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Life-cycle cost analysis of an innovative marine dual-fuel engine under uncertainties

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ABSTRACT

As innovative technologies are being deployed to accelerate shipping decarbonization in response to air emission regulations, there is considerable concern about the cost effectiveness of such technologies from a life-cycle perspective. This study conducts a life-cycle cost analysis (LCCA) on an innovative marine dual-fuel engine under uncertainties, comparing the total life-cycle cost performance of such an engine with that of a conventional diesel engine. By proposing several economic Key Performance Indicators (KPIs) such as the Net Present Cost (NPC), the Net Saving (NS) and the Saving-to-Investment Ratio (SIR), the findings indicate that the dual-fuel engine is more cost-effective than the diesel engine under a given fuel price scenario. The uncertainties are meticulously treated by using scenario sensitivity analyses and a Monte Carlo simulation. The scenario sensitivity analyses reveal that the cost effectiveness of the dual-fuel engine is sensitive to the high gas price scenarios. It is uncovered from the Monte Carlo simulation that there is an adequate degree of confidence when opting for the dual-fuel engine. Furthermore, fuel prices are found to be the most influential cost driver. Different foreseeable carbon pricing scenarios are also simulated to show that the dual-fuel engine is still the most favorable option. Regardless of fuel prices and carbon pricing scenarios, the dual-fuel engine provides a considerable environmental benefit with a CO_2 emission reduction potential of 33%. The findings of this study are of interest within the field of shipping investment appraisals and relevant to decision-makers (i.e. ship-owners and investors).

1. Introduction

1.1. Background

International shipping has been in the limelight recently, following the daunting challenge of decarbonization. The international shipping industry carries 80% of global trade by volume (UNCTAD, 2021). During this process, ships emit approximately 1 billion metric tons of carbon dioxide (CO_2) each year, i.e. equivalent to Japan's annual CO_2 emissions (Ritchie and Roser, 2020). During the period from 2012 to 2018, the total GHG emissions from shipping rose from 977 million tonnes to 1,076 million tonnes. This is an increase by 9.6%. In the same period, there was also an increase (from 2.76% to 2.89%) in the share of shipping emissions in global anthropogenic (man-made) emissions. As trade demand grows, so too will CO_2 emissions from shipping. It is envisaged that these emissions will represent 90% to 130% of 2008 emissions by 2050 under the business-as-usual scenario (IMO, 2020).

International shipping is not directly included in the Paris Climate Change Agreement, with responsibility for emissions reductions lying on the International Maritime Organization (IMO) (Bullock et al., 2022). However, the IMO has made a commitment to the Paris Agreement by adopting an Initial Strategy with a target to halve the total annual GHG emissions from international shipping by 2050, compared with 2008 levels. It also aims at lowering the carbon intensity of international shipping by at least 40% by 2030 and pursuing efforts towards 70% by 2050, compared with 2008 levels (IMO, 2018).

The Initial Strategy comprises a variety of measures that can be listed in short-, medium- and long-term visions: (i) design measures, (ii) operational measures, (iii) market-based measures (MBMs), and (iv) the use of low or zero-carbon fuels. The Energy Efficiency Design Index (EEDI) is a design measure which is mandatory for new-built ships while the Ship Energy Efficiency Management Plan (SEEMP) is an operational measure applied to all ships. The EEDI and SEEMP have been enforced since 2011 under Annex VI Chapter 4 of the International

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Nomenclature

Abbreviations

APS	Announced Pledges Scenario
CBS	Cost Breakdown Structure
CERs	Cost Estimation Relationships
CII	Carbon Intensity Indicator
CO_2	Carbon Dioxide
DWT	Deadweight Ton
EBS	Engine Breakdown Structure
ECAs	Emission Control Areas
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
ETS	Emissions Trading System
EU	European Union
GHG	Greenhouse Gas
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
ISO	International Organization for Standardization
KPIs	Key Performance Indicators
LCA	Life-cycle Assessment
LCC	Life-cycle Costing
LCCA	Life-cycle Cost Analysis
LNG	Liquefied Natural Gas
LOA	Length Overall
MARPOL	International Convention for the Prevention of Pollution from Ships
MBMs	Market-based Measures
MCR	Maximum continuous rating
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
NO_x	Nitrogen Oxide
NPV	Net Present Value
NZE	Net Zero Emissions by 2050 Scenario
O&MMs	Operation & Maintenance Manuals
RPM	Revolutions Per Minute
SCR	Selective Catalytic Reduction
SDS	Sustainable Development Scenario
SEEMP	Ship Energy Efficiency Management Plan
SSS	Short-sea Shipping
STEPS	Stated Policies Scenario
TCO	Total Cost of Ownership
ULSD	Ultra Low Sulphur Diesel
VLSFO	Very Low Sulphur Fuel Oil
WEO2021	Energy Outlook 2021

Variables

$\mathcal{N}$	The number of years in the study period
$\mathcal{P}$	Price of a product [€]
ΔI_t	The additional investment-related costs in year t associated with the alternative
C_F	Carbon emission conversion factor [t-CO_2/t-Fuel]
H	The annual operating hours for each engine mode [h/y]
I	Inflation rate [%]
i	The i^{th} engine mode associated with the corresponding engine load
M_{CO_2}	The annual amount of CO_2 emissions generated from fuel combustion [t-CO_2/y]
N	The total number of engine modes
P	The engine power required for each engine mode [kW]
r	Discount rate [%]
r'	Discount rate for calculating the carbon emission costs [%]
S_t	The savings in year t in operational costs associated with the alternative
t	Year of occurrence, $t = 0$ is the base year
CST	Construction cost [€]
EOL	End-of-life value [€]
FC	The annual fuel consumption [t-Fuel/y]
FGC	The annual fuel gas consumption [t-Fuel/y]
FOC	The annual fuel oil consumption [t-Fuel/y]
FV	Future value of the cost or benefit [€]
LOC	The annual lubricating oil consumption [t-Fuel/y]
MTN	Maintenance cost [€]
NPC	Net present cost [€]
NS	Net Saving [€]
OPR	Operation Cost [€]
PFC	The annual pilot fuel consumption [t-Fuel/y]
PV	Present value of the cost or benefit [€]
SFGC	The specific fuel gas consumption [g/kWh] under specific engine power output, as the function of the engine load [g/kWh]
SFOC	The specific fuel oil consumption [g/kWh] under specific engine power output, as the function of the engine load [g/kWh]
SIR	The saving-to-investment ratio of the alternative relative to the base case
SLOC	The specific lubricating oil consumption under specific engine power output [g/kWh]
SPFC	The specific pilot fuel consumption under specific engine power output [g/kWh]

Convention for the Prevention of Pollution from Ships (MARPOL) (IMO, 2011).

A new wave of mandatory measures will be enforced from 2023 with the IMO's adoption of new amendments to the MARPOL Annex VI including the Energy Efficiency Existing Ship Index (EEXI), the carbon intensity indicator (CII) and the enhanced SEEMP. Being considered the sister to the EEDI, the EEXI is a design measure, applicable to existing ships. The CII, related to an operational measure, measures the operational carbon intensity performance levels of a ship based on a rating scheme (from A to E). The EEXI and the CII are the short-term measures to lower carbon intensity while MBMs are considered the mid-term measures. Lagouvardou et al. (2022) augured that MBMs also have both short-term (logistical) and long-term (technological) consequences.

Such measures are expected to create a profound impact on the shipping industry in its transition towards decarbonization. To accelerate such transition, various available emissions reduction options, extensively reviewed by Bouman et al. (2017) together with under-development innovative options are needed. From the ship-owner perspective, it is a challenging task for them to choose the best option that will gain traction in the industry. This is due to the fact that it is a multi-criteria decision-making process in which a broad range of criteria, including technical, environmental and economic criteria is taken into consideration (Bui et al., 2021a). In addition, investments in such options are costly with a recent study reporting at least $1 trillion needed by 2050 in order to meet the IMO's emission targets (Carlo et al., 2020). Furthermore, there are still significant uncertainties concerning the technical feasibility and economics of these options.

Since the shipping industry is a capital-intensive industry associated with long ship lifespans and a high dependence on the global fuel supply, decisions made today will have a strong effect on the future operations and economic performance of a fleet for many years to come. The total lifespan cost of any appropriate emissions reduction technology can be significant if unwise decisions are made at the early stage. For this reason, it is required a strategic long-term approach that can oversee and control the costs before they are incurred. In this regard, life-cycle cost analysis (LCCA) on such technologies is attracting considerable attention. When adopting such technologies, there is a large uncertainty over fuel prices and the future fuel and energy mix. This seems to be a reason why ship-owners are reluctant to make investments. Therefore, it is important to take these uncertainties into consideration when conducting LCCA.

1.2. Dual-fuel engine retrofit

Apart from the regulatory pressure to achieve the IMO's emission targets, shipowners are coming under commercial pressure to be more competitive in the charter market (DNV, 2021). In order to have a better performance on emissions, shipowners are in need of upgrading their existing fleet to higher operational standards. From this perspective, retrofitting, i.e., the installation of innovative technologies on-boards existing ships is attracting considerable interest. In this respect, dual-fuel engines could be potentially applied for the main propulsion system on retrofitted ships. The subject of this study is a high-efficiency modern dual-fuel engine. The dual-fuel engine provides flexibility because it can be run in either liquid-fueled diesel mode or gas mode. In the diesel mode, it functions similar to a normal diesel engine. In the gas mode, a lean burn combustion process is achieved, thus lowering nitrogen oxides (NO_x) emissions and enhancing efficiency. Furthermore, utilizing a clean and low-carbon fuel (i.e. liquefied natural gas (LNG)) leads to very low exhaust gas emissions. The gas is injected into the engine at a low pressure and it is then ignited by a small amount of pilot diesel fuel injected into the combustion chamber (Wärtsilä, 2020).

The dual-fuel engine can be potentially retrofitted or installed on ships operating in short-sea shipping (SSS). In the context of the European SSS, one should consider the expansion of the EU Emissions Trading System (ETS) to the maritime sector (European Commission (EC), 2021). This is a result of the Fit for 55 package which is a green transition plan set by the EU, aiming to reduce the EU's total GHG emissions by at least 55% by 2030. In this regard, all ships will be required to purchase allowances for each ton of CO_2 they emit. The EU ETS, based on the "polluter pays" principle, is advocated as an efficient MBM at a regional level (Cariou et al., 2021). The IMO MBMs, on the other hand, are intended to impose a tax on emitted GHG emissions at a global level.

There will be a considerable correlation between the utilization of innovative technologies (e.g. the dual-fuel engine) and the introduction of MBMs (e.g. the IMO MBMs and the EU ETS). If ship-owners decide to retrofit their existing fleet with the dual-fuel engine, the economic aspect from a life-cycle perspective will be of paramount importance. At this point, LCCA will become a useful tool to assess and predict the economic performance of this engine over its lifespan.

The remaining part of this study proceeds as follows: Section 2 reviews the life-cycle costing (LCC) studies in the maritime research domain, Section 3 discusses the details of the proposed LCC framework, Section 4 describes the application of the proposed LCC framework to a case study pertaining to the dual-fuel engine and a conventional diesel engine and finally, Section 5 highlights and discusses the findings. Suggestions for future work are also offered in this section.

2. Literature review

2.1. Review on the LCC studies

LCC is an economic method for evaluating the total cost of an asset by considering initial costs and discounted future expenditures that will incur throughout the asset's life cycle. This method was introduced by the U.S. Department of Defense in the 1960s as an attempt to improve its cost-effectiveness in granting competitive awards (Sherif and Kolarik, 1981). Since then, it has been successfully employed in the industrial and consumer sectors.

In the maritime research domain, it has received considerable scholarly attention in recent years. From the methodological perspective, it has been combined with existing approaches for evaluating different options from an economic viewpoint. By combining the LCC method with activity-based costing, Emblemsvåg (2003) proposed an effective cost management method under an uncertain environment. The proposed method was applied in the context of a platform supply vessel operating in the North Sea. With the adoption of systems engineering and sustainable principles, Utne (2009) provided a LCC framework that can be used as a tool for enhancing sustainable designs of the Norwegian fishing fleet.

Furthermore, the LCC method has been integrated with the Life-cycle Assessment (LCA) method to assess the economic and environmental impacts of alternative technologies and ship systems. Having a different view to the ISO 14000 standard, Emblemsvåg and Bras (2012) evaluated the life-cycle economic and environmental impacts of a platform supply vessel by proposing an activity-based cost and environmental management approach. Blanco-Davis and Zhou (2014) conducted a cost-benefit analysis for the retrofitting evaluation of ballast water treatment systems. However, a major drawback of this study is the omission of the maintenance phase. A framework with an integration of the LCC and LCA methods was proposed for the selection of propulsion systems (Jeong et al., 2018). The proposed framework was demonstrated in two case studies. The first one examined the advantages of battery usage in a short-route hybrid ferry. The second one found the optimal engine configuration for an offshore tug vessel.

Favi et al. (2018) developed a framework combining the LCA and LCC methods to assess the environmental and economic performance of recreation vessels (i.e. luxury yachts). From a life-cycle perspective, the environmental and commercial benefits of using solar panel applied to short route ferries were investigated (Wang et al., 2019; Zito et al., 2022). Wang et al. (2021) proposed a framework in which a life cycle emission inventory and the corresponding costs of innovative battery power plants applied on a catamaran ferry were compared to that of conventional diesel engines. In the context of SSS in Croatia, Perčić et al. (2020) proposed strategies to improve the environmental impacts and lifespan costs of passenger ferries. In this study, a combined LCA–LCC method was performed to evaluate the potential of various alternative marine fuels compared to the conventional diesel fuel. Andersson et al. (2020) conducted a comparative analysis to select the marine scrubber systems. The LCC method was applied in this study to compare the payback time of the installation costs of these systems.

Huang et al. (2021) undertook a LCCA on alternatives for the compliance of the IMO's 2020 global sulphur cap under uncertainties. In this study, three alternatives, including fuel switch from Heavy Fuel Oil (HFO) to Very Low Sulphur Fuel Oil (VLSFO) and Marine Gas Oil (MGO), the installation of scrubber and the use of LNG as fuel, were compared in two container vessels of 5000 and 10,000 TEUs.

The total cost of ownership (TCO), a synonym of LCC, of various alternative fuels and corresponding ship power systems was evaluated

Table 1
Review on the LCC studies.

Reference	Software	Target subject	ISO 14040/14044	ISO 15686-5	Uncertainty treatment[a]
Blanco-Davis and Zhou (2014)	Gabi	Ballast water treatment systems	✓		No
Emblemsvåg (2003)	Crystal Ball	A platform supply vessel	*	*	Yes
Emblemsvåg and Bras (2012)	Crystal Ball	A platform supply vessel	*	*	Yes
Utne (2009)	N/M	Norwegian fishing vessels		✓	No
Jeong et al. (2018)	Gabi	Marine propulsion systems Battery usage in a short-route hybrid ferry	✓		No
Favi et al. (2018)	Excel, Visual Basic	Complex vessels (luxury yachts)	✓	✓	No
Wang et al. (2019)	Gabi, RETScreen	Solar panel system applied to a short route ferry	✓		No
Zito et al. (2022)	Gabi, MATLAB	Solar panel system applied to a short route ferry	✓		No
Wang et al. (2021)	Gabi	Battery power plants in a high-speed ferry	✓		No
Perčić et al. (2020)	GREET	Passenger ferries	✓		No
Wang et al. (2018)	Gabi	An optimal hull maintenance strategy for a short route ferry	✓		No
Andersson et al. (2020)	Gabi	Marine scrubber systems	✓		No
Gualeni et al. (2019)	In-house software	Different propulsion layout solutions	✓		No
Huang et al. (2021)	@RISK	Alternatives for container vessels	N/M	N/M	Yes
Lagemann et al. (2022)	Gurobi, Python	Alternative fuels and ship power systems	N/M	N/M	No

N/M: Not mentioned.
*: A different approach was proposed.
[a] Uncertainty treatment by a probabilistic approach such as Monte Carlo simulation.

by using an optimization model (Lagemann et al., 2022). By applying this model to a supramax bulk carrier under a low fuel price and a carbon tax setting, bio-fuels were uncovered to be the most cost-effective and LNG powered-system is considered reliable for several GHG reduction ambitions.

Several studies were mainly oriented to LCA under the maintenance perspective. An optimal maintenance strategy was derived from a study conducted by Wang et al. (2018) after evaluating the life-cycle cost of a short route ferry considering the steel renewal and re-coating processes. Gualeni et al. (2019) proposed a life-cycle performance assessment tool to select the best propulsion layout solution with regard to cost performance.

2.2. Research gaps and contribution

It is perceived from these studies reviewed in the last section that the application of the LCC method is normally situated along with the LCA method, rather than in a stand-alone context. In this regard, from the methodological point of view, most of these studies have adopted the ISO 14040/14044 standards of environmental management. This may lead to misunderstandings or confusions when a specific LCC framework is conducted. The ISO 15686-5 standard on LCC applying to the building sector could be used as a standardized approach that offers a methodological procedure for conducting LCCA (Mondello et al., 2021). Another aspect emerged from the literature review that the uncertainty inherent to any LCC models has not been addressed thoroughly. Prior studies have dealt with the uncertainty by only using deterministic approaches (e.g. sensitivity analysis) which do not offer direct insights into the probabilities of different outcomes. As a result, decision-makers select between alternatives based on their judgements. On the other hand, probabilistic approaches provide a more detailed consideration of the uncertainty by taking into account probability. An example of the probabilistic approach is Monte Carlo simulation. However, only three out of the reviewed studies carried out the uncertainty analysis using Monte Carlo simulation, as demonstrated in Table 1. Favi et al. (2018) suggested the use of Monte Carlo simulation to consider uncertainties throughout the lifespan of studied vessels as future work. Furthermore, to the best of the authors' knowledge, there are not many studies focusing on the life-cycle cost performance of a marine dual-fuel engine in the context of retrofitting practices. In addition, there has been no detailed investigation of the main components and systems of studied subjects with an engineering approach.

The current study aims to address these gaps in the existing literature by proposing a LCC framework that integrates a standardized approach for LCCA (i.e. the ISO 15686-5) for investigating the potential economic benefits of an innovative engine technology (i.e. the dual-fuel engine), taking into account the uncertainties involved over the lifetime of the engine. The ultimate goal is to compare the life-cycle cost performance of the dual-fuel engine with that of a conventional diesel engine. The proposed framework includes the development of a cost model with an engineering build-up approach, resulting in interpretable and effective results using data from numerous sources. Specifically, different cost categories are calculated among the engines' life cycle phases, ranging from construction, operation, maintenance to end-of-life. In addition, the external costs (i.e. carbon emission costs) due to air pollution from internal combustion engines are included in the cost model. Furthermore, the uncertainties are thoroughly treated under scenario sensitivity analyses and a Monte Carlo simulation correspondingly. The former considers the effects of changing key uncertain input variables on the relative merits of the engine alternative, i.e. the dual-fuel engine. The latter is concerned with conducting a statistical technique using the Monte Carlo simulation. In this respect, by introducing uncertainty into the cost model, the probabilities of different outcomes can be calculated.

The application of the proposed framework should make the following contributions to the current literature: (i) it offers a better understanding on a methodological procedure for LCCA, (ii) it conducts a thorough examination of uncertainties by means of the scenario sensitivity analyses and the Monte Carlo simulation, (iii) it will be a useful aid for decision-makers (i.e. ship-owners, investors) as regards retrofitting decision-making and (iv) it provides the assessment of the impacts of carbon pricing on technology investments, contributing to recent discussions concerning MBMs.

3. The proposed LCC framework

As previously mentioned, a uniform LCC framework has not yet been established or some LCC studies have just followed what is needed in the ISO 14040/14044 standards. Having a more detailed perspective, this study proposes a LCC framework in which several steps are demonstrated, as shown in Fig. 1. The framework encompasses the principles taken from the ISO15686-5 standard (ISO, 2017) and processes proposed by Utne (2009), Bui et al. (2021b) and Bui et al. (2022).

3.1. Goal and scope

- Goal: The goal of this study is to evaluate the total life-cycle cost performance of the dual-fuel engine compared with that of a conventional engine. The economic benefits of utilizing the

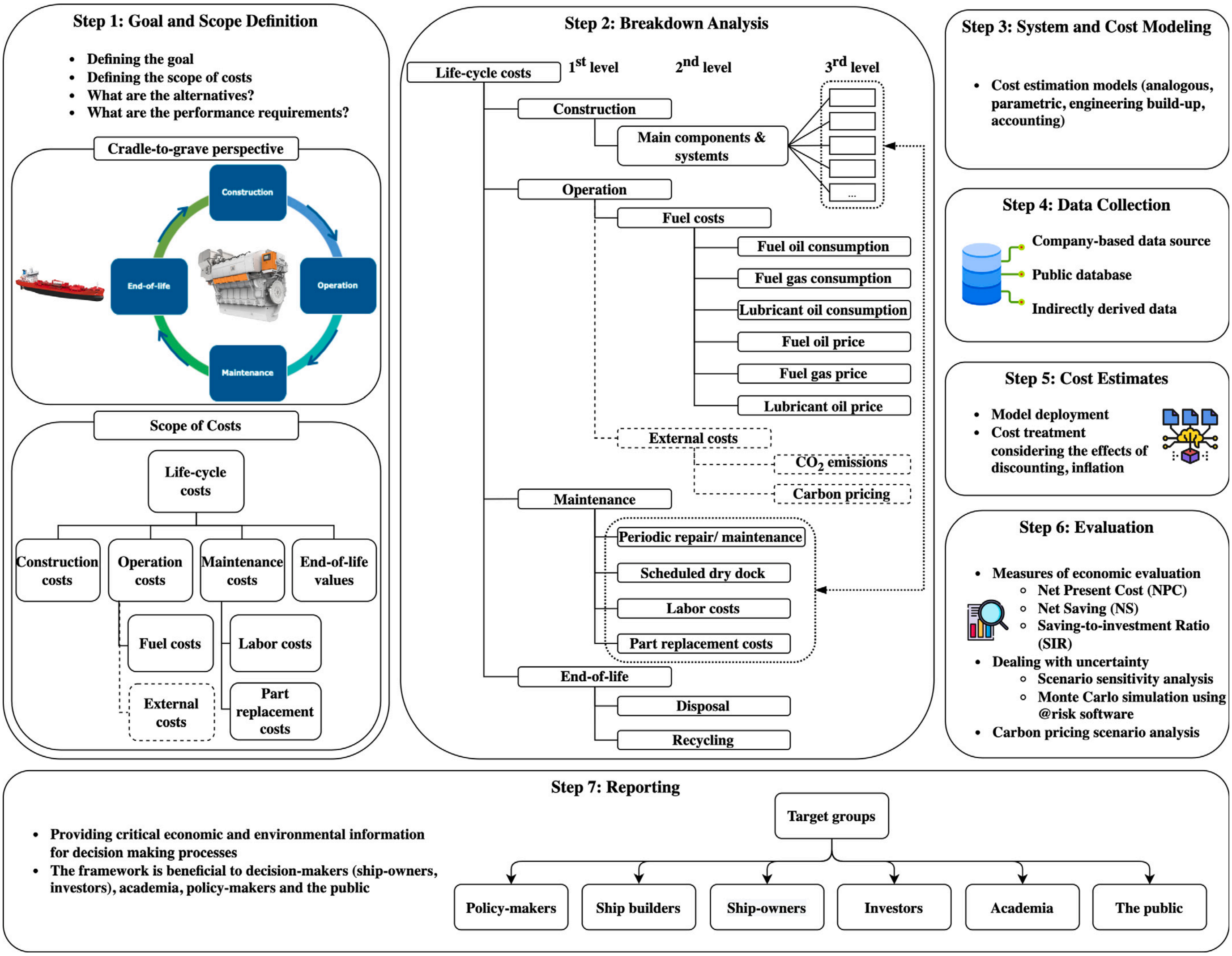


Fig. 1. The proposed LCC framework.

dual-fuel engine are demonstrated from a life-cycle perspective. Furthermore, the environmental benefits of utilizing the dual-fuel engine during its operation are also under consideration.

- Scope: The scope of this study can be revised along the analysis because of the iterative approach. The system is bounded to the use of such engines as the main propulsion systems. From a cradle-to-grave perspective, there are four cost components associated with the engines' life-cycle phases: construction costs, operation costs, maintenance costs and end-of-life values. Apart from that, the external costs (i.e. carbon emission costs) are also taken into account under the operation phase.

3.2. *Breakdown analysis*

To further define the scope of costs included in this study, a Cost Breakdown Structure (CBS) is devised to provide a structured basis in which cost categories are classified on different levels as shown in Step 2 of Fig. 1. The first level comprises the main cost components connected with four life-cycle phases of the engines, i.e., construction, operation, maintenance, and end-of-life. The second and third level includes local costs and factors that are intended to accommodate in the respective phases of the engines.

3.2.1. *Construction costs*

The construction costs include those for assembling the engines before putting them into initial service. In this regard, an Engine Breakdown Structure (EBS) of a conventional diesel engine is provided to indicate the costs of its main components and systems, as shown in Table 2. The EBS is a basis for a structural comparison between the diesel engine and the dual-fuel engine. One of the structural differences between these engines is the fuel injection system because the dual-fuel engine is equipped with a gas system. Furthermore, the installation of the Selective Catalytic Reduction (SCR) system is not applicable to the dual-fuel engine due to its low emissions when operating in the gas mode. The EBS will also play an important role in the later stage when calculating the part replacement costs of the engines' components.

3.2.2. *Operation costs*

The operation costs are the annual expenses incurred in the routine operations of the engines. Fuel costs are the most important cost component of the cost of running ships, accounting for two-thirds of the voyage costs (Stopford, 2009). For this reason, the operation costs used in the base case of this study refer to fuel costs. These costs can be derived from the annual fuel consumption and the annual lubricating oil consumption (LOC).

As regards the diesel engine, the total annual fuel oil consumption (FOC) and the total annual LOC can be determined by using the

Table 2
A general Engine Breakdown Structure (EBS).

2nd Level	3rd Level	Cost	
		Diesel engine	Dual-fuel engine
Main components & systems	Engine basement		
	Camshaft & Valve Mechanism		
	Fuel Injection System		
	Turbocharging & Scavenging System		
	Ancillary System		
	Automation System		
	Low-value Parts		
	Exhaust Gas Cleaning System[a]		N/A
	Total	989K	1,200K

[a] Selective Catalytic Reduction (SCR) technology for NO_x reduction. The SCR cost for the diesel engine was adopted from the International Association for Catalytic Control of Ship Emissions to Air (IACCSEA) (IACCSEA, 0000). The SCR system is not required for the dual-fuel engine. Other costs were obtained from the engine manufacturer (Wärtsilä, 2021a).
Unit K = 1000€.

following equations (Wang et al., 2019).

$$\mathrm{FOC} = \sum_{i=1}^{N} P_i \times \mathrm{SFOC}_i \times H_i \tag{1}$$

$$\mathrm{LOC} = \sum_{i=1}^{N} P_i \times \mathrm{SLOC}_i \times H_i \tag{2}$$

In the case of the dual-fuel engine, it can be run either in diesel mode or gas mode. In the diesel mode, it is a normal diesel engine, therefore the total annual FOC can also be found by adopting Eq. (1). In the gas mode, the main fuel is LNG which is injected into the engine at a low pressure. The lean air–gas mixture is ignited by injecting a small amount of pilot diesel fuel (Wärtsilä, 2020). The total annual pilot fuel consumption (PFC) can also be obtained by adopting Eq. (1). The total annual fuel gas consumption (FGC) can be determined as follows.

$$\mathrm{FGC} = \sum_{i=1}^{N} P_i \times \mathrm{SFGC}_i \times H_i \tag{3}$$

The total annual LOC of the dual-fuel engine can also be calculated by adopting Eq. (2).

Besides the internal costs borne by the engine operations during their lives, the scope of this study is also expanded by including the external costs (also termed externalities) that are expected to be internalized in the near future. They are carbon emission costs that will be included in the operation costs in the later stage where carbon pricing scenarios are taken into account. The carbon emission costs refer to the costs of emitting CO_2 equivalent emissions. These can be perceived as carbon taxes under the IMO MBMs or the carbon allowance under the EU ETS that can be received, bought, or even traded. In order to determine these costs, the environmental impacts of the engines need to be quantified based on the estimation of the annual CO_2 emissions emitted from fuel combustion, as expressed in the following equation (IMO, 2020).

$$M_{CO_2} = \mathrm{FC} \times C_F \tag{4}$$

3.2.3. Maintenance costs

The maintenance costs refer to the costs of regular maintenance tasks that should be done to avoid engine malfunction and extend its lifespan. The practices for such maintenance tasks are based on a time-based maintenance schedule, i.e. the Operation & Maintenance Manual (O&MM) given by the engine manufacturer, where the maintenance intervals for each engine's main component and system are provided. These components and systems are corresponding to the third level of the EBS as indicated previously. Table 3 briefly illustrates the maintenance tasks and the associated intervals of each part of the fuel injection system of the dual-fuel engine. The routine maintenance tasks are normally conducted by crew members from the engine department (i.e., Chief Engineers, Engine Officers, Engine Cadets) when the ship is in service. The heavy maintenance tasks (i.e. major overhauls) are generally performed by technical personnel from the engine manufacturer when the ship is out of service (i.e. on dry-docking). Occasionally, several engine parts can be sent to the engine manufacturer's workshops ashore. In this study, the maintenance costs are categorized into:

- Labor costs for doing the maintenance tasks for the engines' components.
- Part replacement costs (i.e. spare costs) of the engines' components according to the O&MMs.

3.2.4. End-of-life values

Around 96% of ships are recycled when they reach the final phase of their lives (McKenna et al., 2012). Along with hull structure and other significant parts of the ship, the main engine will also be recycled. Therefore, in this study, the values of the engines at the end of their lives are the negative costs or the benefits.

3.3. System and cost modelling

The following is a brief description of models to perform LCCA. It has been perceived in the literature that four cost estimation models exist: analogous, parametric, engineering build-up, and cost accounting. Their characteristics, advantages and disadvantages will be explained as follows.

3.3.1. Analogous model

In this method, the cost of a product can be estimated from the similarities and differences between it and known variants from past projects. It is based on an assumption that similar products have similar costs. Domain knowledge from experts is required to establish similarity functions and analogy rules. With actual historical data available, reasonable cost approximation can be made in a short span of time. This case-based method can be applicable to the cost estimation during the early design stage (Curran et al., 2004; Hueber et al., 2016).

3.3.2. Parametric model

The principle of this method is to formalize the so-called "Cost Estimation Relationship" (CER) which is derived from the mathematical relationships between the costs of a product and its parameters. Such parameters are typically referred to as "Cost Drivers" and they have great influence on the cost changes or at least they are relative to the cost changes. An example of the cost driver is the part size of the product, as the part size increases, so does the manufacturing costs. Statistical analysis can be used under one part family of the product in order to estimate the part costs with regard to the part size. Different CERs can be developed with more cost drivers (e.g., size, weight) in one parametric model. There are several drawbacks of this method:

Table 3
An extraction of the O&MM regarding the fuel injection system of the dual-fuel engine.
Source: Wärtsilä.

3rd level of the EBS	Part	Maintenance task	Interval
Fuel injection system	Fuel filters	Check the pressure drop Change the filter cartridges if a high pressure drop is indicated	50 h
	Fuel system	Check that there are no fuel leaks from the engine	24 h
	Fuel system	Check the clean leak fuel quantity	50 h
	Fuel system	Replace the valve block for Pressure Drop and Safety Valve (PDSV) and Circulation Valve (CV)	24,000 h
	Fuel system	Replace the high-pressure fuel pipes	48,000 h
	HP fuel pump(s)	Replace the HP fuel pump(s)	24,000 h
	Fuel injectors	Replace the fuel injectors	8,000 h
	Centrifugal oil filter	Clean the centrifugal filter	2,000 h
	Fuel feed pump	Overhaul the fuel feed pump	16,000 h
	Main gas admission valve	Replace the main gas admission valves	16,000 h
	Gas system	Monitor the gas leak detection system. Make sure that the gas monitoring system is functioning Check for external gas leaks on the engine by using a portable gas detector.	24 h
	Gas system	Perform a tightness test, after the overhaul, before the engine is started.	32,000 h

This table provides only parts of the fuel injection system of the dual-fuel engine for reference. Remaining parts from other main components and systems are not listed here.

it depends upon a historical database; using this model outside of the database range should be avoided; and it is incapable of demonstrating technological changes or altered system requirements (Curran et al., 2004; Hueber et al., 2016).

3.3.3. *Engineering build-up model*

The bottom-up or engineering build-up model identifies parts, materials, and associated tasks of a product. Their costs are then added up to produce the final cost estimate of the product. As the name suggests, this method is based on a detailed engineering analysis in which a deep understanding of the process interactions, the product design and configuration, and the product system components is required. Additionally, other accounting information regarding material, equipment, and labor is necessary. Unlike the analogous and parametric models, the engineering build-up model is not limited to the range of the underlying historical data. Furthermore, it is capable of providing the level of detail and the causation. When it comes to innovative or new technologies to the industry, it is considered the only available option for cost estimation. On the other hand, domain knowledge and a large amount of data regarding the product details need to be acquired in this method (Curran et al., 2004; Hueber et al., 2016).

3.3.4. *Accounting model*

Cost management and accounting considering the overhead costs are the focal points in this method. In the literature, cost accounting models and systems can be divided into three categories: volume-based costing systems, unconventional costing methods, and modern cost management systems. More information on the accounting model can be found in Emblemsvåg (2003).

With a focus on the development of the EBS, the chosen cost estimation model in the current study is the engineering build-up model. Depending on the amount of data available, the other model such as the analogous model will also be used.

3.4. *Data collection*

Since the engineering build-up model is a systematic approach, the amount of collected data is extensive. The collected data can best be divided into three main categories: company-based data source, public database, and indirectly derived data. The involvement of an engine manufacturer (i.e. Wärtsilä) and several ship-owners in this study was of concern. Table 4 is an illustration of these data categories and their associated sources.

3.5. *Cost estimates*

In the section that follows, a cost model is built and deployed while considering the effects of several important aspects of LCCA (i.e., inflation, discounting, and present value). Furthermore, several measures of economic performance that will be used in the evaluation step are discussed.

3.5.1. *Inflation and discounting*

Since the above-mentioned costs are accumulated over the engine's lifespan, it should be noted that the monetary flows occur at different times. For this reason, the two following aspects should be considered. The first is inflation, which reduces the purchasing power of currency over time. This can be seen by a gradual increase in the general price of goods and services because of the market dynamics. Costs in different year with different purchasing power should not be added together directly to arrive at a meaningful amount. Assuming an inflation rate I, the price $\mathcal{P}$ of a product at time t (in years) can be calculated as expressed in Eq. (5) (Rödger et al., 2018).

$$\mathcal{P}(t) = (1 + I)^t \times \mathcal{P}(0) \tag{5}$$

The second aspect is discounting, which is related to the varying time value of money. The value of money today is not equal to the one projected to be spent in the future. As a result, present and future costs that occur at different points in the life of an engine cannot be compared directly. By using a discount rate chosen to represent the time value of money, all future costs are discounted back to present value costs through the following equation (Rödger et al., 2018; Welch, 2017).

$$\mathrm{PV} = \mathrm{FV}\frac{1}{(1+r)^t} \tag{6}$$

3.5.2. *Net present cost (NPC)*

Once all the costs associated with each phase of the engine's life cycle are estimated and computed, the net present cost (NPC), i.e. the total present value of all costs, can be calculated as the summation of the following costs in present value terms (Kneifel and Webb, 2022).

$$\mathrm{NPC} = \mathrm{PV(CST)} + \mathrm{PV(OPR)} + \mathrm{PV(MTN)} - \mathrm{PV(EOL)} \tag{7}$$

3.5.3. *Net saving (NS)*

Net saving (NS) is a useful measure of economic performance for an alternative investment that reduces the operational costs. NS, expressed in present value terms, can be determined by subtracting the NPC of the alternative (i.e. the dual-fuel engine) from the NPC of the base case (i.e. the diesel engine), as follows (Kneifel and Webb, 2022).

$$\mathrm{NS} = \mathrm{NPC}_{BaseCase} - \mathrm{NPC}_{Alternative} \tag{8}$$

Table 4
Data categories and sources.

Category	Source
Company-based data source	
Construction costs	Wärtsilä (2021a)
Operational profile	Wärtsilä
Engine technical data	Wärtsilä (0000)
Maintenance schedule (O&MMs)	Wärtsilä
Engine materials	Wärtsilä
Engine weights	Engine product guide Wärtsilä (2020, 2021b)
Public database	
Material recycling rates	Greengate Metals (0000)
Marine fuel (gas, oil) prices	Ship & Bunker (2021), Global Maritime Hub (2021)
Wages	Eurostat (2022)
Currency exchange rates	xe.com/currencyconverter
Discount rate	Hunkeler et al. (2008), Rödger et al. (2018)
Indirectly derived data	
Maintenance hour consumption	Questionnaires & Interviews with Chief-Engineers, Engine Officers
Part replacement costs	Interviews with a Technical Manager, Chief-Engineers

O&MMs: Operation & Maintenance Manuals.

3.5.4. Saving-to-investment ratio (SIR)

Saving-to-investment Ratio (SIR), another measure of economic performance of an alternative investment, is a ratio between its saving and its increased investment cost (in present value terms). The formula for the SIR is shown in Eq. (9) (Kneifel and Webb, 2022).

$$\mathrm{SIR} = \sum_{t=0}^{\mathcal{N}} \frac{S_t}{(1+r)^t} \Bigg/ \sum_{t=0}^{\mathcal{N}} \frac{\Delta I_t}{(1+r)^t} \qquad (9)$$

3.6. Evaluation

3.6.1. Measures of economic performance

The essence of this evaluation is to use the above-mentioned measures as critical economic KPIs (i.e. key performance indicators) for the overall decision-making process. To be more specific, these measures will be used to compare the life-cycle cost performance of the dual-fuel engine with that of the diesel engine. The alternative engine is considered economically justified relative to the base engine if its NPC is lower than the NPC of the base engine. This is equivalent to having the NS greater than zero. In addition, the engine alternative is cost-effective relative to the base engine if its SIR is greater than 1.0.

3.6.2. Dealing with uncertainty

LCCA requires assumptions about future behaviors with regard to cost projection, making "best-guess" estimates as if they were certain. However, investments in such an innovative engine are long-lived and necessarily involve some uncertainties regarding fuel prices, the engine's annual operating hours, etc. If there is a substantial uncertainty regarding cost and time information, LCCA may have little value for the final decision-making process. Therefore, it is necessary to assess the degree of uncertainty associated with the results and consider it as additional information when making final decisions. Although it might be uncertain about some input variables occurring in the future, it is worth including them in the economic evaluation instead of relying solely on the first costs.

There are two main approaches to dealing with uncertainty in terms of investment decisions (Kneifel and Webb, 2022). One is the deterministic approach, which measures the impact of investment outcomes by changing one uncertain key input variable or a combination of variables at a time. The result reflects upon how the changes in the input variable change the outcome while all other things remain constant. In contrast, the probabilistic approach assumes that no single input variable can sufficiently express the full range of possible outcomes of a risky investment. Instead, many alternative outcomes must be taken into consideration, and each outcome must be associated with a probability. If the outcome is represented by a probability distribution, statistical analysis can be carried out to measure the degree of risk. With regard to the deterministic approach, the degree of risk is obtained on a subjective basis.

Scenario sensitivity analysis, which falls under the deterministic approach, will be used in this study. In this technique, for input variables with varying degrees of uncertainty, a set of more pessimistic or optimistic variables than the expected ones can be simultaneously tested in various scenarios. In this respect, the NPC is recalculated for testing its sensitivity with regard to the changes in input variables. Regarding the probabilistic approach, a Monte Carlo simulation will be performed in this study. In this regard, a range of values called a probability distribution is assigned for any input variable that has inherent uncertainty. By using something called "random sampling", the simulation is run repeatedly, generating random values from the variable probability distributions. As a result, a cost range of possible NPC outcomes can be achieved, expressed by a probability distribution. The advantage of performing the Monte Carlo simulation is that the entire cost range of the NPC can be sampled accurately and the effects of simultaneous changes in uncertain variables can be assessed (Emblemsvåg, 2022).

3.7. Reporting

The LCCA conducted in this study is from the ship-owner perspective who is striving to comply with emission control regulations by considering retrofitting investment decisions on the dual-fuel engine. At the same time, they are also aware of the life cycle cost performance of such an engine. Therefore, ship-owners are the main target group. Apart from ship-owners, the findings reported in this study can be used as a reference for investors with regard to investment appraisal of the dual-fuel engine. In addition, the findings gained from this study would be beneficial to other target groups such as policy-makers, ship builders, academia and the public.

4. Case study

This section presents a case study of utilizing the proposed framework to compare the total life cycle cost performance of the dual-fuel engine against that of a conventional diesel engine. The selected case ship is a bulk carrier with the deadweight of 7600 [t], and the Length-Over-All (LOA) of 112 [m]. The specifications of these engines are demonstrated in Table 5.

Based on the domain knowledge from experts and the availability of data, the following assumptions have been made in this study without having significant effects on the final results.

- The common lifespan of ships and their associated systems is 20+. However, the period of analysis chosen in this study is 20 years, which matches those observed in previous studies (Wang et al., 2019).

Table 5
Specifications of two engines.

Specification	Diesel engine	Dual-fuel engine
Cylinder configuration	8L32	8V31DF
No of cylinder	8	8
Cylinder bore [mm]	320	310
Power per cylinder [kW]	580	600
Power [kW]	4640	4800
RPM	750	750
Fuel type	MGO	ULSD (in diesel mode) LNG (in gas mode)

MGO: Marine Gas Oil; ULSD: Ultra Low Sulphur Diesel.

- For being consistent throughout this study, the currency used is Euro (€) with the exchange rate as follows. 1 US dollar (USD) equals to €1.132.
- In the construction phase, the costs of engine delivery are omitted. This is due to the fact that these costs can be the same for these engines. In addition, the installation costs of the MGO tank system for the diesel engine and the LNG tank system for the dual-fuel engine are not considered.
- In the maintenance phase, the costs of handling LNG storage facilities are not included.
- The external costs from the construction phase are omitted. This may be explained as follows. One of the main sources of CO_2 emissions from this phase is the iron and steel-making processes. However, the CO_2 emissions from such processes are significantly less, compared to the CO2 emissions from the operation phase.
- The external costs due to air pollution from disposal or recycling process at the end of lives of the engines are not included.

This section is organized in the following way: the first part presents a base case where the carbon emission costs do not come under the umbrella of the operation costs, the second part deals with the presence of the carbon emission costs when taking into account several carbon pricing scenarios.

4.1. The base case

4.1.1. Construction costs

The construction costs for the diesel engine and the dual-fuel engine were determined after a discussion with the engine manufacturer, as given in Table 2.

4.1.2. Operation costs

Table 6 presents an operational profile of the case ship operating the diesel engine. The engine load, as a percentage of the maximum continuous rating (MCR) of the engine, varies under different engine modes. The SFOC is expressed as a function of the engine load. For these reasons, the SFOC needs to be adjusted in connection with the changes of the engine load. The SFOC adjustment of the engine was determined by interpolation/extrapolation with reference to the values given in Table 7 (Wärtsilä, 0000). Fig. 2 indicates graphically the relation curve between the engine load and the relative SFOC. For a diesel medium-sized four-stroke engine, it is desirable to maintain the engine load at around 80% for optimal fuel consumption and engine performance (Jalkanen et al., 2012). The total annual FOC and LOC of the diesel engine can be obtained with the help of Eqs. (1) and (2) respectively, as shown in Table 6.

In terms of the case ship operating the dual-fuel engine, the same operational profile was used with the following assumptions:

- The dual-fuel engine is running on Ultra Low Sulphur Diesel (ULSD) in the diesel mode, i.e. in “Manoeuvring”.
- The dual-fuel engine is running on LNG in the gas mode, i.e., in “Engine Mode 1” and “Engine Mode 2”.

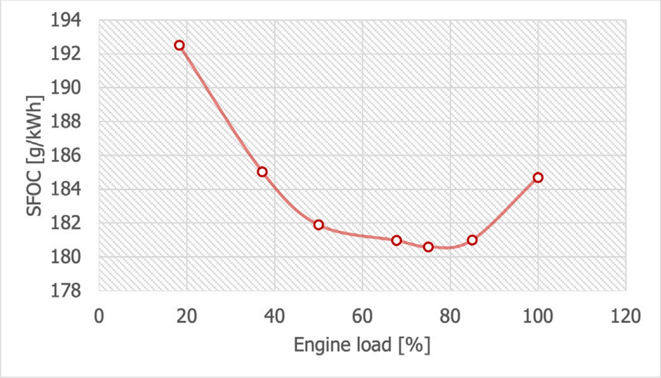


Fig. 2. SFOC-engine load relation curve of the diesel engine.

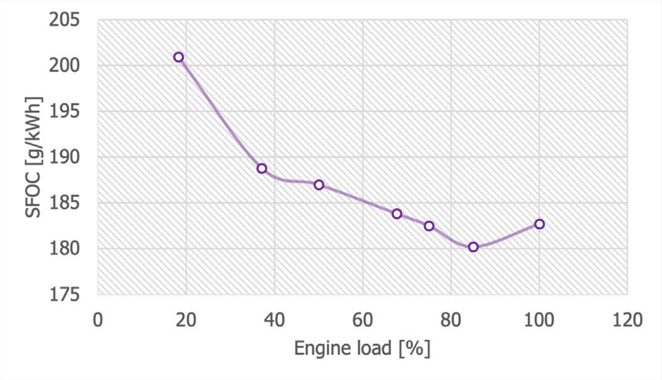


Fig. 3. SFOC-engine load relation curve of the dual-fuel engine in the diesel mode.

As mentioned before, in the diesel mode, the dual-fuel engine operates as a normal diesel engine. Therefore, the total annual FOC and LOC can be achieved in a similar way to what has been done for the diesel engine. Fig. 3 depicts the relation curve between the engine load and the relative SFOC in the diesel mode. The interpretation of this figure is similar to Fig. 2. The engine load should be with the lowest SFOC in order to reduce fuel consumption and enhance engine performance.

In the gas mode, it is essential to find the total annual PFC and the total annual FGC. The PFC can be calculated by adopting Eq. (1). The FGC can be calculated with the help of Eq. (3). Table 9 provides the reference values for the SFOC, SLOC, the specific pilot fuel consumption (SPFC) and the specific fuel gas consumption (SFGC) (Wärtsilä, 0000). Fig. 4 displays the relation curves between the engine load and the relative SFGC, SPFC in the gas mode. The differences between the SFGC in different engine loads are marginal. Taken together, Table 8 demonstrates the operational profile and the total annual FOC, LOC, FGC, and PFC of the dual-fuel engine.

There is a rather significant outcome when comparing the annual fuel consumption (by mass) of these two engines. Due to having a higher low heating value (i.e. net calorific value), the dual-fuel engine uses less amount of gas than the amount of diesel the diesel engine uses (1767.3 [t] versus 2447.8 [t]). In order to calculate the operation costs of these engines, fuel prices were derived from real public data sources in the Rotterdam region as presented in Table 10.

4.1.3. Maintenance costs

As previously stated, there are two cost categories of the maintenance costs, which are further explained as follows.

Table 6
The case ship's operational profile operating the diesel engine.

Operation mode	Annual hours [h/y]	Speed [Knot]	Percentage [%]	Power [kW]	Engine load [%]	SFOC [g/kWh]	Annual FOC [t/y]	SLOC [g/kWh]	Annual LOC [t/y]
Port	1200	0	14%	0	0	0	0	0	0
Manoeuvring	100	0	1%	846.7	18.2%	192.5	16.3	0.06	0.01
Engine Mode 1	300	18.1	3%	3139.6	67.7%	181.0	170.5	0.24	0.22
Engine Mode 2	7100	15.3	82%	1720.9	37.1%	185.0	2261.1	0.13	1.59
Total	8700						2447.8		1.81

Table 7
Reference values for the SFOC & SLOC of the diesel engine.

Engine load [%]	SFOC [g/kWh]	SLOC [g/kWh]
100	184.7	0.35
85	181	
75	180.6	
50	181.9	

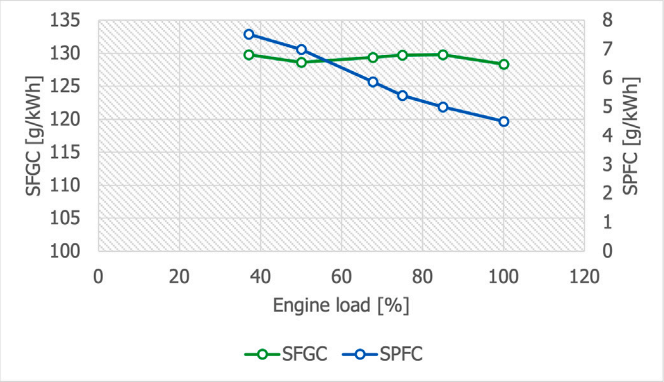


Fig. 4. SFGC/SPFC-engine load relation curves of the dual-fuel engine in the gas mode.

- The labor costs for doing the maintenance tasks for the engines' components. These costs are driven by the engines' annual operating hours, the period of analysis, the recommended maintenance intervals, the number of components, the hourly wages, and the maintenance hour consumption. It should be borne in mind that the actual operation conditions, the quality of the fuel used, the fuel type, and the annual operating hours have a significant impact on the recommended maintenance intervals. The hourly wages selected in this case study are 30 [€/h] (Eurostat, 2022). Domain knowledge is required to obtain the maintenance hour consumption. In this regard, in-depth interviews were carried out with crew members from various shipping companies. They are Chief Engineers and Engine Officers who have at least 5 years of seafaring experience. They were asked to provide information about the amount of time they spent doing the maintenance tasks for every engine component.
- The part replacement costs (i.e. spare costs) of the engines' components according to the O&MMs. These costs were obtained by using an analogous model and conducting thorough interviews with a Technical Manager and Chief Engineers from several shipping companies. Based on their domain knowledge and available historical data of similar engines, the part replacement costs were estimated in a satisfactory way.

4.1.4. End-of-life values

The engines reach the recycling yard for demolition at the end of their lives. Therefore, the materials of the engines and their associated components will be recycled. Table 11 lists the most important structural materials of the engines. The benefits of recycling such materials are presented in the same table. The weights of the engines are provided in Table 12. Such information is contributing to the calculation of the end-of-life values of the engines.

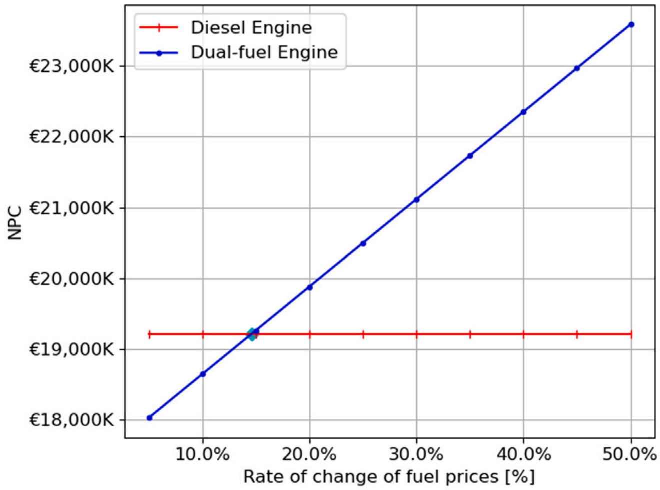


Fig. 5. Rising LNG price and steady MGO price scenarios.

4.1.5. LCC appraisal

Table 13 provides an overview of the cash flow for the LCC appraisal, consisting of the above-mentioned costs accumulated over the period of 20 years. It needs to be said that the maintenance costs, including the labor costs and the part replacement costs are inflated values where they are exposed to the effects of the inflation rate of 3.1%. Furthermore, all future costs are discounted back to their present values by using a nominated discounted rate. The selection of an appropriate discounted rate is dependent on the type of cost. For internal costs, it is associated with the cost of borrowing. In the private sector, a discount rate might fall into the range of 5%–15%, depending on the required return on investment (Hunkeler et al., 2008). A lower discount rate can be chosen following the financial crisis in 2008 (Rödger et al., 2018). For the public sector, the discount rate is generally specified between 3% and 5% for the economic analysis of publicly funded projects (Langdon, 2007). Under the scope of the private sector, the chosen nominated discounted rate in this study is 5%.

It is apparent from the Table 13 that the operation costs have the biggest impact on the life-cycle cost performances of these engines. Albeit having higher construction costs and maintenance costs, the dual-fuel engine has a better performance with regard to the operation costs. The life-cycle cost performances of these engines can be compared by evaluating the measures of economic performance (i.e. economic KPIs), as shown in Table 14. These measures reveal that the dual-fuel engine is clearly cost-effective with the lowest NPC and the NS greater than 0. Furthermore, the SIR of 4.95 means that the dual-fuel engine will generate an average return of €4.95 for every €1 invested.

Table 8
The case ship's operational profile operating the dual-fuel engine.

Operation mode	Annual hours [h/y]	Speed [Knot]	Percentage [%]	Power [kW]	Engine load [%]	SFOC [g/kWh]	Annual FOC [t/y]	SLOC [g/kWh]	Annual LOC [t/y]	SFGC [g/kWh]	Annual FGC [t/y]	SPFC [g/kWh]	Annual PFC [t/y]
Port	1200	0	14%	0	0	0	0	0	0	0	0	0	0
Manoeuvring	100	0	1%	873.6	18.2%	200.9	17.6	0.08	0.01	131.1	N/A	N/A	N/A
Engine Mode 1	300	18.8	3%	3249.6	67.7%	183.8	N/A	0.30	0.30	129.4	126.2	5.9	5.7
Engine Mode 2	7100	15.9	82%	1780.8	37.1%	188.8	N/A	0.17	2.11	129.8	1641.1	7.5	95.1
Total	8700						17.6		2.42		1767.3		100.9

Table 9
Reference values for the SFOC, SLOC, SPFC & SFGC of the dual-fuel engine.

Engine load [%]	SFOC [g/kWh]	SLOC [g/kWh]	SPFC [g/kWh]	Heat rate [kJ/kWh]	SFGC [g/kWh]
100	182.7	0.45	4.5	7058	128.3
85	180.2		5.0	7138	129.8
75	182.5		5.4	7134	129.7
50	187.0		7.0	7076	128.7

The calorific value for LNG: 55000 [kJ/kg] is used to convert the heat rate into the SFGC.

Table 10
Fuel information.

Type of fuel	Price [€/t]	CF [t-CO2/t-Fuel]	Calorific value [kJ/kg]
MGO	508.1[a]	3.20600[c]	–
ULSD	576.8[b]	3.15104[c]	–
LNG	561.1[a]	2.75000[c]	55,000
Lubricating oil	2300[b]	–	–

[a] Source: Global Maritime Hub (2021).
[b] Source: Ship & Bunker (2021).
[c] Source: IMO (2020).

Table 11
Metal material content of engines.
Source: Wärtsilä, Greengate Metals (0000).

Material	Weight ratio [%]	Benefits of recycling [€/kg]
Steel	16	0.25
Cast iron	80	0.25
Aluminum	2	0.7
Cooper	2	6.35

Table 12
Engine weights.
Source: Wärtsilä (2020, 2021b).

Criteria	Diesel engine	Dual-fuel engine
Weight [t]	43.6	58.9

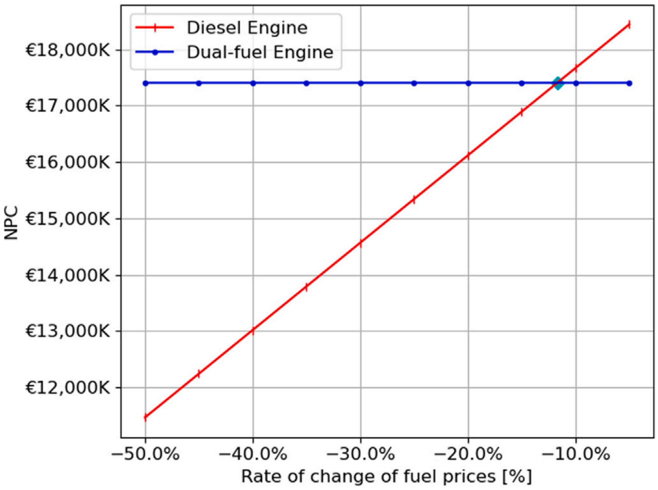


Fig. 6. Steady LNG price and decreasing MGO price scenarios.

4.1.6. *Scenario sensitivity analysis*

In the section that follows, an investigation on the sensitivity of the NPCs of these engines with regard to the changes of uncertain variables is demonstrated. The uncertain variables considered are fuel prices and discount rate.

(a) Scenario sensitivity analysis on fuel prices: In order to investigate at which fuel price will the decision favor one engine over another, various price scenarios with respect to MGO and LNG were simulated. These price scenarios were treated under two aspects: the LNG price increases while the MGO price remains stable; the LNG price is kept steady while the MGO price decreases.

   (i) Scenarios under the rise of LNG price: Fig. 5 depicts several scenarios where the LNG price increases while the MGO price remains constant. As marked in this figure, the break-even point, i.e. the intersection of the NPC lines, can be identified at the point when the LNG price increases by 14.6%, precisely. This is the point where the corresponding price for LNG is 643 [€/t], which is equal to 1.3 the MGO price. Therefore, when the LNG price is comparatively higher, the economic viability of the dual-fuel engine can be downgraded.

   (ii) Scenarios under the slump of MGO price: Scenarios where the MGO price decreases while the LNG price is constant were also tested. As marked in Fig. 6, the break-even point is the point when the MGO price decreases by 11.6%, precisely. This is corresponding to the price of MGO of 449 [€/t], which is equal to 0.8 the LNG price. In this respect, the dual-fuel engine becomes the cost-effective option compared to the diesel engine.

Table 13
Summary of the LCC appraisal in the base case.

Cost category	20 year cash flow: Diesel engine		20 year cash flow: Dual-fuel engine	
	Non-discounted costs	Discounted costs	Non-discounted costs	Discounted costs
Construction costs	989K	989K	1,200K	1,200K
Operation costs	24,960K	15,553K	21,308K	13,277K
Maintenance costs	4,614K[a]	2,678K	5,050K[a]	2,940K
Labor costs	697K[a]	411K	720K[a]	425K
Part replacement costs	3,917K[a]	2,267K	4,330K[a]	2,515K
End-of-life value	17K	6K	22K	8K

[a] Inflated values with the inflation rate of 3.1%.
Unit K = 1000€, Discount rate $r = 5\%$.

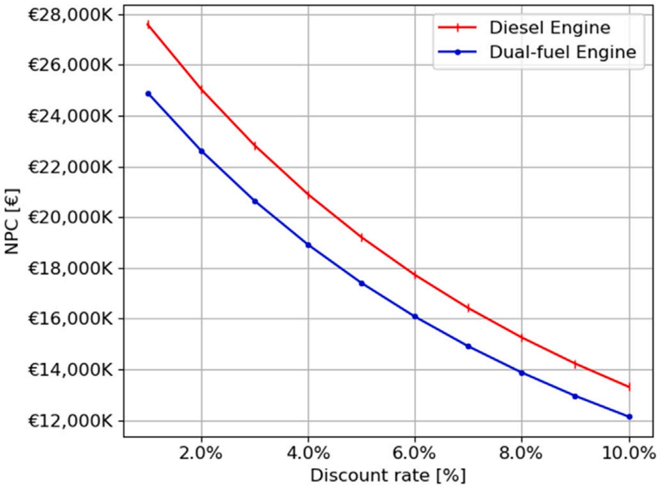


Fig. 7. Scenarios of discount rate fluctuations.

Table 14
Measures of economic performance in the base case.

Measure of economic performance	20 year economic calculations (discounted costs)	
	Diesel engine	Dual-fuel engine
Net Present Cost (NPC)	19,213K	17,409K
Net Saving (NS)	–	1,804K
Saving-to-ratio (SIR)	–	4.95

Unit K = 1000€.
Discount rate $r = 5\%$.

Table 15
Triangular distributions of variables.

Variable	(Min, Most Likely, Max)
MGO price [€/t]	(383.2, 469.4, 541.9)
LNG price [€/t]	(360.2, 482.2, 687.8)
Discount rate [%]	(1, 5, 10)
Inflation rate [%]	(1, 3.1, 5)
Annual operating hours [h/y]	(5500, 7500, 8760)
Hourly wages [€/h]	(20, 30, 46.9)

(b) Scenario sensitivity analysis on the discount rate: This was performed by varying the discount rate from 1 to 10%, as shown in Fig. 7. This figure is quite revealing in several ways. First, when the discount rate increases, there is a clear trend of decreasing the NPCs as well as the cost gap between the dual-fuel engine and the diesel engine. Second, it is more advantageous to opt for the dual-fuel engine regardless of the changes in the discount rate.

(c) Scenario sensitivity analysis on fuel prices and the discount rate: Fig. 8 provides an overall interconnected sensitivity of fuel prices and the discount rate on the NPCs of these engines. This underlines the effects of fuel prices and the discount rate on the NPCs of these engines.

4.1.7. Uncertainty analysis

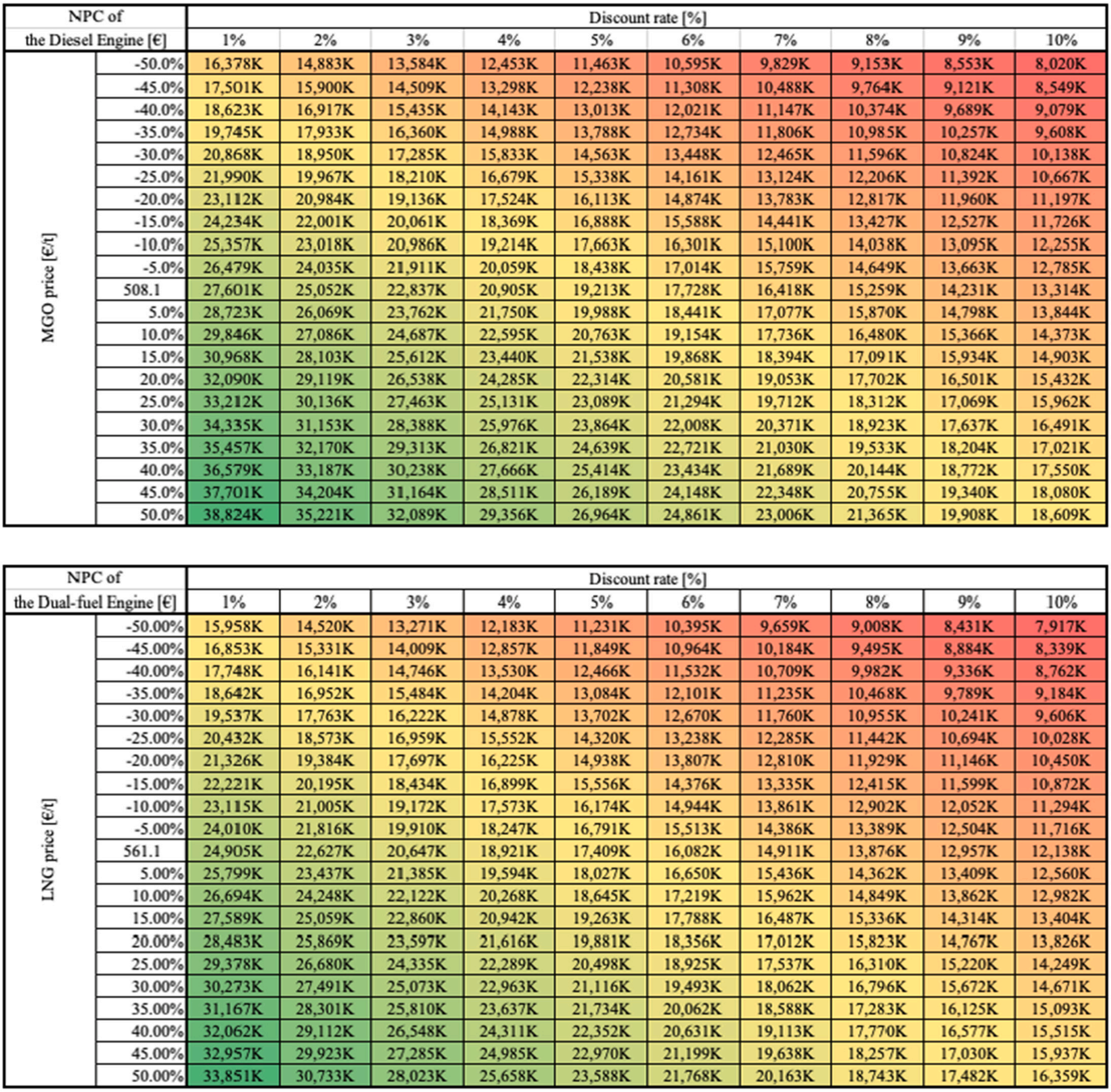
What follows is an account of uncertainty analysis running the Monte Carlo simulation in which the uncertainty is introduced in the model. In this regard, it is important to model the uncertainty (i.e. variables such as fuel prices, the discount rate) as either uncertainty distributions or fuzzy numbers and intervals (Emblemsvåg, 2003). Apart from fuel prices and the discount rates, the inflation rate, the annual operating hours, and the hourly wages were identified as uncertain variables. To model these variables, triangular distributions were chosen for several reasons. First, these variables are believed to be normally distributed but the uncertainty is quite large. When the uncertainty is quite large, a normal distribution appears to express too little on the ends of the distribution, and this is undesirable. Second, triangular distributions deal with asymmetry better than the normal ones. The triangular distributions of these variables are shown in Table 15. It needs to be mentioned that the min, most likely and max values of the variable distributions with regard to fuel prices were derived from a real public data source (Ship & Bunker, 2021).

The Monte Carlo simulation was run using the @RISK software. The number of iterations was set at 10,000. Fig. 9 depicts the results of the Monte Carlo simulation, demonstrating a distribution overlay of the NPCs of the respective engines. Given 10,000 iterations that were randomly generated, the NPC range of the diesel engine can be found from €26.7 million to €29.8 million with the probability of 62%. The probability of the NPC of the dual-fuel engine falling under this range is 68.6%. Therefore, it can be concluded that the dual-fuel engine is adequately superior to the diesel engine.

Apart from handling the uncertainty in the model, the @RISK software is capable of tracing the critical cost drivers. It can be seen from Fig. 10 that fuel prices are the dominant cost driver, influencing the NPC results the most.

4.2. The case of carbon pricing

Although MBMs (e.g., the IMO MBMs and EU ETS) have not yet been enforced, their relevance for the shipping industry is envisaged to grow in the near future. For this reason, carbon pricing will have an impact on the investment appraisal of emissions reduction technologies (Metzger, 2022). Therefore, it is worth considering them as external costs in the LCCA conducted in this study. Trivyza et al. (2019) and Perčić et al. (2020) examined the impacts of carbon pricing/carbon allowance on the life-cycle costs of the studied subjects in several scenarios based on the data obtained from World Energy Outlook 2019 and 2020 respectively. Recent years have witnessed an increasing trend in carbon prices. In this study, several carbon pricing scenarios corresponding to the latest data obtained from World Energy Outlook 2021 (WEO2021) were considered. It is noted that carbon prices in the WEO2021 were applied to other non-CO_2 emissions, such



NPC of the Diesel Engine [€]		Discount rate [%]									
		1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
MGO price [€/t]	-50.0%	16,378K	14,883K	13,584K	12,453K	11,463K	10,595K	9,829K	9,153K	8,553K	8,020K
	-45.0%	17,501K	15,900K	14,509K	13,298K	12,238K	11,308K	10,488K	9,764K	9,121K	8,549K
	-40.0%	18,623K	16,917K	15,435K	14,143K	13,013K	12,021K	11,147K	10,374K	9,689K	9,079K
	-35.0%	19,745K	17,933K	16,360K	14,988K	13,788K	12,734K	11,806K	10,985K	10,257K	9,608K
	-30.0%	20,868K	18,950K	17,285K	15,833K	14,563K	13,448K	12,465K	11,596K	10,824K	10,138K
	-25.0%	21,990K	19,967K	18,210K	16,679K	15,338K	14,161K	13,124K	12,206K	11,392K	10,667K
	-20.0%	23,112K	20,984K	19,136K	17,524K	16,113K	14,874K	13,783K	12,817K	11,960K	11,197K
	-15.0%	24,234K	22,001K	20,061K	18,369K	16,888K	15,588K	14,441K	13,427K	12,527K	11,726K
	-10.0%	25,357K	23,018K	20,986K	19,214K	17,663K	16,301K	15,100K	14,038K	13,095K	12,255K
	-5.0%	26,479K	24,035K	21,911K	20,059K	18,438K	17,014K	15,759K	14,649K	13,663K	12,785K
	508.1	27,601K	25,052K	22,837K	20,905K	19,213K	17,728K	16,418K	15,259K	14,231K	13,314K
	5.0%	28,723K	26,069K	23,762K	21,750K	19,988K	18,441K	17,077K	15,870K	14,798K	13,844K
	10.0%	29,846K	27,086K	24,687K	22,595K	20,763K	19,154K	17,736K	16,480K	15,366K	14,373K
	15.0%	30,968K	28,103K	25,612K	23,440K	21,538K	19,868K	18,394K	17,091K	15,934K	14,903K
	20.0%	32,090K	29,119K	26,538K	24,285K	22,314K	20,581K	19,053K	17,702K	16,501K	15,432K
	25.0%	33,212K	30,136K	27,463K	25,131K	23,089K	21,294K	19,712K	18,312K	17,069K	15,962K
	30.0%	34,335K	31,153K	28,388K	25,976K	23,864K	22,008K	20,371K	18,923K	17,637K	16,491K
	35.0%	35,457K	32,170K	29,313K	26,821K	24,639K	22,721K	21,030K	19,533K	18,204K	17,021K
	40.0%	36,579K	33,187K	30,238K	27,666K	25,414K	23,434K	21,689K	20,144K	18,772K	17,550K
	45.0%	37,701K	34,204K	31,164K	28,511K	26,189K	24,148K	22,348K	20,755K	19,340K	18,080K
	50.0%	38,824K	35,221K	32,089K	29,356K	26,964K	24,861K	23,006K	21,365K	19,908K	18,609K

NPC of the Dual-fuel Engine [€]		Discount rate [%]									
		1%	2%	3%	4%	5%	6%	7%	8%	9%	10%
LNG price [€/t]	-50.00%	15,958K	14,520K	13,271K	12,183K	11,231K	10,395K	9,659K	9,008K	8,431K	7,917K
	-45.00%	16,853K	15,331K	14,009K	12,857K	11,849K	10,964K	10,184K	9,495K	8,884K	8,339K
	-40.00%	17,748K	16,141K	14,746K	13,530K	12,466K	11,532K	10,709K	9,982K	9,336K	8,762K
	-35.00%	18,642K	16,952K	15,484K	14,204K	13,084K	12,101K	11,235K	10,468K	9,789K	9,184K
	-30.00%	19,537K	17,763K	16,222K	14,878K	13,702K	12,670K	11,760K	10,955K	10,241K	9,606K
	-25.00%	20,432K	18,573K	16,959K	15,552K	14,320K	13,238K	12,285K	11,442K	10,694K	10,028K
	-20.00%	21,326K	19,384K	17,697K	16,225K	14,938K	13,807K	12,810K	11,929K	11,146K	10,450K
	-15.00%	22,221K	20,195K	18,434K	16,899K	15,556K	14,376K	13,335K	12,415K	11,599K	10,872K
	-10.00%	23,115K	21,005K	19,172K	17,573K	16,174K	14,944K	13,861K	12,902K	12,052K	11,294K
	-5.00%	24,010K	21,816K	19,910K	18,247K	16,791K	15,513K	14,386K	13,389K	12,504K	11,716K
	561.1	24,905K	22,627K	20,647K	18,921K	17,409K	16,082K	14,911K	13,876K	12,957K	12,138K
	5.00%	25,799K	23,437K	21,385K	19,594K	18,027K	16,650K	15,436K	14,362K	13,409K	12,560K
	10.00%	26,694K	24,248K	22,122K	20,268K	18,645K	17,219K	15,962K	14,849K	13,862K	12,982K
	15.00%	27,589K	25,059K	22,860K	20,942K	19,263K	17,788K	16,487K	15,336K	14,314K	13,404K
	20.00%	28,483K	25,869K	23,597K	21,616K	19,881K	18,356K	17,012K	15,823K	14,767K	13,826K
	25.00%	29,378K	26,680K	24,335K	22,289K	20,498K	18,925K	17,537K	16,310K	15,220K	14,249K
	30.00%	30,273K	27,491K	25,073K	22,963K	21,116K	19,493K	18,062K	16,796K	15,672K	14,671K
	35.00%	31,167K	28,301K	25,810K	23,637K	21,734K	20,062K	18,588K	17,283K	16,125K	15,093K
	40.00%	32,062K	29,112K	26,548K	24,311K	22,352K	20,631K	19,113K	17,770K	16,577K	15,515K
	45.00%	32,957K	29,923K	27,285K	24,985K	22,970K	21,199K	19,638K	18,257K	17,030K	15,937K
	50.00%	33,851K	30,733K	28,023K	25,658K	23,588K	21,768K	20,163K	18,743K	17,482K	16,359K

Fig. 8. Fuel prices and the discount rate sensitivity.

Table 16
CO_2 price scenarios.
Source: OECD (2021).

Scenario	Price (€/t-CO_2)		
	2030	2040	2050
Stated Policies Scenario (STEPS)	57.46	66.3	79.56
Sustainable Development Scenario (SDS)	106.08	150.28	176.8
Net Zero Emissions by 2050 (NZE)	114.92	181.22	221

as methane (OECD, 2021). Table 16 provides information regarding the carbon pricing forecast for these scenarios in the EU region in 2030, 2040 and 2050 respectively. These values were used as reference values for interpolation of the annual carbon prices. Assuming 2022 is the base date for this study, the carbon price for 2022 is zero since neither MBMs (e.g., the IMO MBMs and EU ETS) is implemented in the shipping industry. Fig. 11 displays the results of the annual carbon prices. The considered carbon pricing scenarios are summarized as follows.

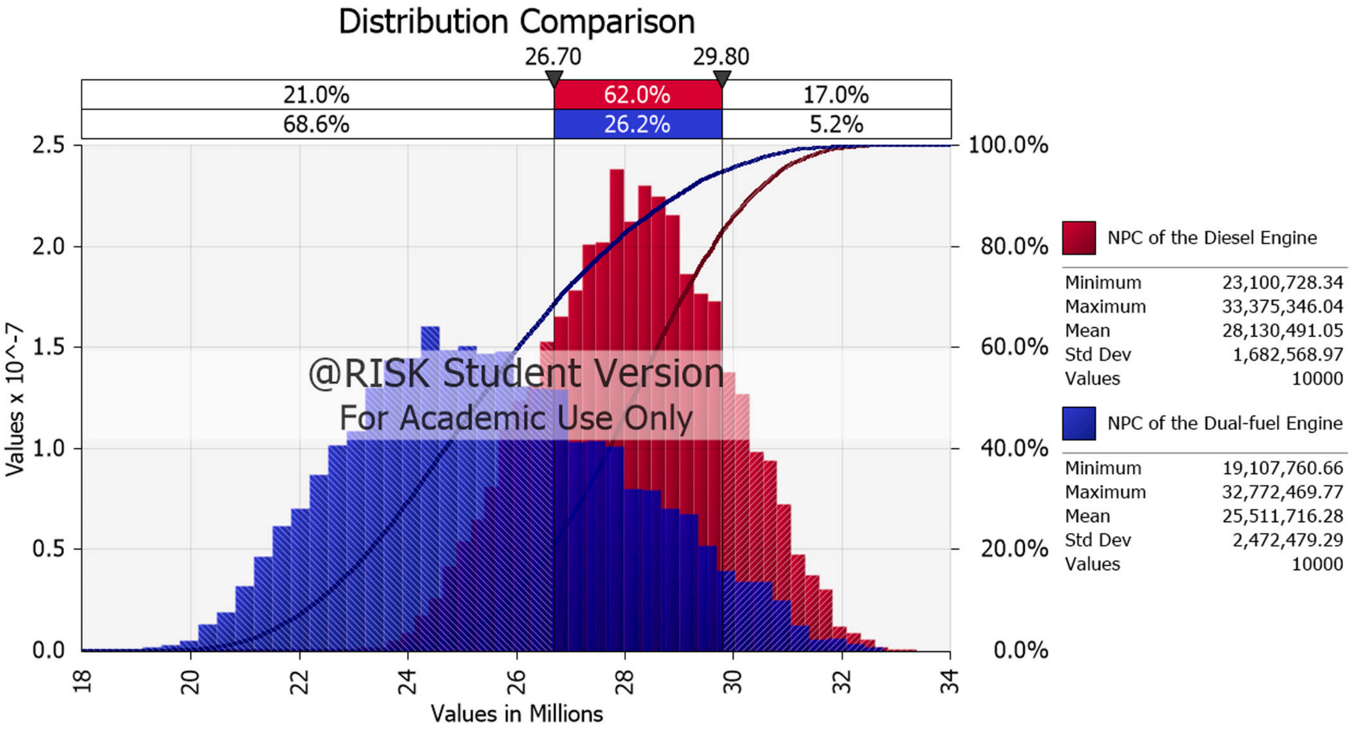


Fig. 9. Overlay graph of the NPC of the diesel engine and the NPC of the dual-fuel engine.

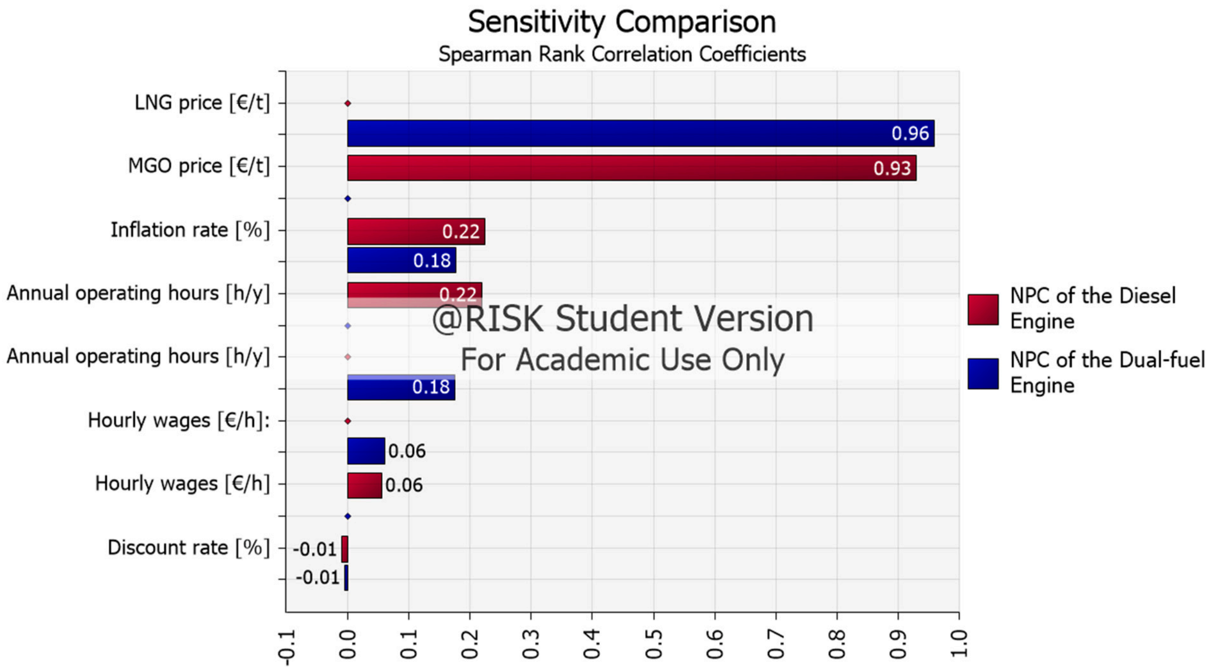


Fig. 10. Sensitivity chart.

(i) Stated Policies Scenario (STEPS) includes not just existing policies and measures but also those that are under development. An example of a measure that is under development is the EU's Fit for 55 package.

(ii) Sustainable Development Scenario (SDS) is the so-called "well below 2°" pathway to meet the Paris Agreement targets. It is noted here that the WEO21 also included the Announced Pledges Scenario (APS) which entails all of the climate commitments made by governments all over the world. However, the carbon prices for the SDS and the APS in the EU region were set the same. For this reason, only the SDS was considered in this study.

(iii) Net Zero Emissions by 2050 Scenario (NZE) is a narrow but achievable pathway for the global energy sector to reach net

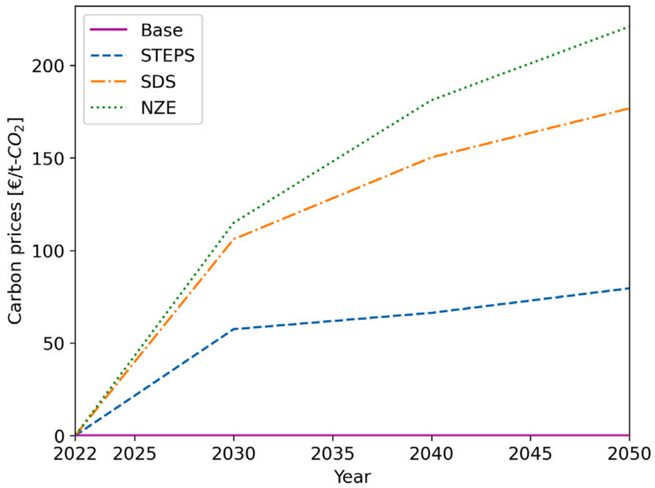


Fig. 11. Carbon pricing scenarios.

zero CO_2 emissions by 2050. Advanced economies are expected to achieve this target ahead of others.

Table 17 compares the NPC and NS results derived from the carbon pricing scenario analysis of the diesel engine and the dual-fuel engine. Fig. 12 depicts the cost category results (i.e. 20 year discounted costs). As stated earlier, the operation costs in the base case only consider the fuel costs while the operation costs in the three carbon pricing scenarios take into account the carbon emission costs. These costs were derived from the annual CO_2 emissions (Eq. (4)) and the annual carbon prices (Table 16). Since emitting CO_2 to the atmosphere has a detrimental effect on society, a lower discount rate should be chosen for long time periods. For this reason, calculations for the carbon emission costs were done by accounting for the discount rate of 3.5% (Smith, 2021). The effects of carbon pricing on the cost performances of these engines in the respective scenarios can be seen in Fig. 12. If either the IMO MBMs or EU ETS is implemented, it would lead to substantially higher carbon emission costs, thereby increasing the NPCs of these engines considerably in the higher carbon price scenarios (i.e., SDS and NZE). However, the dual-fuel engine is more cost-effective than the diesel engine because it yields lower NPCs in all carbon pricing scenarios. The carbon prices above 100 [€/t-CO_2] in the SD and NZE scenarios lends support to previous findings in the literature where Metzger (2022) argued that carbon prices of 100 [USD/t-CO_2] might increase substantially the Net Present Value (NPV) of a technology investment. The impacts driven by the carbon prices might be even higher as mentioned by ben Brahim et al. (2019). The proposal of the carbon levy of 100 [USD/t-CO_2] (i.e equivalent emissions) was submitted by the Marshall Islands and the Solomon Islands in the IMO's Marine Environment Protection Committee (MEPC76) meeting (Lagouvardou et al., 2022). The results are suggestive of a correlation between the cost effectiveness of emissions reduction technologies (e.g. the dual-fuel engine) and the potential introduction of MBMs. This indicates that MBMs are required to promote the adoption of future energy technologies.

It is also worth noting that the dual-fuel engine can offer an environmental benefit irrespective of fuel prices or carbon pricing scenarios. The environmental benefit of switching over to the dual-fuel engine can be quantified by using Eqn. (4) and the carbon emission conversion factor C_F given in Table 10. Given 20 years of operation, Table 18 details a considerable reduction in CO_2 emissions when opting for the dual-fuel engine. To be specific, a reduction in CO_2 emissions of 33% can be achieved, or 52,291 [t] of CO_2 would be eliminated.

Table 17
Measures of economic performance in carbon pricing scenarios.

Scenario	NPC		NS
	Diesel engine	Dual-fuel engine	
STEPS	30,487K	24,927K	5,560K
SDS	42,585K	32,994K	9,591K
NZE	46,261K	35,446K	10,815K

Unit K = 1000€.
Discount rate $r = 5\%$, inflation rate $I = 5\%$.
Discount rate for calculating the carbon emission costs $r' = 3.5\%$.

Table 18
20-year CO_2 emissions in operation.

Criteria	Diesel engine	Dual-fuel engine
Total CO_2 emissions [t]	156,954	104,663
Amount saving [t]		52,291
Percentage reduction [%]		33%

5. Conclusion

This study has proposed a LCC framework for evaluating the life-cycle cost performance of an innovative marine dual-fuel engine considering uncertainties involved over its lifetime. There are several important areas where this study makes noteworthy contributions to the current literature. First, it proposes a methodological framework for LCCA integrating the ISO 15686-5 standard and a detailed engineering build-up approach. Second, the uncertainties are extensively treated by the scenario sensitivity analyses and the Monte Carlo Simulation, filling the gap in the existing literature. Third, the insights gained from this study may be of assistance to decision makers (i.e., ship-owners and investors) as regards retrofitting decision-making. Fourth, it has an important policy implication for developing MBMs to promote the adoption of future emissions reduction technologies.

The proposed framework includes the development of a life-cycle cost model for the engine's life phases (i.e., construction, operation, maintenance and end-of-life) taking into account cases with and without carbon pricing (i.e. the base case). Furthermore, the KPIs pertinent to the measures of economic performance (i.e. the NPC, NS and SIR) have been offered to compare the potential benefits of adopting the dual-fuel engine against a conventional diesel engine. The main findings of this study are summarized as follows:

- The most dominant phase in the life cycles of the studied engines is the operation phase (i.e. the one with the highest cost).
- In the base case, the dual-fuel engine appears to be more cost-effective than the diesel engine since it has lower NPC (€17,409K versus €19,213K), the NS (€1,804K) greater than zero and the SIR (4.95) greater than 1.0.
- The uncertainty analysis using scenario sensitivity analyses uncovers that fuel prices are highly influential in affecting changes in the NPCs of these engines. Specifically, the cost effectiveness of the dual-fuel engine is sensitive to the high gas scenarios.
- The uncertainty analysis using the Monte Carlo simulation provides an adequate degree of confidence when opting for the dual-fuel engine. Furthermore, fuel prices are found to be the dominant cost driver.
- In the case of carbon pricing, the carbon prices result in significantly higher NPCs of these engines in the high carbon price scenarios. Nevertheless, the dual-fuel engine is still more cost-attractive than the diesel engine.
- Regardless of fuel prices and carbon pricing scenarios, a 33% reduction in CO_2 emissions can be achieved by opting for the dual-fuel engine.

It is critical to note that the fuel prices considered in this paper were derived from the current high price situation in the market in

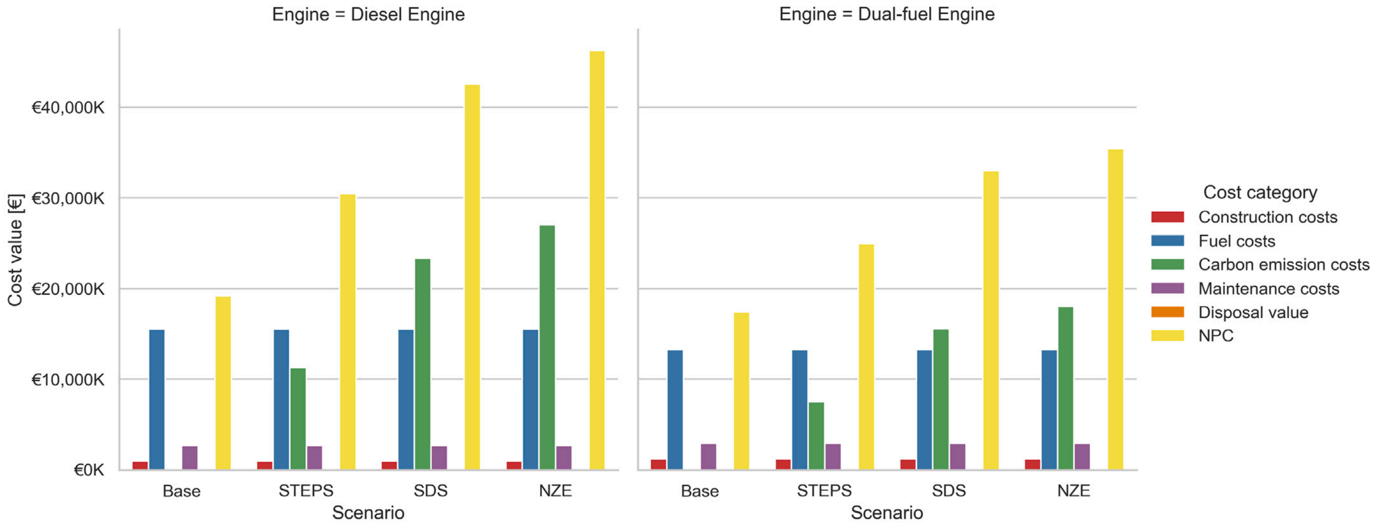


Fig. 12. Results of 20 year discounted costs under carbon pricing scenarios.

which the LNG price is higher than the MGO price. Looking into the past, this is unusual and regarded as temporary since the LNG price is expected to decrease in the near future (Ship & Bunker, 2021; The Loadstar, 2021). If the high LNG price persists, the dual-fuel engine is still a promising option since it brings flexibility for ship operators to switch to ULSD or VLSO in the diesel mode. The switch between fuels can be done seamlessly without loss of power or speed. Such fuel flexibility ensures regulatory compliance in Emission Control Areas (ECAs), while providing ship operators with the option of choosing the fuel according to cost and availability. It should also bear in mind that LNG has been well-established around the world with available bunkering infrastructure. Earlier studies have also demonstrated that LNG has been considered reliable today and for near future regulatory compliance (Trivyza et al., 2019; DNV, 2021).

However, the findings in this study are subject to a limitation in terms of lacking the costs of handling LNG tanks in the maintenance phase and the external costs incurred by air pollution from the construction and end-of-life phases. The monetization of the external costs from these phases would provide a complete socio-economic assessment. Additionally, this study is limited by the fact that the installation costs of the fuel tank systems, i.e., MGO for the diesel engine and LNG for the dual-fuel engine were not included. The possibility of having a higher installation cost for the LNG tank system cannot be ruled out. These limitations highlight the difficulty of collecting data on the respective phases. Considerably more work will need to be done when more data and information on these costs are available. LCCA is an intriguing area that could be usefully explored in further research on techno-economic assessment of future energy technologies.

CRediT authorship contribution statement

Khanh Q. Bui: Methodology, Software, Formal analysis, Investigation, Writing – original draft, Visualization. **Lokukaluge P. Perera:** Conceptualization, Writing – review & editing, Supervision. **Jan Emblemsvåg:** Writing – review & editing, 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.

Data availability

The authors do not have permission to share data.

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