assume the vessel is sailing at 60% of its maximum continuous rating power for 180 days annually.

Compressed hydrogen may be interesting to consider both from a power system as well as a fuel perspective. Compressing hydrogen instead of liquifying may offer less efficiency losses and hence cheaper production costs. Due to the high storage system costs (approx. 170 mUSD according to Rivard et al., 2019) for the given range of the vessel, we have discarded that option though as it would always be an inferior compromise relative to liquid hydrogen. Our set $\mathbb{F}$ of fuel options f comprises the fuels shown in Table 3 with their associated costs per time period t as well as well-to-tank and tank-to-wake emissions. We apply a resolution of 10 years for discretizing the lifetime periods t. For a detailed discussion on fuel and power system options beyond cost-efficiency, we refer to DNV GL (2019) and Mestemaker et al. (2020).

The well-to-tank and tank-to-wake emission factors are based on Lloyd's Register and UMAS (2020). Fuel prices for the entire lifetime are derived from the same report's lower bound price scenario and include a linearly increasing carbon tax from $0\$/tCO_2$ in 2020 up to $288\$/tCO_2$ in 2050. The last row in Table 3 indicates the resulting discretized tax values for each period. Both emissions and prices take into account upfront energy losses, e.g. when converting hydrogen to ammonia, within the fuel production chain (Lloyd's Register and UMAS, 2020). Note that prices for e-fuels are based on lower bound estimates for completely renewable electricity. Hydrogen and ammonia from natural gas are assumed to be produced with carbon capture and storage. Fig. 2 plots the development of fuel prices over time. For each of the three fuel groups (fossil, bio and electric), the proxy fuel, i.e. the fuel from which the remaining prices of the group are derived, is plotted with a bold arc.

Retrofits can be undertaken after each time period t at a cost $C^{R}_{s'st}$. The total retrofit costs are shown in Table 4. These costs are based on machinery, tank and piping modifications as well as shipyard labor and lost income during retrofitting. The individual costs per vessel and category are depicted in Fig. 3 (retrofits between conventional power systems) and Fig. 4 (retrofits to ammonia and hydrogen): Each ray indicates a cost category (e.g. machinery), for which the retrofit costs for a specific retrofit (e.g. VLSFO to LNG) are plotted. Cost estimates for individual systems within the shown categories can be retrieved from compiled databases such as MARIN (2021).

Table 1
Data for reference Supramax bulker.

Category	Parameter	Unit	Value
ship	deadweight	dwt	63,000
	range	nm	15,000
	brake power	kW	7,500
	specific fuel consumption (diesel)	kg/kWh	0.17
	design speed	kn	14
	fuel weight	t	1366
operation	average engine power	%	60
	days at sea	days/year	180

Table 2
Ship power system options s and respective fuel consumption.

		Ship power system option, s					
	Parameter	1 VLSFO ship	2 LNG ship	3 LH2 ship	5 Ammonia ship	6 LPG ship	7 Methanol ship
	factor of tank weight (relative to HFO)	1.0	2.7	6.5	3.0	2.0	3.9
	tank weight [t]	1 366	3 629	8 932	4 147	2 732	5 328
C^N_s	newbuilding price [mUSD]	30	37	45	40	35	35
C^{LO}_{st}	lost opportunity costs per 10 years [mUSD]	0	0.4	2.7	0.5	0.3	0.7
K_{fs}	compatible fuels	VLSFO, Bio-diesel, E-diesel	Bio-LNG, E-LNG, fossil LNG	liquid E-hydrogen, liquid NG-hydrogen	E-ammonia, NG-ammonia	fossil LPG	Bio-methanol wood, bio-methanol waste stream, E-methanol

Table 3
Set of fuel options $\mathbb{S}$ with associated costs C^F_{ft}, well-to-tank emissions E^{WTT}_{ft} and tank-to-wake emissions E^{TTW}_f. Based on Lloyd's Register and UMAS (2020).

			2020–2030 C^F_{ft} $[USD/MWh]$	**2030–2040** C^F_{ft} $[USD/MWh]$	**2040–2050** C^F_{ft} $[USD/MWh]$	E^{WTT}_f $[kgCO2/MWh]$	E^{TTW}_f $[kgCO2/MWh]$
f	1	VLSFO	**49.1**	**83.1**	**110.7**	25.2	270.0
	2	Bio-diesel	**91.7**	**117.8**	**143.3**	−136.8	313.2
	3	Bio-methanol wood	**87.9**	**97.8**	**109.5**	−216.0	244.8
	4	Bio-methanol waste stream	**77.6**	**95.7**	**113.3**	−144.0	255.6
	5	Bio-LNG	**76.9**	**88.7**	**97.1**	−158.4	172.8
	6	E-diesel	**439.2**	**383.4**	**327.6**	−262.8	262.8
	7	E-methanol	**282.6**	**244.8**	**207.0**	−262.8	262.8
	8	E-LNG	**232.2**	**199.8**	**167.4**	−180.0	180.0
	9	E-ammonia	**183.6**	**154.8**	**124.2**	0.0	0.0
	10	liquid E-hydrogen	**172.8**	**144.0**	**115.2**	0.0	0.0
	11	NG-ammonia	**100.3**	**99.0**	**99.3**	61.2	0.0
	12	liquid NG-hydrogen	**89.7**	**88.8**	**87.6**	64.8	0.0
	13	fossil LNG	**32.5**	**52.6**	**72.0**	27.0	180.0
	14	fossil LPG	**40.1**	**66.2**	**91.3**	28.8	240.1
		Carbon tax [USD/tCO$_2$]	**50.5**	**147.5**	**241.0**		

For this case study, we assume an interest rate equal to the discount rate. This simplification enables us to express all time-dependent costs in present cost levels and thus improves transparency by simplifying the problem.

We implement and finally solve our bi-objective linear integer optimization solve our linear integer optimization model in Gurobi 9.1.

4.1. Results

Using the Gurobi solver, the solution time of the mathematical model is below one second on an ordinary PC. By iteratively increasing ε, the solver can identify solutions on the Pareto front, as shown in Fig. 5. The accumulated costs and emissions are computed for a total lifetime of 30 years, split into three discrete time periods of 10 years each as described in Section 3. Based on Table 1, the annual energy consumption of our vessel is 39,200 MWh, corresponding to about 3370 million tonnes of oil equivalent (MTOE). For each solution we indicate the initial power system choice y_{s0}, marked with a number, and the fuel choice at each of the following three time periods, indicated by lowercase letters.

For our given scenario, we see LNG as the most dominant solution on the Pareto front with a retrofit to ammonia at the lower end of lifetime emissions. The most cost-efficient solution for achieving zero well-to-wake emissions is liquid hydrogen without any retrofit.

Many of the indicated Pareto-optimal solutions rely on bio-fuels at one or more periods. In order to show the difference between electro- and bio-fuels, as well as highlighting the cost of making wrong decisions, we compute and plot both objective functions for all permissible combinations. This is done by means of a Python implementation of our mathematical model without any optimization routines. Fig. 6 depicts the solution space for our scenario, excluding solutions over 300 mUSD TCO. The orange and green dots were generated by computing all permissible combinations of decision variables (power system and fuel at each point in time). The dots indicate their respective objective function values, regardless of whether the combination leads to a Pareto-optimal or inferior solution. Green dots indicate solutions which use biofuels at one or more time periods. Orange dots indicate combinations without biofuels at all time periods. The Pareto-fronts are shown for each of the subsets (green for bio- and orange for non-bio) separately. For comparison,

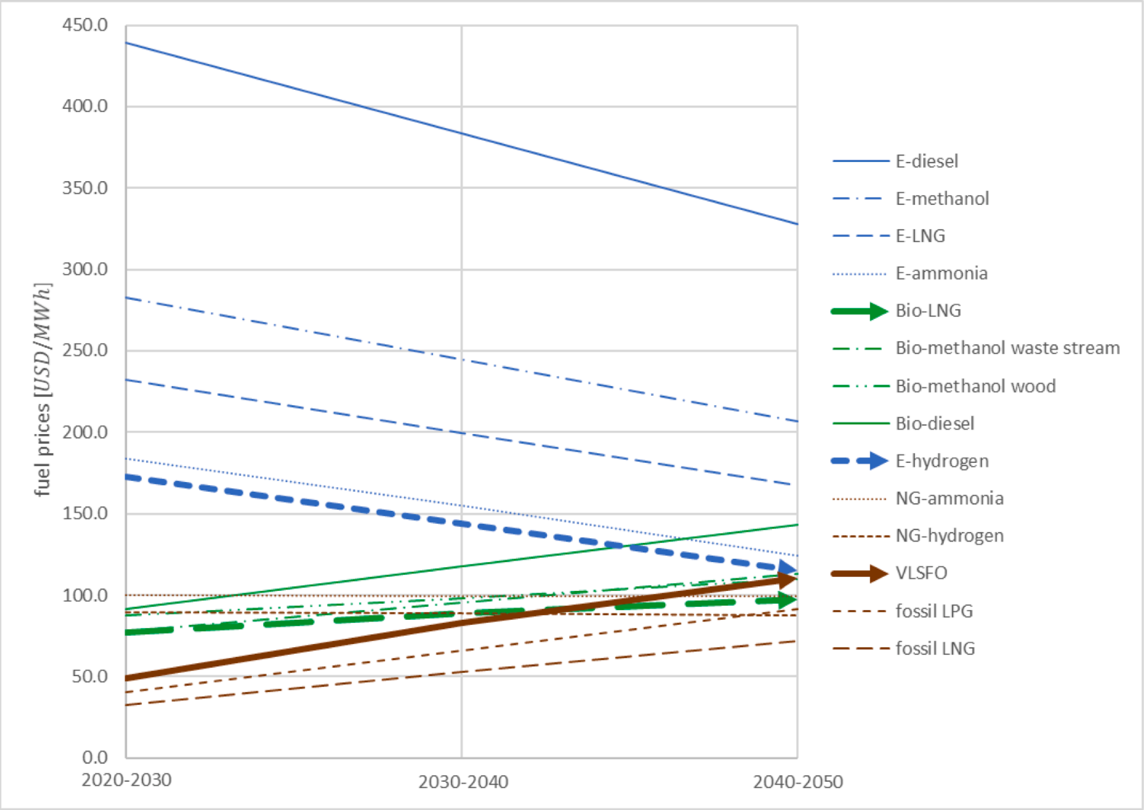

Fig. 2. Fuel prices over time periods. Fuels grouped as fossil, bio- and e-fuels. Fuels are sorted ascendingly according to prices within each group. Based on Lloyd's Register and UMAS (2020).

Table 4
Retrofit costs $C^R_{s'st}$ in [mUSD]. Green: low cost, red: high cost.

from/to	VLSFO ship	LNG ship	LPG ship	Methanol ship	Ammonia ship	LH2 ship
VLSFO ship	0.0	9.3	9.3	6.0	15.0	24.6
LNG ship	3.5	0.0	2.5	6.7	11.3	22.6
LPG ship	4.0	7.8	0.0	6.7	8.2	22.6
Methanol ship	1.0	9.3	9.3	0.0	15.0	24.6
Ammonia ship					0.0	22.6
LH2 ship					6.7	0.0

Source: various, inhouse calculations.

we note that the TCO for the VLSFO baseline solution without the assumed carbon tax would be about 40% lower.

On the first glance, a large scatter both in terms of emissions and costs can be observed. The cost – environmentally and economically – associated with wrong decisions is hence significant. Within the lower bound carbon tax scenario, bio-fuels yield lower costs for the same emissions level. In our case, bio-fuels can approximately half the cost increase for a given emission level.

The most cost-effective solution (LH2) that yields zero well-to-wake emissions is about 120 mUSD more expensive than the cheapest solution (approx. 120% of the cheapest solution's TCO, in our case using fossil LNG throughout the entire lifetime). However, we could more than half the lifetime emissions when accepting a moderate increase of 50% in TCO. Note that we have not included fixed costs for e.g. crewing in our comparison. The relative cost increase may thus be lower than the one presented here.

We now take a closer at the solutions contained the Pareto set, indicating the choice of power system with the same number as used in Figs. 5–7. We see that the bio-based solutions all involve LNG (1), with a switch to ammonia for the lowest-emission solutions. The Pareto-optimal set for non-bio solutions contains LNG (1 & 2), LPG (4), LH2 (3) and ammonia (2 & 5) as fuels. The more costly low-emission solutions are ships designed directly for LH2 (3) or ammonia (5). Solutions with a TCO below 152 mUSD involve a retrofit from LNG or LPG to ammonia (2 & 4). Within the given scenario, methanol does not appear to be an optimal cost-emission compromise solution.

The following figure illustrates schematically the pathways of Pareto-optimal solutions.

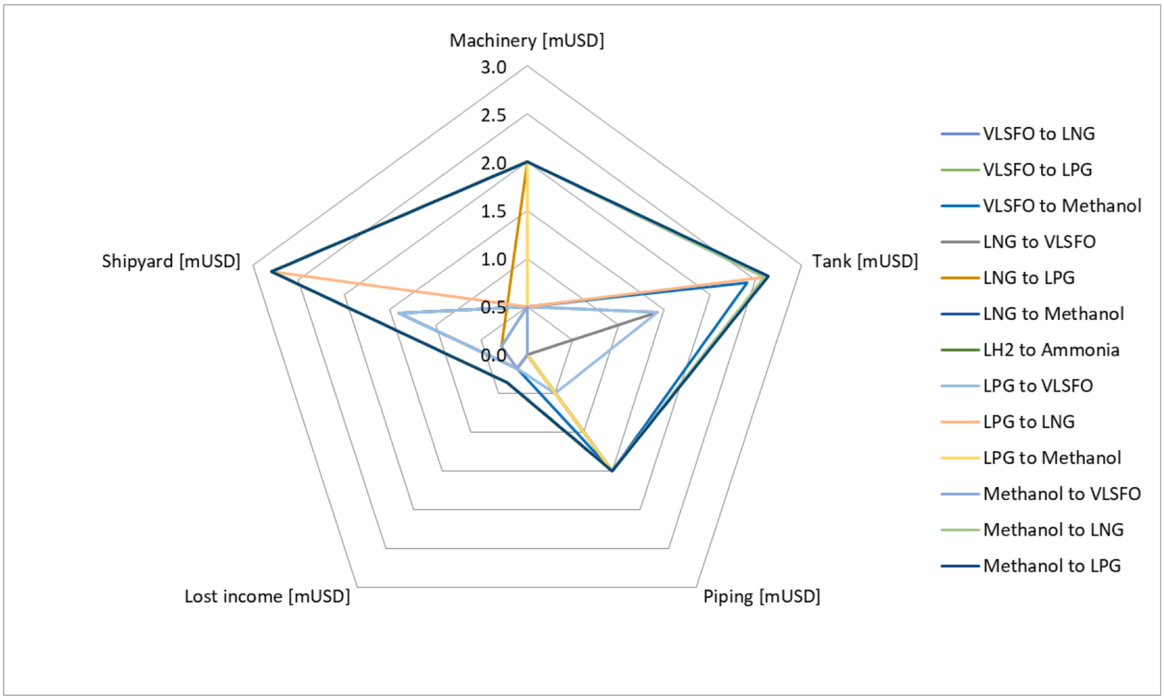

Fig. 3. Retrofit costs per vessel and category. Conventional power systems.
Source: various, inhouse calculations.

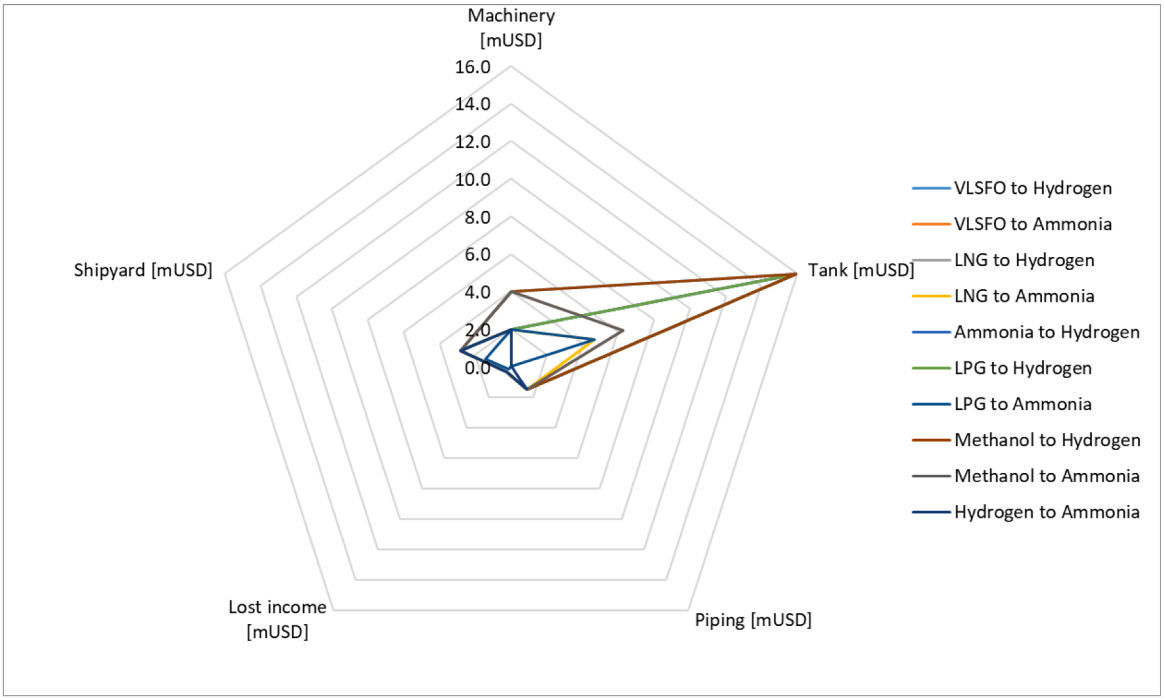

Fig. 4. Retrofit costs per vessel and category. Ammonia and hydrogen.
Source: various, inhouse calculations.

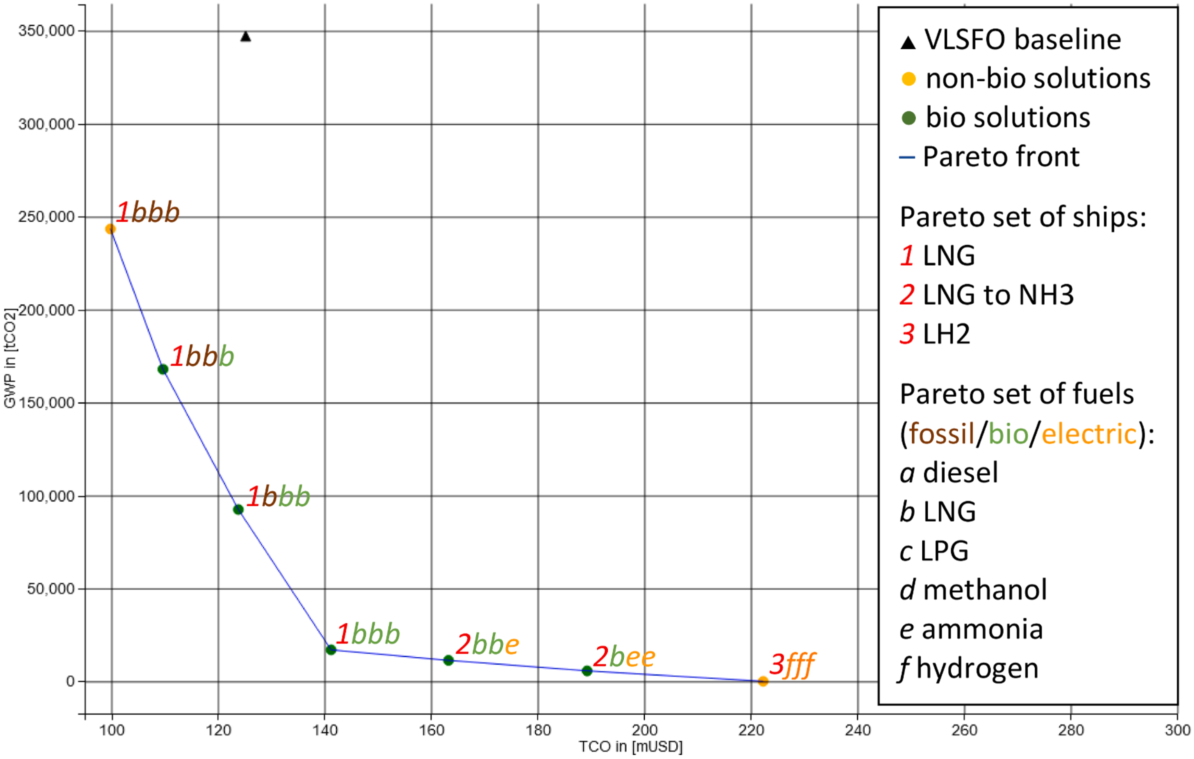

Fig. 5. Lifetime cost and emissions for Pareto-optimal solutions.
Source: own calculations.

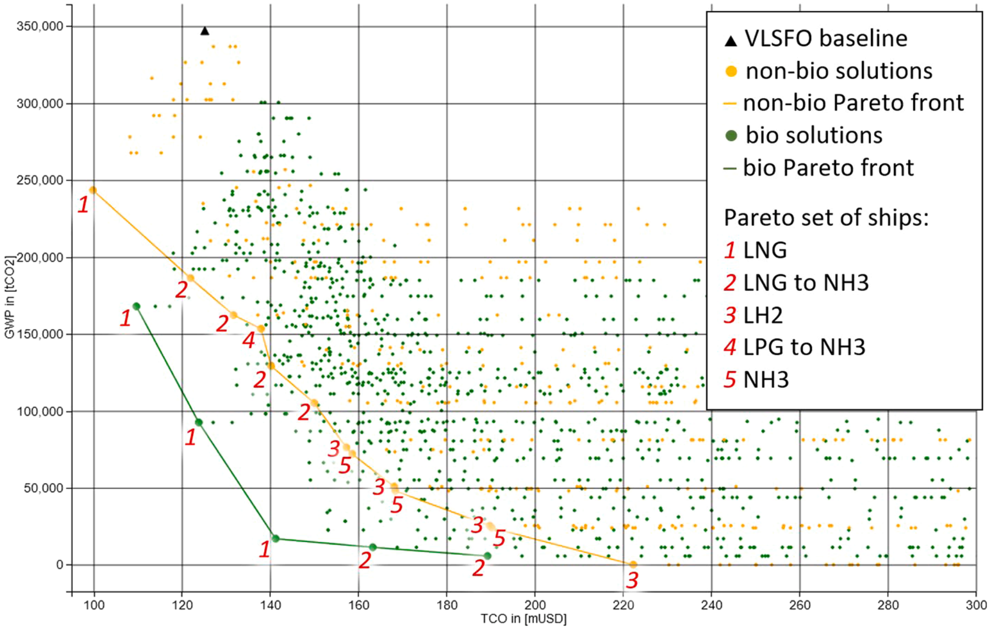

Fig. 6. Lifetime costs and emissions for the entire solution space.
Source: own calculations.

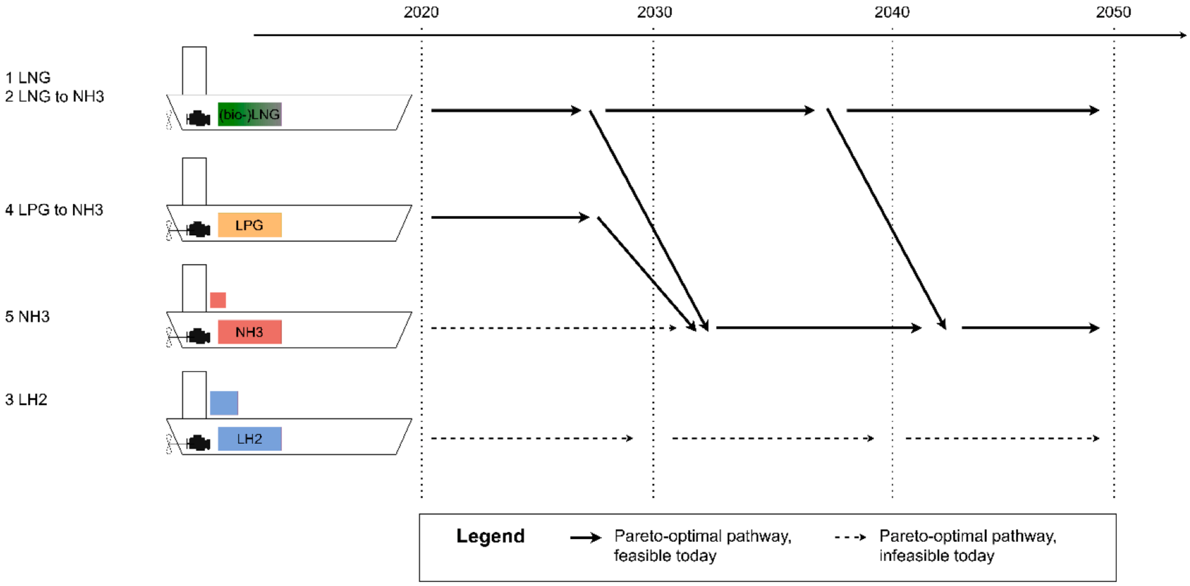

Fig. 7. Schematic timeline illustration of Pareto-optimal solutions.

4.2. *Flexibility-bound solution*

Relaxing our retrofit cost parameter $C^R_{s's t}$ to zero will yield a flexibility-bound solution, i.e. a solution driven by flexibility opportunities rather than flexibility costs. We plot the flexibility-bound Pareto front compared to the initial one in Fig. 8.

The optimal set of solutions to our problem, under the given scenario, is affected by lower retrofit costs. Zero retrofit costs yield a ship power system that is directly responsive to the exogenous scenario. The choice of optimal, alternative low-emission fuels is hence

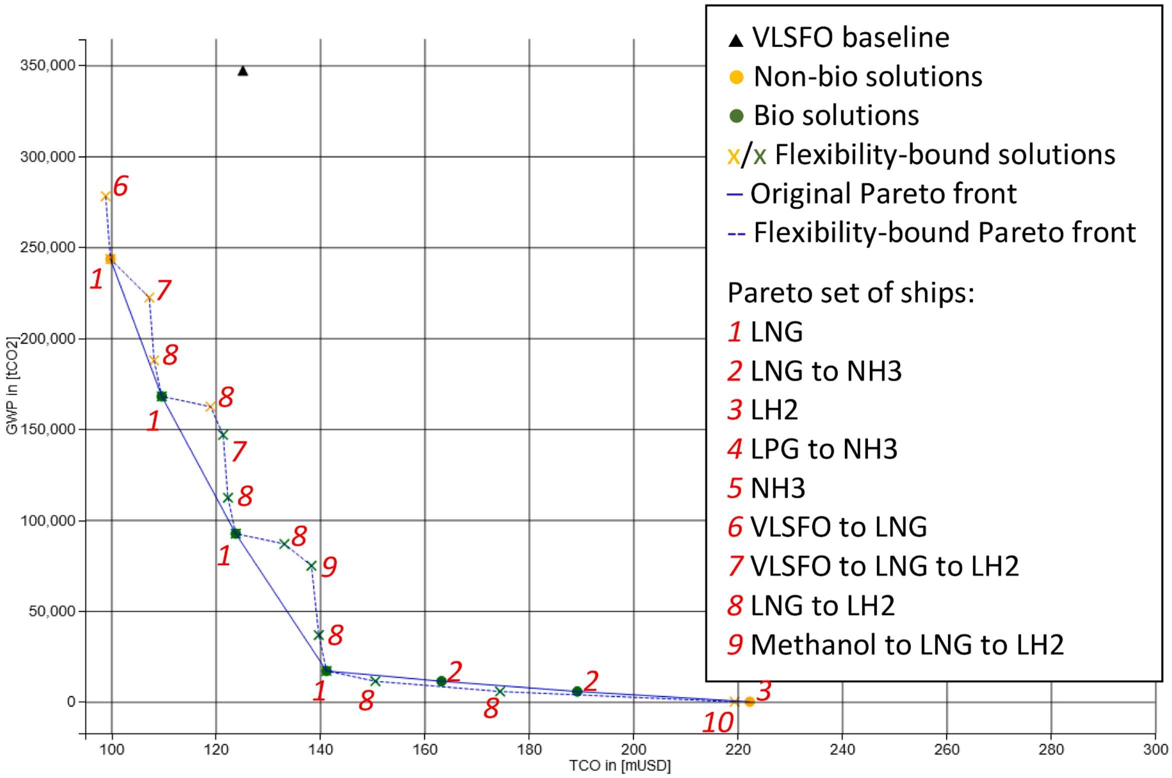

Fig. 8. Pareto front for initial and flexibility-bound problem.

affected by the legacy aspects of a ship. Moreover, we see that two solutions (7 and 9) involve two retrofits along the lifetime. These solutions are a by-product of removing the retrofit costs. The solutions may be less realistic themselves but exemplify that adaptable systems can be beneficial. Solution (6) appears to be slightly cheaper than LNG (1), not the least because of the cheaper building cost of the VLSFO baseline vessel. LNG ships (1) running on bio-LNG have not been superseded; these did not involve any retrofit before. Looking at the more costly, low-emission spectrum of the Pareto front, we see that retrofits from LNG to LH2 are now Pareto-optimal (8), instead of LNG to ammonia (2). The reason for this may be sought in the initially high retrofit costs for LH2 (22.6 mUSD). The high costs to a large extend are due to the expensive tank system. Except for a double retrofit solution (9), methanol does not show to be an optimal cost-emission compromise for the flexibility-bound problem either.

The above results obtained from our optimization model can now help us answering our initial questions:

1. *How would a transition from cheap fossil to cheap electric energy influence the optimal ship power system choice?*

The optimal power system choice would follow the change in primary energy sources from fossil to electro-fuels. Ship legacy aspects, i.e. retrofit costs, affect the optimal choice of power system and thereby choice of fuel.

2. How does our here-and-now decision, i.e. the newbuild’s power system choice, change when considering a large variety of power systems, including retrofits, fuel options and different emission reduction ambitions?

If we assume VLSFO as today’s preference, our here-and-now decision would change. LNG, with potential retrofits to ammonia or hydrogen, shows to be a rather robust solution for a broad range of emission ambitions.

3. Are retrofits included in the optimal solution?

The answer to this question depends on the availability of bio-fuels: In case bio-fuels were available, no retrofit would be required. In case biofuels were not available and hydrogen- as well as ammonia-powered ships are deemed infeasible today, retrofits would be required for reaching the low end of the emission ambitions.

5. Conclusion and further work

Our chosen deterministic scenario is based on lower bound prices for all fuels combined with a carbon tax. Within this scenario, bio-fuels appear to be more cost-effective than electro-fuels for reducing emissions. Whether and in which quantities bio-fuels should be available to shipping thus seems to be a relevant discussion.

Our here-and-now decision, i.e. what ship to invest in, is affected by the desired emission level as well. Assuming that, from a practical standpoint, ammonia- and hydrogen-powered ships cannot be operated as of tomorrow, the more important question would be when to retrofit from LNG to ammonia rather than if. Retrofits to hydrogen would require a reduction in storage system costs to become attractive. While ammonia also seems to be the most favored solution by Lloyd’s Register and UMAS (2020), our proposed model provides additional insight by explicitly considering retrofits and tracing a ship along its lifetime. Although a Supramax bulk carrier may be seen as a representative type of cargo ship, the conclusions drawn from this model are ship- and scenario-specific. More extensive experiments are hence required before generalizing these findings to a broader range of ships.

Within the given scenario our model can provide valuable decision support by considering the ship power system pathway (legacy) of a ship. The model requires only a few generic input parameters and can therefore be applied to other vessel segments too. Thus, the model contributes to transparently identifying robust solutions with respect to unknown ship emission ambitions within one or potentially several individual scenarios.

There is considerable uncertainty with respect to the exogenous factors such as fuel prices and retrofit costs. This could be accounted for by means of a stochastic model (King and Wallace, 2012). The relatively low computational effort for solving our deterministic model should allow for such extensions.

Balland et al. (2015), Andersson et al. (2020) and Mestemaker et al. (2020) show that other factors, such as safety or technical complexity, are important to consider in real-world decision making. From a practical standpoint, these only need to be considered if they would change the solution to our problem. While LNG could be seen as reliable today, experience is yet to be built up for ammonia and hydrogen as marine fuels. Approaching the problem from stochastic standpoint could help answering whether safety and complexity aspects need to be factored in at the earliest decision point.

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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