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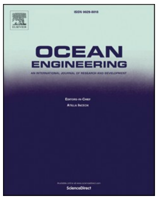

Life cycle emission and cost assessment for LNG-retrofitted vessels: the risk and sensitivity analyses under fuel property and load variations

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ABSTRACT

There are various energy efficiency and emission reduction regulations enforced by the national and international maritime authorities for the shipping industry to adopt greener technologies. In this light, LNG-fueled vessels can be a promising alternative for ocean going diesel operated ships. It will be more beneficial if the price of LNG is lower than diesel to make that an economically viable fuel. Otherwise, there are concerns over the emission/economic considerations under the cost-benefit analyses of such fuels during their lifetimes with the initial investment risk for the technology, related infrastructure including fueling facilities and technology retrofitting processes.

This study is an attempt to address the respective emission, energy, and cost concerns of LNG as a possible greener fuel with innovative dual-fuel engines within the SeaTech H2020 project (seatech2020. eu) initiative. The fuel life cycle of LNG in two scenarios of fuel property modification and load management for the cost analysis is considered. The life cycle assessment (LCA) section is designed to compare typical diesel and LNG fuels with selected short and deep-sea ship routes. Moreover, it is found that the effect of the ship travel distance on the amount of emissions is not significant when compared with the respective ratio. The life cycle cost assessment (LCCA) indicated that the fuel quality is more influential than the load variations in ship navigation. A 39% GHG emission reduction and up to a 22% fuel efficiency can be achieved under more optimal operational conditions by replacing LNG with diesel. The results also showed that the feasibility of using good quality LNG (higher Wobbe Index) instead of poor diesel characteristics in a selected ship is guaranteed within 30% of the sensitivity range. The fuel consumption variations under different engine loads (50% max to 85% min) can decrease the payback period from 6-years to 4-years as per the LCCA.

1. Introduction

The recent European Commission's (EC) sustainability plan for reliable and efficient power supply sources suggests several measures to mitigate climate change, by having measurable GHG reduction targets by 2030 and 2050 (Zappa et al., 2019). The international maritime organization (IMO) has introduced a 50% reduction of GHG emissions for shipping fleets by 2050 (Ölçer et al., 2018) and declared new energy efficiency measures (such as carbon intensity indicator (CII) and energy efficiency existing ship index (EEXI) compliance) to create energy efficient ships having a lower carbon footprint (IMO, 2021).

In order to support new strict emission regulations, the life cycle assessment (LCA) can be applied on ship operations which can operate with multiple alternative fuels (e.g., hydrogen, ammonia, methanol (Seddiek and Ammar, 2022)) or renewable energy sources such as solar and wind (Park et al., 2022), powered battery (Perčić et al., 2022), and fuel cells (Korberg et al., 2021). There are several research studies considered different powering sources and compared them with conventional diesel-fueled ships to demonstrate the feasibility and potential in green technologies in achieving the respective emission reduction targets. Zito et al. (2022) analyzed an environmental and economic life cycle of a solar hybrid ferry operated in short-sea operations. Based on the same survey, around € 500 K can be saved by using solar panels in a ship propulsion system compared to a diesel-powered engine in a selected ferry.

Liquefied natural gas (LNG) is known as a preferred alternative fuel in the shipping industry (Lee et al., 2020) in the recent year, which imposes less operational and maintenance costs and reduced emissions

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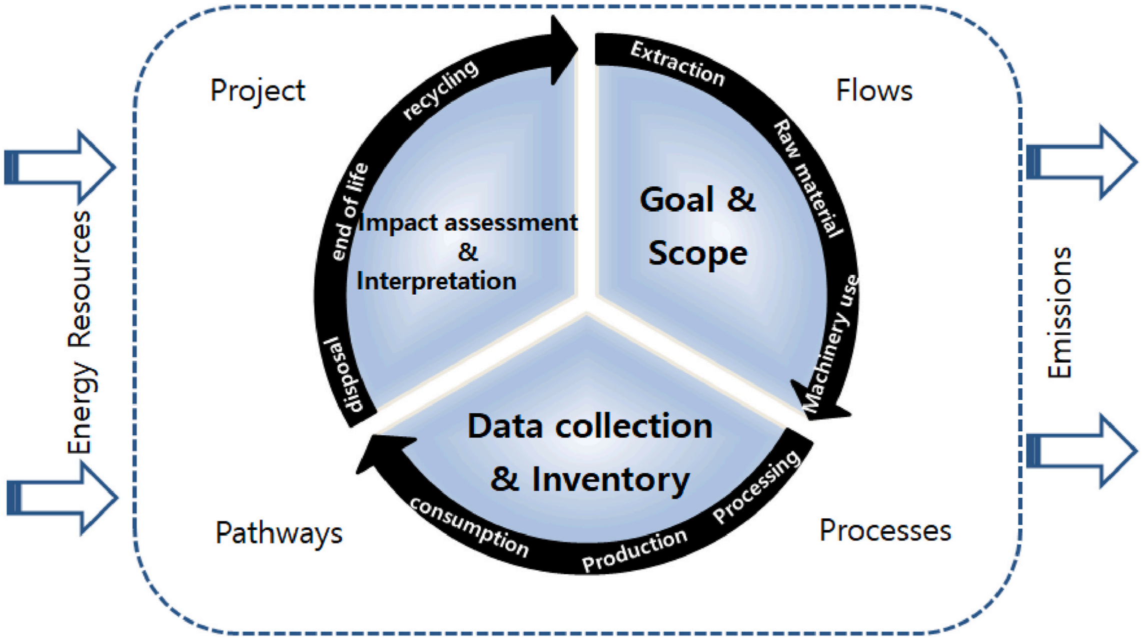


Fig. 1. The LCA workflow.

thereby no after-treatment requirements, although the initial and installment costs are somewhat higher (Livanos et al., 2014). Despite the discussed challenges such as high initial investment costs as well as powering system reconfiguration complexities for LNG, the number of LNG-powered vessels are growing (32% shipping energy demand for LNG by 2050) (Dnv-Gl, 2020; Van et al., 2019). The advantages of LNG can be categorized as its desirable non-toxic, non-corrosive, and odorless characteristics (Wan et al., 2019) with lower prices (i.e., under certain market conditions) from one side and the obviated need to use exhaust gas after-treatment devices such as selective catalytic reduction (SCR) units and scrubbers on the other side (Acciaro, 2014). In this context, Wang et al. (2021a) addressed that LNG-fueled ships are in better economic terms of the capital recovery factor (CRF) and life cycle cost (LCC), where the ship sailing index, fuel price, lifetime, and fuel gas supply systems can be varied. The study concluded that when the sailing time is low and the fuel price is high, onboard Boil-off gas (BOG) reliquefaction can be an optimal solution. The aforementioned papers have not focused on fuel and the fueling system specifications with fuel price uncertainties that can influence the overall assessments. Bui et al. (2021) have recently undertaken a thorough life cycle cost assessment (LCCA) on a retrofitted marine engine wherein the net present cost (NPC) as a financial indicator is used to evaluate the potential cost-effectiveness of dual-fuel marine engines. The results of the same research confirm the significance of fuel price variations under the investment and environmental considerations, i.e. a 33% CO_2 reduction while a selected dual-fuel marine engine is running on LNG. Lee et al. (2022) carried out an environmental LCA on eco-friendly fuels of marine gas oil (MGO), LNG, and hydrogen for a nearshore ferry. The study discussed that NOx and SOx emissions during the tank-to-wake process for MGO and LNG are lower, where CO2 emissions due LNG combustion can be lower. However, the hydrogen fuel from the well-to-wake process showed a considerable 10% increment in the global warming potential (GWP) level compared to LNG. Mio et al. (2022) provided a comprehensive review of the normalized LCA and several quantitative measures regarding various maritime transportation systems. A comparison is performed in the same study for different categories of ships with normalization LCA calculations that ultimately support eco-friendly shipbuilding and operational benchmarking efforts. Law et al. (2021) performed a comparative analysis of possible fuels for the shipping industry by considering the lifecycle energy and cost aspects, where 22 pathways are investigated with heavy fuel oil (HFO) as the baseline case. These different pathways are compared under different related factors, including the energy intensity, fuel mass, costs, and GHG emissions. It has been concluded that for short-sea shipping battery technology supported by renewable energy can be an efficient approach, however fossil fuels with carbon capture technology can also be a viable solution. Bui et al. (2022a) have undertaken a LCCA to assess the financial performance of a renovated dual-fuel engine with diesel-LNG. The study discussed several relevant factors' effect on the feasibility criteria of dual-fuel engines while the sensitivity and uncertainty considerations are also accommodated into the financial calculations. Agarwala (2022) put forward a question of whether LNG is a suitable fuel towards the decarbonization of shipping. The merits and demerits of the same fuel is surveyed and the controversies over the fulfillment of zero-emission transitions in shipping are reported. The LCA and costing implications of several marine fuels with different vessels with propulsive systems are investigated in (Kanchiralla et al., 2022), recently. The investigated fuels in this study include e-hydrogen, e-ammonia, e-methanol, and electricity, while a selected vessel is powered by marine engines and fuel cells with carbon capturing technology. The results indicated that the best combination would be fuel cells with e-ammonia to reduce the respective emissions and associated carbon control costs. In this context, the LCA of LNG, i.e., as a marine fuel, is highlighted in (Al-Douri et al., 2022) and possible solutions to reduce GHGs are emphasized in the same study. An 18% lifecycle emission reduction is expected with LNG, i.e. instead of conventional fuels, while incorporating renewable energy during the liquefaction process of LNG an extra 10% reduction is viable.

As discussed previously, one of the main considerations in the shipping industry in relation to emission reduction approaches is to use of alternative greener fuels in propulsion systems (LNG as the proposed fuel instead of diesel as the base fuel in many situations). However, the viability of greener fuels in shipping should be studied under the economic feasibility. The performed LNG-fueled LCA and LCCA in the recent years only provided some financial analyses with mainly the net present value (NPV) as an indicator. This study introduces several complementary and comprehensive financial indicators such as the benefit-to-cost ratio, payback period, year to positive cash flow, and internal rate of return as secondary evaluator indexes to evaluate the cost-benefit analysis of LNG. Most of the recent literature has not considered any sensitivity and risk assessment techniques, such as

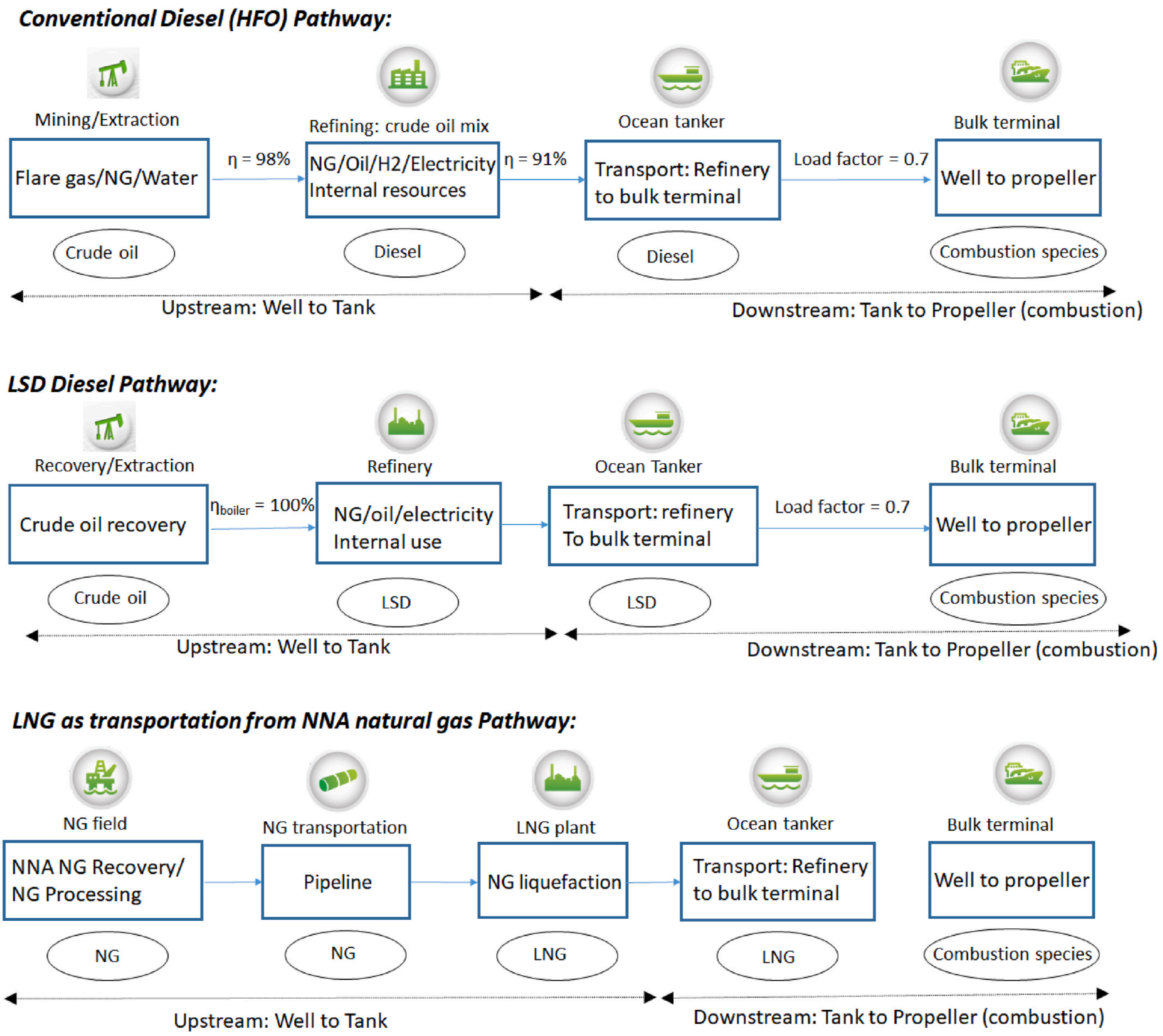


Fig. 2. Flow work diagram of step-by-step pathways for selected fuel types.

energy/emission/economic data with the Monte Carlo simulation. This is beneficial in the financial risk evaluations by specifying relevant uncertainties related to the input variables and analyzing its impact on the financial indicators or key performance indicators (KPIs). The main step is to define two scenarios in the LCCA structure that are dealing with two fuel types, i.e., diesel and LNG, their chemical property modifications as well as engine load variations. These two scenarios, to the author's knowledge, have not been reported, previously and the long-term effect of fuel properties on the financial impact of vessel performances can be informative for the shipbuilder, operators, and policymakers.

This striking contrast in LNG-fueled vessels is investigated insightfully in the proposed LCCA study. It is noted that any change in the fuel property, the respective pricing and emission factors should be updated accordingly during the LCCA. In the environmental LCA sense, the emissions are monitored separately during the well-to-tank (WtT) and tank-to-propeller (TtP) phases. The TtP process is developed for different routes of a selected ship in these studies.

In this research study, the LCA concept is utilized by using the emission assessment software (GREET). Then, the respective costs to the environment, i.e. by releasing such ship emissions, are substituted to obtain the final output as a monetary value. The LCCA results are then coupled with the clean energy technology analyzer (RETScreen) (Ganoe et al., 2014), where its functioning procedures are illustrated in Fig. 1. As shown in the figure, the very first process is to transform a product from the birth until the disposal of its life and recycling processes, however during each process the respective emissions have to be detected and calculated to estimate the total emission amount in the whole process.

2. Methodology

The first phase of this study is comprised of the LCA of selected fuel grades by considering selected ship routes and the respective voyage distances accompanied by the detailed LCCA with economical values for an engine operational lifetime of 20 years for two basic fuels of diesel and LNG.

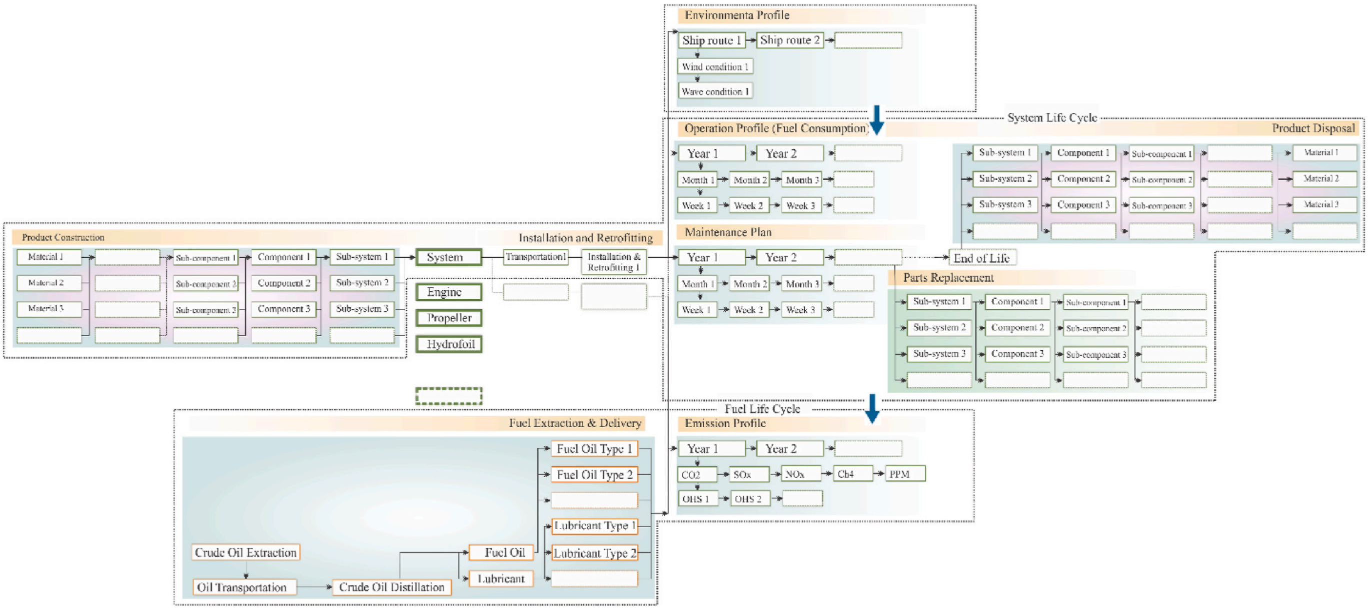


Fig. 3. The overall LCCA road map of the SeaTech Project and the fuel lifecycle system boundary.

2.1. *The LCA and LCCA implementation*

The implementation of the fuel LCA and LCCA are explained in this section, since an integrated approach has been proposed by this study, i.e. that is classified into the LCA approach for emission analysis and the LCCA approach for energy and emission implications.

2.1.1. *LCA approach*

Fuel and its usage as a pivotal and strategic product have various environmental and economic implications. The LCA technique follows the sequences of processes from the very first (from the oil and gas field) to the end (as ship emissions) and the end of the fuel lifecycle, while tracking the emissions to the atmosphere at each stage.

Firstly, the boundary of the operational blocks along with the energy sources and then the functional unit must be defined for each fuel in this pathway. According to the LCA guidelines introduced by standards ISO 14040 (ISO 14040, 2020) and ISO 14044 (ISO 14044, 2020), the objectives, scope of work, and data inventory must be prepared for the assessment while there are several supplementary standards of the impact assessment requirements for the advanced LCA. The functional unit of the LCA boundary is 1 g/MJ that is the grams of emissions per 1 MJ of the used energy unit from each process from the fuel production to the consumption pathway. In the GREET software, the input and output data as inventory are organized in groups. The existing emission factors in GREET for various combustion technologies are used to calculate the total energy produced and total emissions released by the combustion process. This allows the material Life Cycle Inventories (LCIs) to reflect future efficiency improvements in the combustion process associated with the respective engine technologies modeled in GREET. The non-combustion process emissions (e.g., sulfur emissions from processing sulfide ores) are included in the inventory by adding the same to the combustion emissions.

The fuel pathway and included processes are demonstrated in Fig. 2 as a workflow representation. The location and operation name at each stage or process during the WtT and TtP periods for conventional diesel (HFO), low-sulfur-diesel (LSD), LNG from non-north American (NNA) and natural gas (NG) are shown in the same figure. The emissions at the end of each process block (the square blocks) are registered and compiled together at the end. Each fuel type has been considered under the following characteristics: the pathway mix, group efficiency, machinery efficiency (e.g. gas turbine, boiler, engine, etc.), transportation characteristics such as the distance, fuel consumption (or energy density), and urban share for its lifecycle from the fuel extraction to its end of life as ship emissions.

The respective input-output models (the variables shown in Fig. 2 are fed to equations below to estimate the emissions) are applied by considering the relevant stages through a selected fuel production pathway, i.e. the inputs in this model consists of the following parameters of the emission mass ratio, mixer reference, source type, amount of a resource (*a(f)*), and technology should be defined, appropriately. The resources are the inputs such as the density, lower heating value, and carbon ratio of the fuel, etc. The energy and emissions are the outputs of the respective models and are required for the LCA to estimate the emissions released and the energy demand. The energy demand is calculated by (GREET. LCA software, 2020):

$$E(f) = a(f)E_{up}(f) \tag{1}$$

where the respective emissions are estimated as:

$$Em(f) = a(f)Em_{up}(f) + a(f)\sum_{t\in T} s(f,t)Ef(f,t) + Em_{other} \tag{2}$$

where *E(f)* and *Em (f)* represent the energy and emission vectors per input *f*, respectively. Also, $E_{up}(f)$ signifies the energy vector associated with the upstream energy to produce *f*. Additionally, *T* gives the technology set along the processes of the pathway, *s* is the share and *Ef* is the emission factor.

For the stationary processes, the energy efficiency and group efficiency are used to account the losses that can occur during each stage. The energy intensity for a selected vessel during its operations is estimated by:

$$ei(f_t,f) = \frac{ec(f)\times hp(f_t)\times loadFactor}{PayLoad(f_t)\times speed} \tag{3}$$

where f_t is the resource transported, *f* is the energy source, i.e. the fuel to power, *ec(f) is* the energy production by the respective fuel, and *hp* the required horsepower of a selected vessel.

2.1.2. *The LCCA approach*

According to Fig. 3, the LCCA of the technologies that can improve energy efficiency and emission reduction are presented. The technology development is started from the material level to system level. The fuel

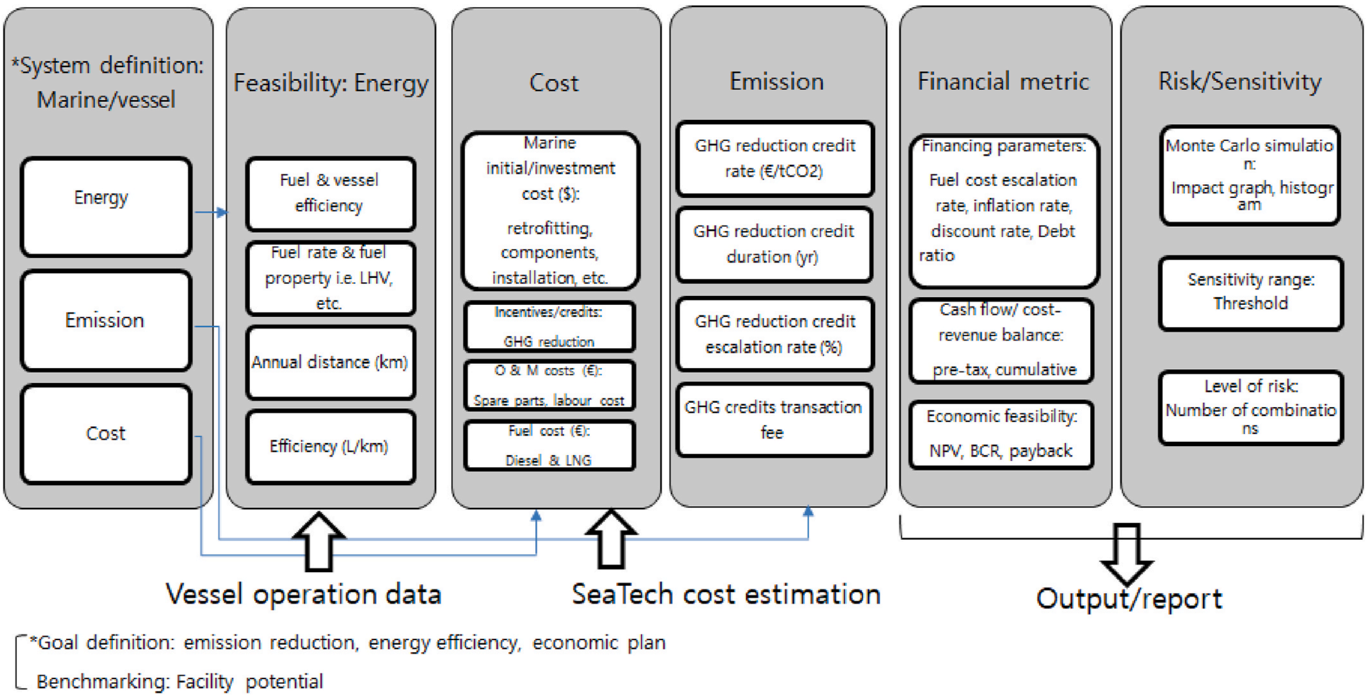


Fig. 4. Clean technology assessment workflow.

and system life cycles are interconnected and have a bilateral impact on each other. This approach is created a part of the SeaTech H2020 project (seatech2020. eu) (SeaTech Consortium, 2020). This study is mainly focusing on the fuel life cycle where diesel and LNG fuels are considered on the same LCCA.

Conventional vessels have to be modified or retrofitted to facilitate LNG based engines and that retrofitting process includes changes in the powertrain system, fueling system, tanks, pumps, and heat exchangers. The total cost of any retrofitted power systems can include diesel engine modification its consequential maintenance costs, fuel costs, carbon credits, and operation costs that are utilized in the LCCA. The cash flow during the lifetime of an LNG-retrofitted vessel allows for calculating the financial indicators which can provide detailed information about the viability of a retrofitted project. Because of the technical and financial parameter variations such as fuel pricing fluctuations, the sensitivity analysis is a proper tool to introduce the input parameter variations and observe its impact on the output parameters to achieve realistic conclusions. The RETScreen clean energy Project platform is used to carry out the LCCA.

Fig. 3 shows the overall picture of different stages of LCCA during a retrofitting process with the steps of product constructions, installation and retrofitting, operation profile, maintenance plan and parts replacement, and product disposal. One should note that the environmental profile can also influence on the retrofitted systems. The fuel replacement not only deals with the fuel properties of diesel and LNG but also involves the powertrain system configuration that are represented in different blocks and sub-systems breakdown. The detailed list of costs inventory per year have to be listed and used during the calculations and then distributed over the years of lifetime of the vessel and ship systems as demonstrated in Fig. 3.

Fig. 4 shows various components of the LCCA that will be explained in the following sections. By determining the location and facility information in the marine transportation, the LNG-powered technology benchmarking in a selected vessel is ready for the first phase of the cost analysis. In the second phase, the feasibility study is performed where the inputs of the model should be set, including the energy model delineation (the vessel fuel efficiency, energy intensity, etc.), cost estimation (incremental initial cost and exploitation cost), and emission analysis (the amount of GHG, credit rate, etc.). The model outputs from the same software are calculated as a dataset in the financial and risk analysis phase of the LCCA. Finally, the interpretation of the results where a comparison is made between the base (conventional fuel) and the proposed case (clean or efficient fuel), where the recommendations can be presented to the engine manufacturers and shipowners for decision making.

Table 1
Main vessel's design characteristics.

Bore × Stroke (mm^2)	310 × 430
Mean effective pressure/MEP (MPa)	2.96
Engine speed (rpm)	650
Main engine power (kW)	1346.8
Design ship speed (kn)	8.0
Displacement/deadweight (ton)	14804.5/10543.2
Design drought (m)	8.0

2.2. *The vessel specification (definition of the energy system's efficiency)*

In this study, a dual-fuel engine with LNG is used as the main fuel, and a very small portion of pilot diesel is also used in the combustion chamber. The SeaTech project aimed to launch a new powertrain system operated, i.e., an innovative retrofitted dual-fuel engine (diesel-LNG). One should note that the decision makers in shipping are interested to evaluate the feasibility and sustainability of retrofitting an existing diesel engine with an innovative dual-fuel engine. The costs of such an innovative engine with the economic and environmental benefits gained using LNG with proper energy density during the engine lifetime has been the focus of this study.

Since a very small portion of diesel fuel is used to support the ignition process in the same engine, the effect of diesel in a dual-fuel mode operation is assumed to be negligible and therefore has not been taken into the LCCA. The engine combustion process is characterized as a low-temperature combustion (LTC) process that reduces considerable NOx emissions and due to the low C/H ratio in molecular composition compared to a conventional diesel engine, the low CO_2 content from the

Table 2

Annual engine characteristics of the ship based on the classified clusters.

Cluster Number	Operating Hours	Average Engine Power (kW)	Average Engine Speed (RPM)	Average Ship Speed (kn)
1	922.4	1557.83	549.62	11.21
2	1272.12	2671.66	634.14	12.73
3	1446.82	2435.96	623.7	13.04
4	252.1	634.9	475.04	6.33
5	327.6	3554.9	719.15	14.62
6	109.88	2105.19	614.31	7.16
7	289.65	1165.83	719.6	5.28

exhaust gas is also expected. However, the main GHG challenge of LNG is attributed due to the methane slip during WtT (BOG and liquefaction) and TtP (unburned CH_4 in the combustion chamber) phases. The selected vessel particulars with the respective main marine engine are presented in Table 1. Since these data are registered transiently, the average values over the selected operation period are reported in this study.

The marine engine is operated under 7 engine modes that are identified by analyzing the data clusters that are related to engine power and speed data sets. The engine specifications that are extracted from the data sets are provided in Table 2. The engine power, engine speed, distance, operating hour, and ship speed information of the selected vessel based on the clustered data are listed in the same. One should note that these data clusters are related to engine operational modes.

The average weighted quantity (AWQ) is defined as the weights allocated for each data cluster of engine operations so that can have a closer approximation of the respective fuel consumption in each engine mode. Based on the above assumption, the following weighted operational mode characteristics are calculated:

$$AWQ = \frac{\sum_{i=1}^{i=7} w_i q_i}{\sum_{i=1}^{i=7} w_i} \tag{4}$$

An investigation on different fuel types is carried out by assuming that usage of both fuels leads to the same engine power output and an identical ship speed profile to allow a logical comparison between both fuels. To maintain the engine power and vessel speed conditions (operation time and travelled distance) at a fixed level for both fuels, a coefficient must be defined and then applied to the fuel consumption rate of diesel and LNG in the selected engine. This coefficient is obtained by:

$$C(kWh/km) = \frac{AWS}{AWP} \tag{5}$$

C is the coefficient that is applied to the specific fuel consumption results in the vessel fuel efficiency term that shows how much fuel is consumed by the vessel over a given distance. The vessel efficiency then is computed by multiplying the same coefficient with the specific fuel consumption (SFC) of each case:

$$System\ Efficiency\left(\frac{L}{100km}\right) = C(kWh/km) \times SFC(L/kWh) \tag{6}$$

The specific fuel consumption at each engine load for diesel and LNG are specified based on the experimental observations of the SeaTech engine and that information is provided by the engine manual. The study is classified based on two scenarios (Scenario 1: the fuel property variations and Scenario 2: the engine load variations of ship operations). Each scenario consists of two cases (case 1: small difference between diesel and LNG fuel consumptions, case 2: large difference between diesel and LNG fuel consumptions, case 3: 50% engine load, and case 4: 85% engine load). In Scenario1, which is based on fuel property variations the engine load is considered as a constant and taken at full load (100%) with a 177.2 g/kWh fuel oil (diesel) consumption rate and 7128 kJ/kWh of fuel gas (LNG) consumption rate in the main engine. In Scenario2, which deals with the following marine engine operating conditions, i.e. the highest consumption occurred at the 50% engine load (SFC_d = 180.4 g/kWh, SFC_{LNG} = 7157 kJ/kWh) and the lowest consumption at the 85% engine load (SFC_d = 172.5 g/kWh, SFC_{LNG} = 7059 kJ/kWh), are considered while the fuel properties of diesel and LNG are kept unchanged. The specific fuel consumption in the four cases are converted per L/kWh and then multiplied by the constant coefficient of the engine characteristic to attain the engine's average fuel efficiency.

2.3. The LCCA calculation (economic evaluations)

The transportation costs for construction materials and equipment can vary widely depending upon the available transport modes. In many instances for the LCCA calculations, the engine construction cost has also been included in the investment cost category, i.e. based on the used material costs according to the weight ratio of the materials.

2.3.1. Emission economy

The GHG emissions consists of three main components of CO_2, CH_4, and N_2O and those emissions are stated per equivalent unit of tCO_2 for the overall GHG emissions. The CO_2 emission factor for the LNG has converted to kg/GJ as an input parameter in the emission calculations. Note that the case sensitive emission factor is based on the heating value

Table 3

Summary of emission factors and total GHG released per consumed fuel in the selected engine.

	CO2 emission factor (kg/GJ)	CH4 emission factor (kg/GJ)	N2O emission factor (kg/GJ)	Fuel consumption (kWh)	GHG emission factor (kg CO2/kWh)	GHG emission tCO2
Case 1 (δ)						
Diesel (#2 oil)	67.48	0.001963	0.0005537	22385279.7	0.244	5454.3
LNG	55.89	0.27	0.00019	19947943.0598	0.229	4560.1
Case 2 (Δ)						
Diesel (#2 oil)	70	0.002	0.0006	23164547.66	0.253	5854.9
LNG	48.6	0.2348	0.0001652	18,062,472	0.199	3590.5
Case 3: 50% load						
Diesel (#2 oil)	70	0.002	0.0006	23152195.9027	0.2528	5851.8
LNG	55.89	0.27	0.00019	20387663.6302	0.2286	4660.6
Case 4: 85% load						
Diesel (#2 oil)	70	0.27	0.0006	22138324.8011	0.2528	5595.5
LNG	55.89	0.27	0.00019	20105690.3188	0.2286	4596.2

and that must be specified. This is performed by using different LNG qualities/heating values (LNG: CO_2 emission factor = 2750 g/kg fuel) (https://www.ipcc.ch and revised IPCC Guidelines for; Consistent Methodology for Estimating Greenhouse, 2015). The LNG emission factor for CH_4 and N_2O are based on IPCC guideline (https://www.ipcc.ch and revised IPCC Guidelines for), while diesel emission factors are extracted automatically by the software library of the fuel properties. The LNG has comparatively lower CO_2 and N_2O factors compared to diesel, however the CH_4 factor is higher. The emission factors and annual fuel consumptions can be used to calculate the GHG emission reduction from LNG with compared to diesel by considering both high and low fuel consumption situations. The GHG reduction by using LNG instead of diesel for different cases can be estimated as:

$$\begin{aligned}\Delta_{GHG} = \left(e_{base,GHG}FC_{base} - e_{prop,GHG}FC_{prop}\right) = \Big(&(GWP_{CO_2}EF_{CO_2} \\ &+ GWP_{CH_4}EF_{CH_4} + GWP_{N_2O}EF_{N_2O})_{base=diesel}\mathrm{FC}_{base=diesel} \\ &- (GWP_{CO_2}EF_{CO_2} + GWP_{CH_4}EF_{CH_4} + GWP_{N_2O}EF_{N_2O})_{prop=LNG}\mathrm{FC}_{prop=LNG}\Big)\end{aligned} \tag{7}$$

where *e* represents the GHG emission factor, *FC* is the fuel consumption, *EF* is the emission factor of individual species participating in GHGs. The subscript 'prop' stands for the proposed LNG-powered powertrain. The GWP coefficients applied to each emission factor are extracted according to the international panel on climate change (IPCC) (CHANGE, 2007). The GHG emission factors can vary according to the use of fuel in different industrial categories, transportation types, vessel/vehicle types as well as the type and quality of fuels. In this study, the emission factors are modified based on the fuel quality. The emission factor can be used to calculate the reduction in GHGs and that can be transformed into a monetary value. The above parameters of Eq. (7) are listed in Table 3 for different case studies under the two described scenarios.

2.3.2. Economic feasibility calculations

Based on the entered input data, the financial indicators mentioned below are computed and then analyzed under this study, facilitating the technology/fuel evaluation process for the decision-makers, i.e. ship owners.

2.3.2.1. Internal rate of return (IRR) or rate of investment (RoI). The internal rate of return (IRR) is defined as the discount rate that makes the Net Present Value (NPV) of the project to be zero. It resulted by solving the below equation for the IRR (Natural Resources Canada, 2005):

$$0 = \sum_{n=0}^{N} \frac{C_n}{(1 + IRR)^n} \tag{8}$$

where *N* is the project life in years (20 years in this case), and C_n is the cash flow in year n (C_0 is the cash flow for year zero, i.e., the equity of the project minus incentives). The IRR can be undefined in some cases, especially when the study resulted in an instant positive cashflow in year zero.

2.3.2.2. Simple/equity payback. The simple payback (SP) period is the number of years it takes for the cash flow (excluding debt payments) to equal the total investment (which is equal to the sum of the debt and equity) (Natural Resources Canada, 2005). The assumption about this parameter is that the sooner the payback, the more desirable the investment. Although this index does not show the profitability of the investment, it is useful as the secondary evaluator. The SP period is estimated as:

$$SP = \frac{C - IG}{(\mathrm{C}_{egy} + \mathrm{C}_{GHG}) - (\mathrm{C}_{O\&M} + \mathrm{C}_{fuel})} \tag{9}$$

Table 4
The LNG and associated NG attributes based on the LNG quality classifications.

LNG type	Methane composition (%)	LNG density (kg/L)	NG density (kg/m^3)	LNG HHV (MJ/L)	NG HHV (MJ/m^3)	WI (MJ/m^3)
Light LNG	98.0	0.4277	0.7129	23.626	40.48	53.06
Medium LNG	92.0	0.4456	0.7428	25.444	41.77	53.64
Heavy LNG	87.0	0.4648	0.7747	28.1	44.24	55.63

Where *IG* is the incentives and grants gained during the project economic balance, and *C* is the total initial cost of the investment. $C_{O\&M}$ accounts for the yearly operational and maintenance costs incurred by replacing the clean energy (LNG in gas mode operations) by the retrofitting investment, C_{fuel} is the annual cost of fuel, C_{egy} is the annual energy saving, and C_{GHG} is the GHG reduction incentive or income. However, the simple payback period is different from the equity payback period (or so-called year-to-positive cash flow). The year-to-positive cash flow (N_{PCF}) is the first year that the cumulative cash flows for the project are positive.

It is estimated by solving for N_{PCF} from the following equation:

$$0 = \sum_{n=0}^{N_{PCF}} \widetilde{C}_n \tag{10}$$

where C_n is the after-tax cash flow in year *n*.

2.3.2.3. Net present value (NPV). The NPV of the technology investment is the total value of all future cash flows, discounted at the discount rate, in today's currency. It is calculated by discounting all cash flows as given in the following formula (Natural Resources Canada, 2005):

$$NPV = \sum_{n=0}^{N} \frac{\widetilde{C}_n}{(1 + r)^n} \tag{11}$$

where *r* is the discount rate.

2.4. Fuel specification

The classification of various diesel fuel (MDO) grades is done in accordance with the respective fuel density values. One should note that the fuel density is linked to the corresponding heating value, therefore the following equation is used to correlate the fuel density to the net specific energy (CIMAC HFO Working Group, 2003):

$$\begin{aligned}LHV_{MDO} = &\left(46.423 - 8.792\rho^2_{@15C}10^{-6} + 3.17\rho_{@15C}10^{-3}\right)[1 - 0.01(\mathrm{w} + \mathrm{a} + \mathrm{s})] \\ &+ 0.0942\mathrm{s} - 0.024\mathrm{w}\end{aligned} \tag{12}$$

where *w, a,* and *s* denote water, ash, and sulfur contents (expressed by mass percentage) at each corresponding density at 15 °C in kg/m^3. Applying $\rho = 800$ kg/m^3 and $\rho = 900$ kg/m^3 and reading the associated *w, a,* and *s* for the bunker fuel heating value is computed. The HHV = 45.897 MJ/kg (36.7176 MJ/L) is resulted for $\rho = 800$ kg/m^3 and for $\rho = 900$ kg/m^3, the HHV = 44.353 MJ/kg (39.9177 MJ/L) is obtained.

The LNG fuel quality relates to its methane content, therefore that can be used to rate this fuel. The lean or light LNG (methane >95%) has lower heating values, while the rich or heavy LNG (methane <95%) contains higher heating values. In order to quantify the LNG quality, the Wobbe Index (WI), a well-established criterion based on the ratio of the fuel heating value and density for LNG, is represented below (Wood et al., 2011):

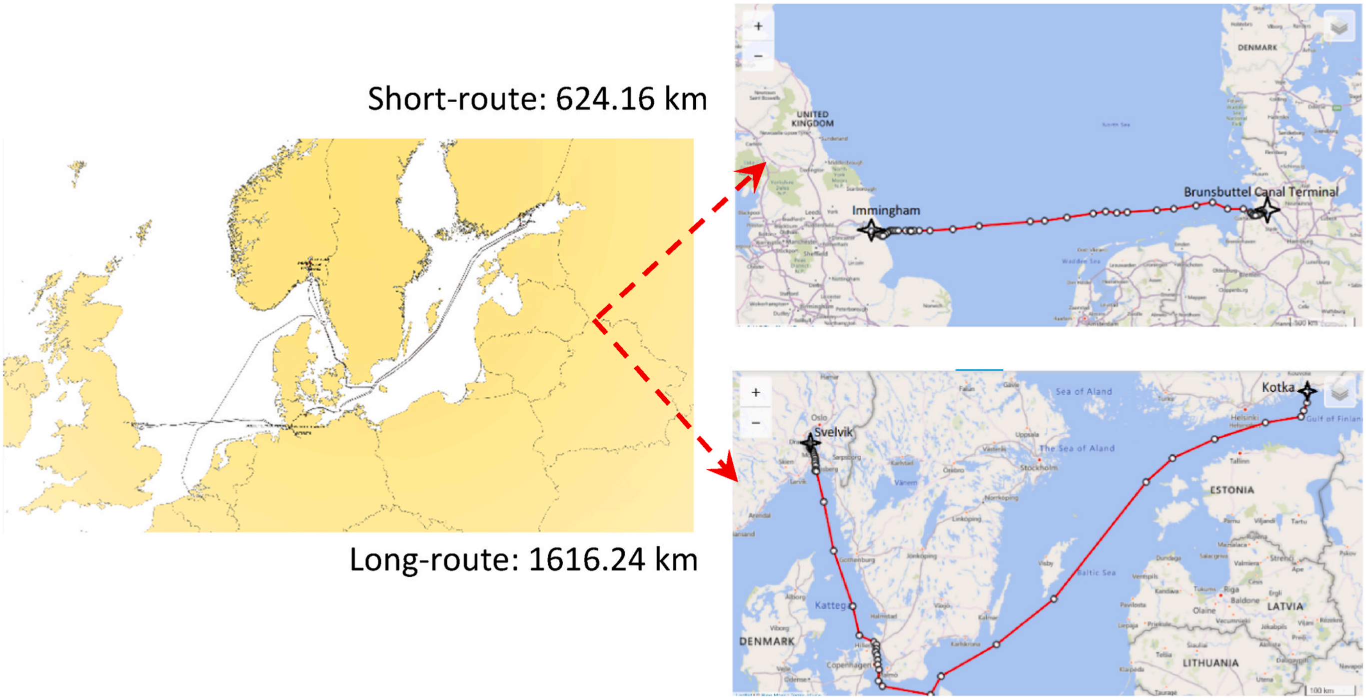


Fig. 5. Shipping routes with distance calculations: (a) Immingham (England)- Brunsbuttel Canal Terminal (Germany): ~624.16 km, (b) Svelvik (Norway)- Kotka (Finland): ~1616.24 km.

$$WI_{CNG} = \frac{HHV(MJ/m^3)}{\sqrt{S_G}} \tag{13}$$

where S_G represents the special gravity of LNG. The LNG classification is based on its density and that is presented in Table 4 (Benito, 2009).

An increment in methane in the composition of LNG leads to a lower density of *WI* criterion as well as energy content in a unit of LNG. For example, the heating value of lean LNG (lower density) is 23.62 MJ/L and rich LNG (the higher density due to having more proportion of hydrocarbons) is 28.1 MJ/L.

Therefore, WI = 53.06 (MJ/m^3) and WI = 55.63 (MJ/m^3) are used for the purpose of fuel modification scenarios since they represent two different qualities of LNG in an acceptable range of fuels (the pricing for high-quality LNG is taken 5% higher than the low-quality LNG).

- Air density is taken 1.225 kg/m^3 to calculate S_G to be used in *WI*

3. Result and discussion

The first part of this study deals with the emission factor variations with different fuels of interest at different phases of the LCA pathway. The estimated emissions are calculated from the combustion process of a marine engine in a selected vessel for the specific ship routes. The next part constitutes the economic evaluation with a feasibility index for each case and then the Monte Carlo and multi-regression methods have been applied for the sensitivity and risk analyses of the technology investment in a big picture of 20 years (the engine life). The cash flow diagram along with the financial input parameters allows for exploring the upcoming opportunities and threats for the decision-makers in shipping.

3.1. LCA results

The LCA calculations in this study is based on a selected ship routes that consist of two short routes (R1) and one longer route (R2) from the port of Immingham (England) to Brunsbuttel canal terminal (Germany) for 624.16 km and from the port of Svelvik (Norway) to Kotka (Finland) for 1616.24 km (Taghavifar and Perera, 2022). Two main fuel types of diesels and LNG are analyzed by GREET 2020 in both upstream (in the production: WtT) and downstream (in the consumption: TtP) phases. The selected ship routes in the study consist of the GPS data in a given timeframe for a selected vessel, where the respective ship routes are presented in the left plot of Fig. 5. From the selected ship routes in the same figure, two paths characterized as short and long routes that are selected for the emission calculations during the TtP (in the combustion) process of the LCA. In this study two types of diesel fuels, i.e., conventional heavy fuel oil (HFO) and low Sulfur diesel (LSD: <0.5% S), are taken to examine and compare the respective emissions with LNG with various fuel qualities.

In Fig. 6, the emissions from the life cycle perspective are presented under the WtT and TtP categories with the downstream being classified to R1 and R2 routes for diesel (HFO and LSD) and LNG. The results indicate that GHG emissions associated with GWP100 for LSD during the production and combustion phases are the highest. While GHG emissions of the TtP shows a slight increase compared to the WtT, LNG shows an average emission reduction of 29.2%. In general, for all species of Fig. 6 the emissions from LNG as a result of the combustion process (during the transportation phase declined compared to the WtT (extraction/recovery). The methane amount of LNG during the production and post-combustion processes is considered as 0.18 g (due to methane slip or leakage) and ~0.4 g due to unburned CH_4 from the exhausts (Schinas and Butler, 2016). Additionally, an increment of the emission species from R1 path to R2 is noticeable, although this change from the short route to the longer route is not remarkable because the reported emissions per the traveled distance are not on an annual basis. The analysis per mission or distance allows to closer control and monitor of the released emissions and take necessary measures rather than the annual-based LCA analysis. LSD shows an unusual trend in NOx emissions such that the NOx emissions of the TtP is lower than the WtT. This can be attributed to the LSD extraction process which requires extra machine operations on crude oil. Additionally, the LSD's chemical composition in fuel oxidation brings about low-temperature combustion characteristics.

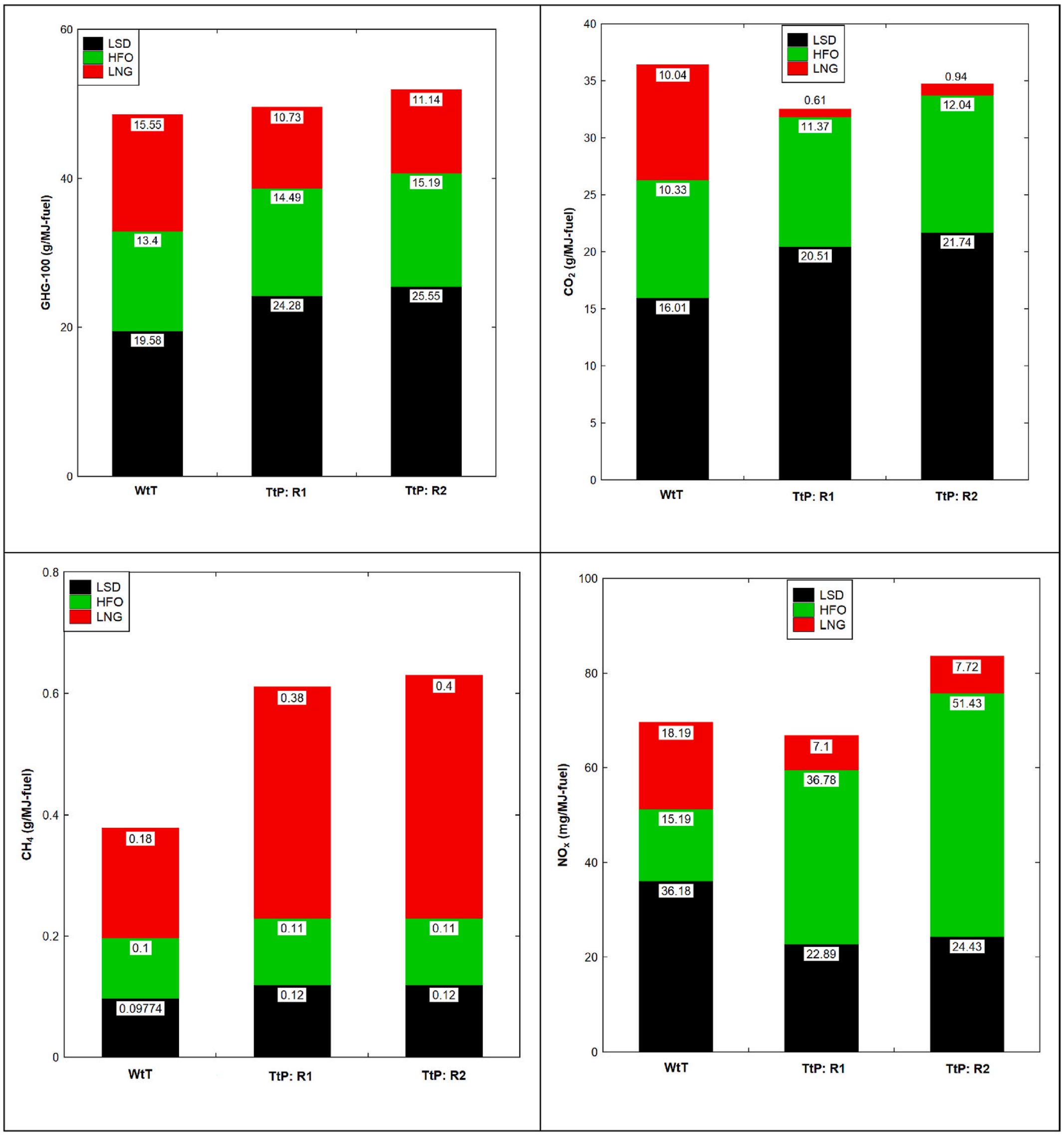


Fig. 6. The major species GHG100, CO2, CH4, and NOx released during fuel production as a stationary process and fuel combustion as in transportation for R1 and R2 routes in the respective fuel life cycle.

Table 5
Fuel/energy amount comparison between diesel and LNG.

	Base case (diesel)	Proposed case (LNG)	Base case (diesel)	Proposed case (LNG)	Base case (diesel)	Proposed case (LNG)	Base case (diesel)	Proposed case (LNG)
	Scenario 1: Fuel properties				Scenario 2: Operational condition (load)			
	Case 1		Case 2		Case 3		Case 4	
Fuel HV (MJ/L): Density (kg/L)	39.91: 0.9	25.44: 0.445	36.71: 0.8	28.1: 0.464	38.67: 0.85	27: 0.44	38.67: 0.85	27: 0.44
Annual distance (km)	100,197.13	100,197.13	100,197.13	100,197.13	100,197.13	100,197.13	100,197.13	100,197.13
[a]Fuel rate/pricing (€/L) (Wood et al., 2011)	1.0644	0.578	0.9462	0.6067	1.01	0.578	1.01	0.578
Average efficiency (L/100 km)	2014.857	2866.8524	2266.7142	2595.8787	2171.904	2712.6282	2076.7929	2675.4845
Fuel consumption (L)	2,018,829	2,872,504	2,271,183	2,600,996	2,176,186	2,717,976	2,080,887	2,680,759
Fuel consumption-total (kWh)	22,385,280	19,947,943 (10.9% ↓)	23,164,548	18,062,472 (22%↓)	23,152,196	20,384,817 (12%↓)	222,138,325	20,105,690 (9.2%)

[a] Fuel update pricing based on Rotterdam 27/05/2022 (Rotterdam Bunker Prices).

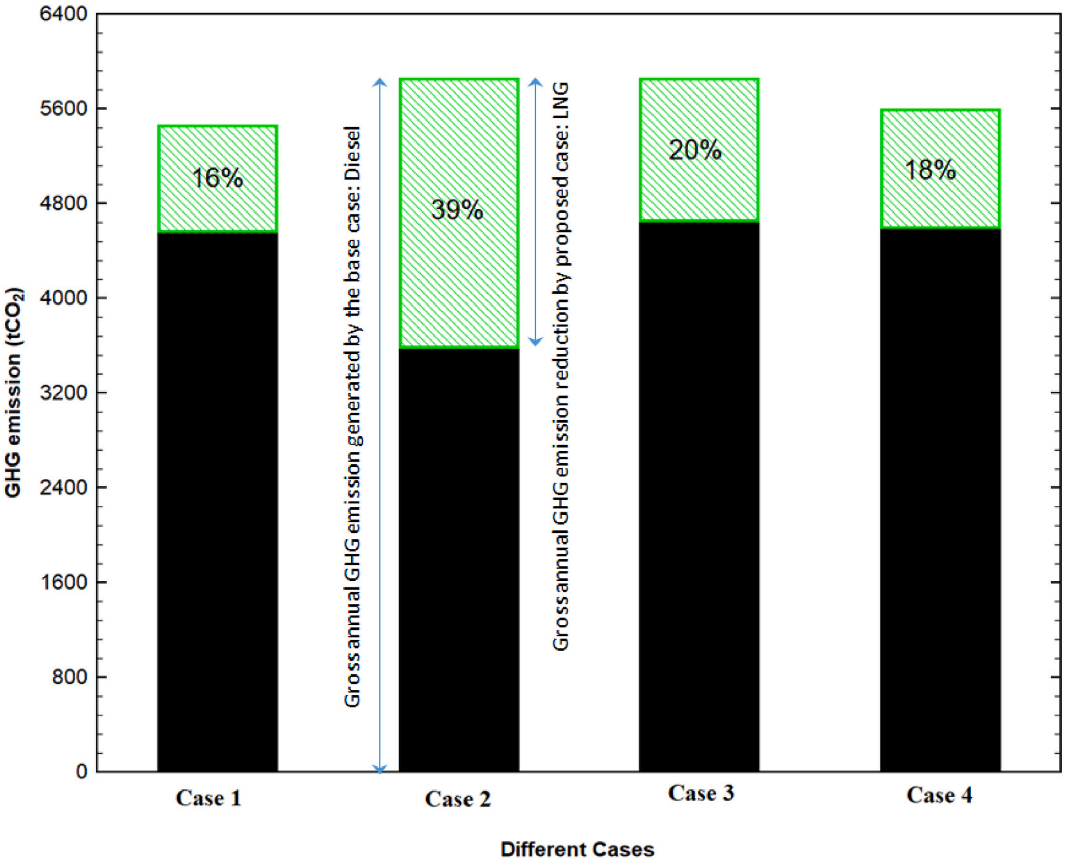


Fig. 7. The GHG emission for the base and proposed fuels under different investigated cases (green bar represents the amount of reduced GHG by using LNG instead of diesel).

3.2. *Energy efficiency and emission reduction in the LCCA context*

The results of energy modeling for a comparison of the base case with diesel and the proposed case with LNG are summarized in Table 5. For all cases, the annual distances of ship routes are taken the same and the engine power is assumed to be identical. Under these assumptions, the resulting fuel efficiency per liter for LNG is higher than diesel in 100 km, however, since LNG has a higher energy density the total fuel consumption is comparatively lower for the same power requirements. In Scenario 1, the change in the fuel efficiency occurs due to the fuel property variations (density and heating value), where the engine load is constant at 100% load, so the fuel consumptions under diesel and LNG are fixed. In Scenario 2, as seen in Table 3, the fuel property is a constant, and the variations happen under different engine loads of 50% (max) and 85% (min). With different engine loads, the fuel consumption has different values, and this influences the fuel price during the LCCA. In terms of ship energy efficiency with different fuels, it can be stated that using LNG causes a 10.9% reduction, even in an unfavorable situation (δ: diesel has good quality and LNG has poor quality). Meanwhile, the fuel change from diesel to LNG with favorable fuel properties (Δ: poor diesel feature to good quality LNG with higher index of WI) can double the fuel efficiency by up to 22%. Dealing with Cases 3 and 4 of Scenario 2 regarding the engine operation modes, it can be inferred that between the engine load conditions of max/min specific fuel consumptions, no significant changes are observable. In a general sense, at a 50% engine load a 12% energy consumption reduction can be achieved that is mostly related to a higher fuel consumption particularly for a diesel engine. The results indicate that the fuel replacement to LNG is most prominent when the vessel runs on a 50% engine load i.e. when the fuel consumption is at its maximum state and the profitability of the investment can be expected in a 50% part-load condition. Another reason is that in this specific operational range, diesel engines are not that efficient.

The calculated fuel consumption, presented in Table 5, is used to estimate the GHG emissions of the base case and the proposed case of different scenarios. The global warming potential (GWP) of GHGs according to IPCC 2014 in this research study has been taken as 28 tCO2 = 1 tCH4 and 265 tCO2 = 1 tN2O. On the other hand, the emission factors of CH_4 and N_2O for LNG are updated according to GREET, where LNG is treated as a transportation fuel (Mix of non-north American NG and flare gas) in a well-to-use lifecycle assessment. In the fuel property modification of Scenario 1, the emission factors are changing along with the fuel properties. Since the emission factors are defined as the mass of emissions produced from a functional energy unit (1 MJ), the changes in the heating values of fuel affect the emission factors for different fuel types and properties in a vessel powertrain. Fig. 7 demonstrates the GHG emissions for diesel and LNG-fueled vessel operational conditions that are somewhat similar and the GHG reduction by the proposed LNG under different cases of fuel property selections and engine load operations. By adopting 50% and 85% engine load conditions, no significant GHG reduction can be observed by substituting LNG instead of diesel. The higher GHG reduction is observed in case 3 that is because of the higher fuel consumption occurred in the 50% load compared to the 85% load. The GHG reduction by LNG instead of diesel in different cases of Scenario 2 (case 3 and case 4) is noteworthy. By adopting HV in an acceptable range of diesel and LNG, where the energy efficiency of diesel decreases and LNG efficiency increases, both emission factors and consumed fuel amounts undergo a change leading to a 23% more GHG reduction in case 2. This issue implies that the proposed case and base case fuel qualities are critical for ship owners and this impacts long-term environmental implications as well as economic gains.

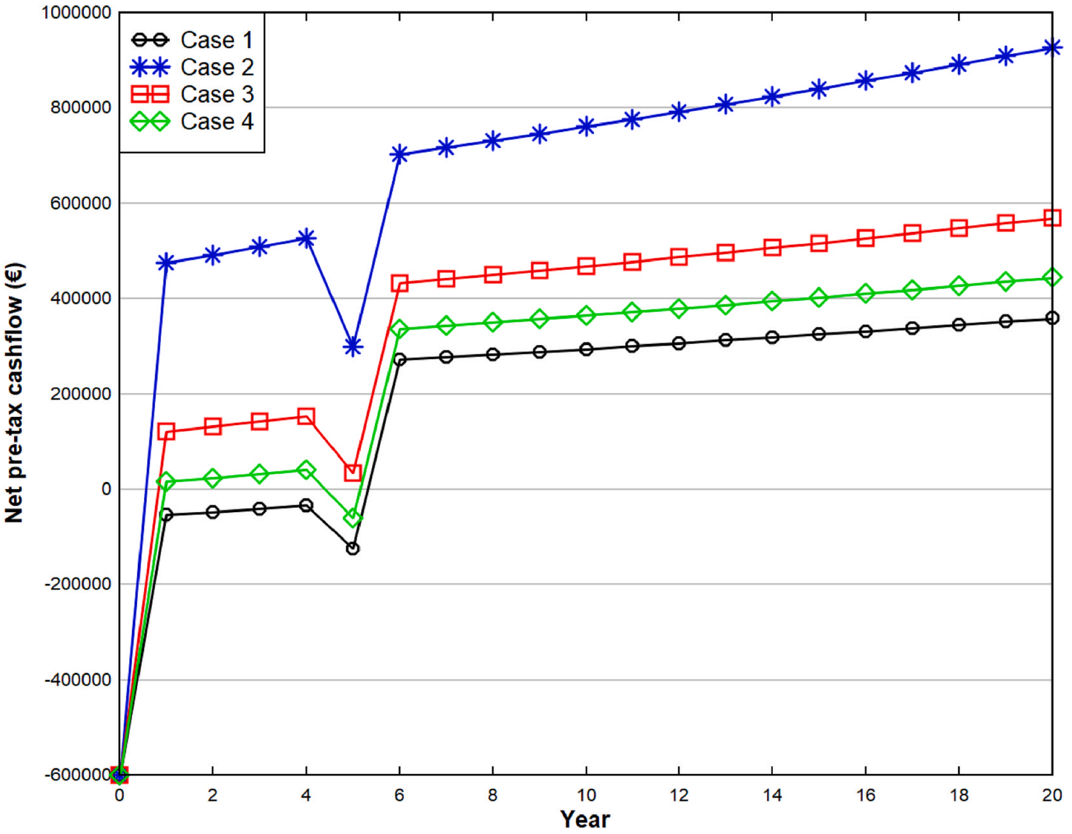


Fig. 8. The net yearly cash flow of the LNG replacement project for different cases over the lifetime of the project.

3.3. *Cost and financial assessment*

The LCCA considers fuel life cycle costing in vessel from the fuel use in the combustion chamber to post-combustion emissions with its consequent carbon credit prices and GHG reduction. Therefore, the fuel extraction/refinery process from the well (WtT) to petrochemical plant for the purification has not been accounted for in the LCCA as socio-political issues are more dominant than technical issues in the fuel market.

For the TtP LCCA analysis, however, the cost assessment consists of the initial cost and exploitation cost. The initial (capital) cost is spent once at the start of the investment and is deemed as the required investment cost to install the proposed clean/efficient technology. On the other side, the exploitation cost is defined as the expected cost over the life span of 20 years. In this study, the exploitation cost is composed of the subsets of the maintenance cost of the LNG retrofitted engine, operating cost (labor and spare parts), powering or fuel cost, and GHG emission credit cost. It must be noted that in the undertaken study, the initial cost, maintenance cost, and operating cost are used as the inputs in the program as the difference monetary amounts between the base (diesel) case and the proposed (LNG) case. For example, the incremental maintenance cost is the price difference of the LNG and primary/conventional diesel engine maintenance costs.

The maintenance cost evaluation is based on the 0.014 €/kWh coefficient for a diesel-powered engine and 0.015 €/kWh for an LNG-powered engine 1 (Iannaccone et al., 2020; Perčić et al., 2020). Applying these factors into the annual fuel consumption per kWh and differentiating the total amounts, an aggregated saving by the LNG setup can be achieved. The maintenance savings for different cases are $LCMC_1$ = €14,175, $LCMC_2$ = €53,367, $LCMC_3$ = €18,358, and $LCMC_4$ = €8351. This shows that the more fuel consumption reduction by the LNG-fueled powering in the vessel, the more maintenance saving can be compensated. Although the unit of maintenance cost for the LNG-fueled engine is more expensive. The more savings resulted from an LNG-fueled engine can be convinced by highly integrated and highly automated LNG-powered systems (Wang et al., 2021b). Under operating cost, the extra labour cost and spare part cost are defined that should be afforded for the LNG retrofitted system (€14 K and €248 K, respectively (Bui et al., 2022b)) equally for all the cases of 1–4. Based on the fuel rate (price per unit of fuel consumption) and the amount of fuel consumption provided in Table 3, the life cycle fuel cost (LCFC) for the base and the proposed options of different cases are calculated and used for the financial assessment or cash flow modeling of the project. The income of the project from the emission reduction is considered in the overall economic balance of the project. The GHG reduction credit rate is 100 €/tCO_2 (Van et al., 2019), although there are other carbon credit policies (the current policy (CP), the stated policies (SP), and the net zero emission by 2050 (NZP)), the best suited policy (the stated policies (SP) scenario) for the current project is adopted. The GHG reduction revenue duration is for 4 years with the credit escalation rate of 2%. The credit that can be collected by observing the environmental policies and less carbon footprint fuels can favor profitability of the project as $LCEC_1$ = €88,520, $LCEC_2$ = €224,175, $LCEC_3$ = €117,988, and $LCEC_4$ = €98,935.

The initial investment cost based on the firsthand information of the SeaTech project partners are estimated that involves the following items.

The price for the LNG tank/LNG system is not as simpler to calculate, since it depends a lot on the amount of LNG needed to store on the vessel. Below is one example though which should fit the kind of installation we are looking at in SeaTech project. It consists not only of the tank, since a lot of add on equipment is needed. We have a product called LNGPac, which you can find more info about online if you are interested.

- 1x LNG tank C-type 400 cbm single shell with in-line Tank Connection Space (7 MARVS), including tank saddles

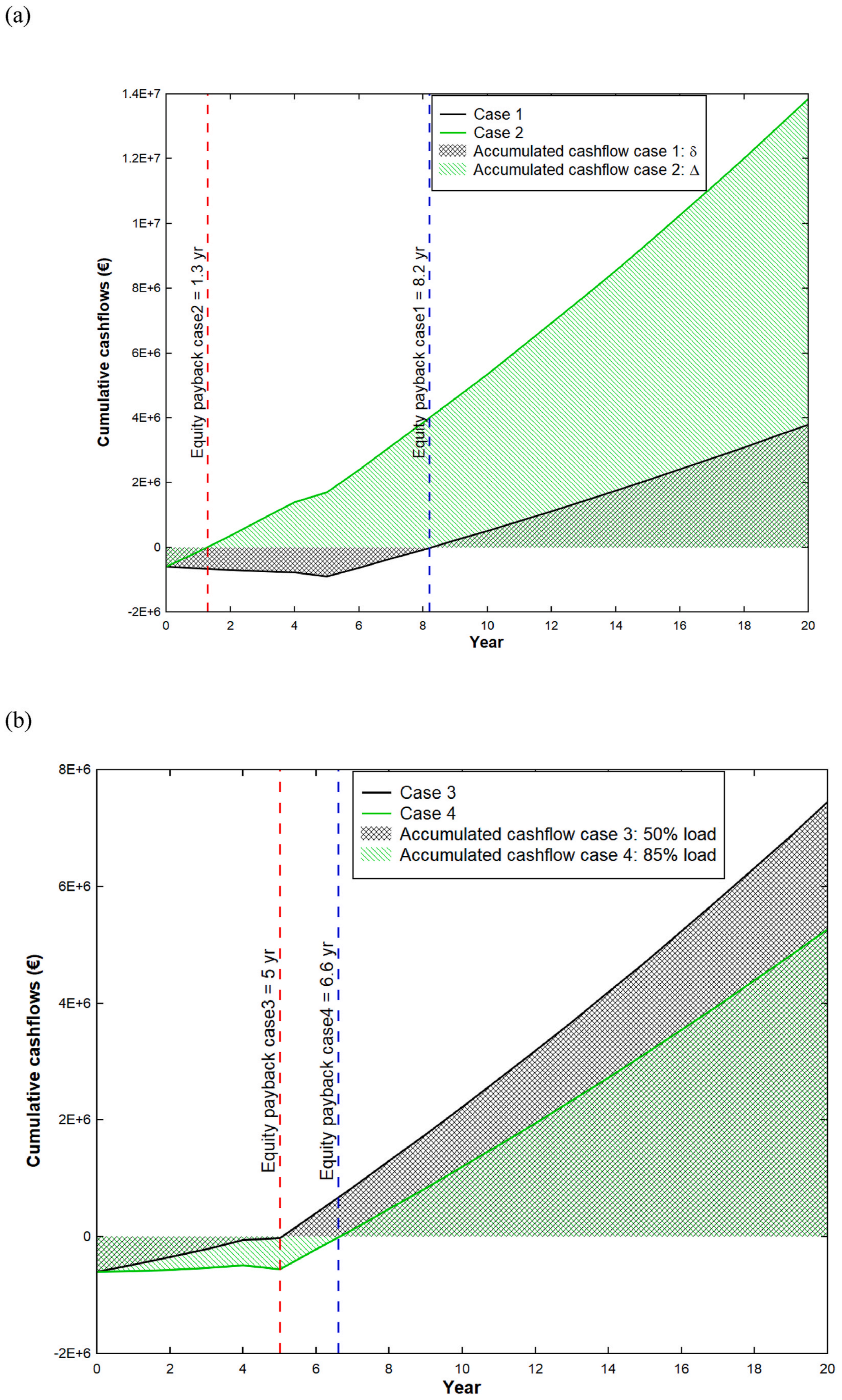


Fig. 9. The net cumulative cash flow of the LNG replacement project for (a) Scenario1 and (b) Scenario2 over the lifetime of the project.

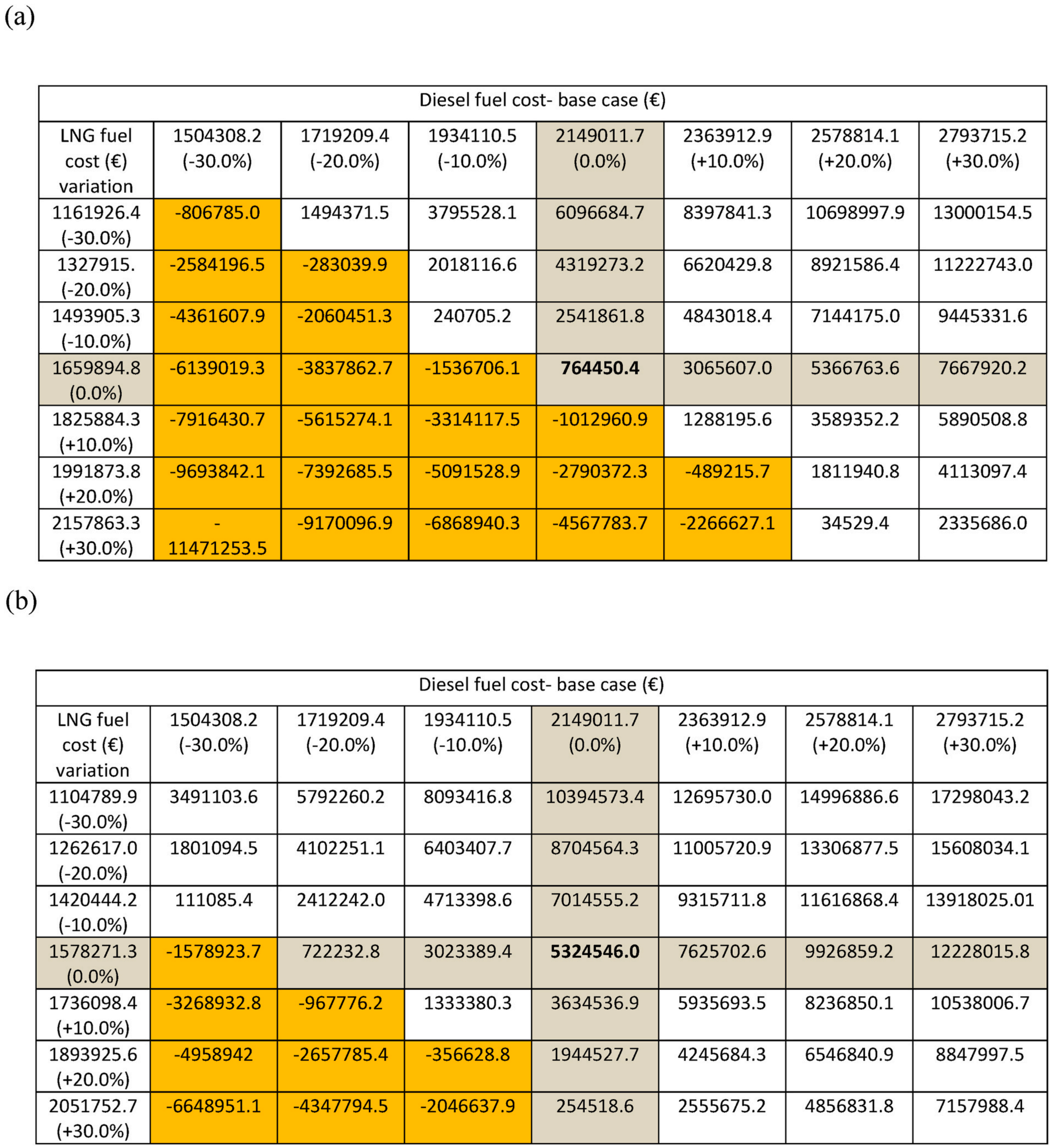
Table 6
Key financial viability indicators for different scenarios and cases.

	Scenario 1: Fuel properties		Scenario 2: Operational condition (load)	
	Case 1	Case 2	Case 3	Case 4
NPV (€)	764,450	5,324,546	2,389,545	1,417,278
Payback (yr)	7.3	2.8	4.8	6
MIRR (%)	6.3	14	10.2	8.1
BCR	2.3	9.9	5	3.4
Annual lifecycle saving (€/yr)	83,743	583,285	261,766	155,258

- 1x Bunkering station DN100 + vapour return DN80
- 1 Tank Connection Space located at the dished end of the LNG tank, designed as continuation of the LNG tank itself, containing:
  - o 2x LNG pumps
  - o 1x Main gas evaporator
  - o 1x Gas heater (for Boil Off gas management)
  - o Process valves and instruments (sensors, etc)
- 1x Heating media system set of components (delivered as loose items, including 2x Glycol water pumps, 2x heat exchangers, valves and instruments, 1x expansion tank)
- LNGPac Automation
- 40 Man-days system commissioning

Indicative price for the above-mentioned solution is 2.400.000 €.

Based on the summary of costs/savings/revenue on the annual period of the economic aspect of the project from the energy modeling and cost estimations, the cash flow for different cases can be presented over the lifetime of the project. This cash flow process can be demonstrated by specifying the financial input parameters such as inflation rate



(a)

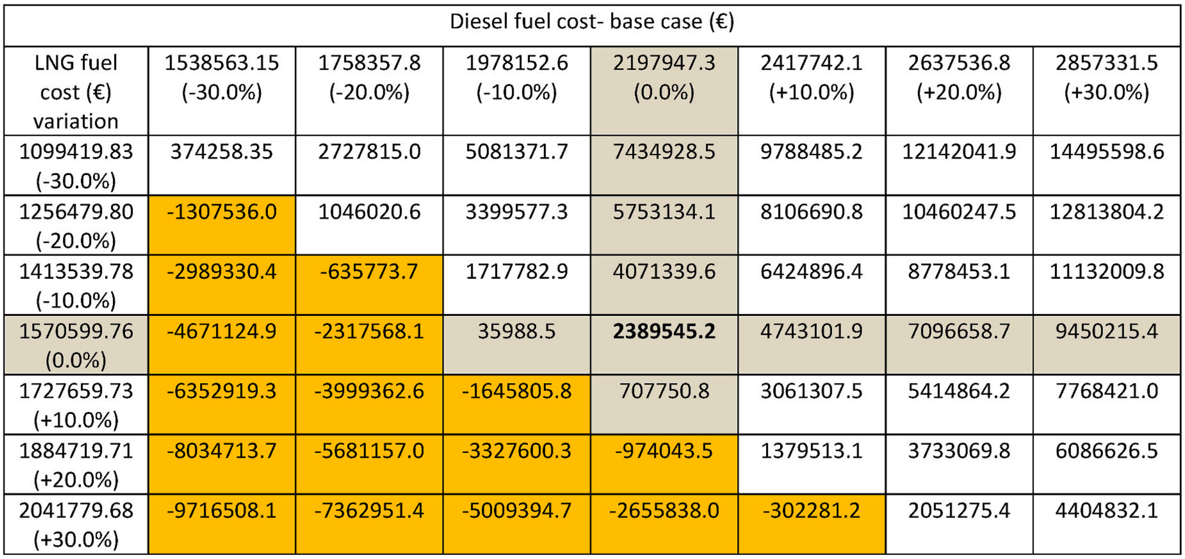
	Diesel fuel cost- base case (€)						
LNG fuel cost (€) variation	1504308.2 (-30.0%)	1719209.4 (-20.0%)	1934110.5 (-10.0%)	2149011.7 (0.0%)	2363912.9 (+10.0%)	2578814.1 (+20.0%)	2793715.2 (+30.0%)
1161926.4 (-30.0%)	-806785.0	1494371.5	3795528.1	6096684.7	8397841.3	10698997.9	13000154.5
1327915. (-20.0%)	-2584196.5	-283039.9	2018116.6	4319273.2	6620429.8	8921586.4	11222743.0
1493905.3 (-10.0%)	-4361607.9	-2060451.3	240705.2	2541861.8	4843018.4	7144175.0	9445331.6
1659894.8 (0.0%)	-6139019.3	-3837862.7	-1536706.1	**764450.4**	3065607.0	5366763.6	7667920.2
1825884.3 (+10.0%)	-7916430.7	-5615274.1	-3314117.5	-1012960.9	1288195.6	3589352.2	5890508.8
1991873.8 (+20.0%)	-9693842.1	-7392685.5	-5091528.9	-2790372.3	-489215.7	1811940.8	4113097.4
2157863.3 (+30.0%)	-11471253.5	-9170096.9	-6868940.3	-4567783.7	-2266627.1	34529.4	2335686.0

(b)

	Diesel fuel cost- base case (€)						
LNG fuel cost (€) variation	1504308.2 (-30.0%)	1719209.4 (-20.0%)	1934110.5 (-10.0%)	2149011.7 (0.0%)	2363912.9 (+10.0%)	2578814.1 (+20.0%)	2793715.2 (+30.0%)
1104789.9 (-30.0%)	3491103.6	5792260.2	8093416.8	10394573.4	12695730.0	14996886.6	17298043.2
1262617.0 (-20.0%)	1801094.5	4102251.1	6403407.7	8704564.3	11005720.9	13306877.5	15608034.1
1420444.2 (-10.0%)	111085.4	2412242.0	4713398.6	7014555.2	9315711.8	11616868.4	13918025.01
1578271.3 (0.0%)	-1578923.7	722232.8	3023389.4	**5324546.0**	7625702.6	9926859.2	12228015.8
1736098.4 (+10.0%)	-3268932.8	-967776.2	1333380.3	3634536.9	5935693.5	8236850.1	10538006.7
1893925.6 (+20.0%)	-4958942	-2657785.4	-356628.8	1944527.7	4245684.3	6546840.9	8847997.5
2051752.7 (+30.0%)	-6648951.1	-4347794.5	-2046637.9	254518.6	2555675.2	4856831.8	7157988.4

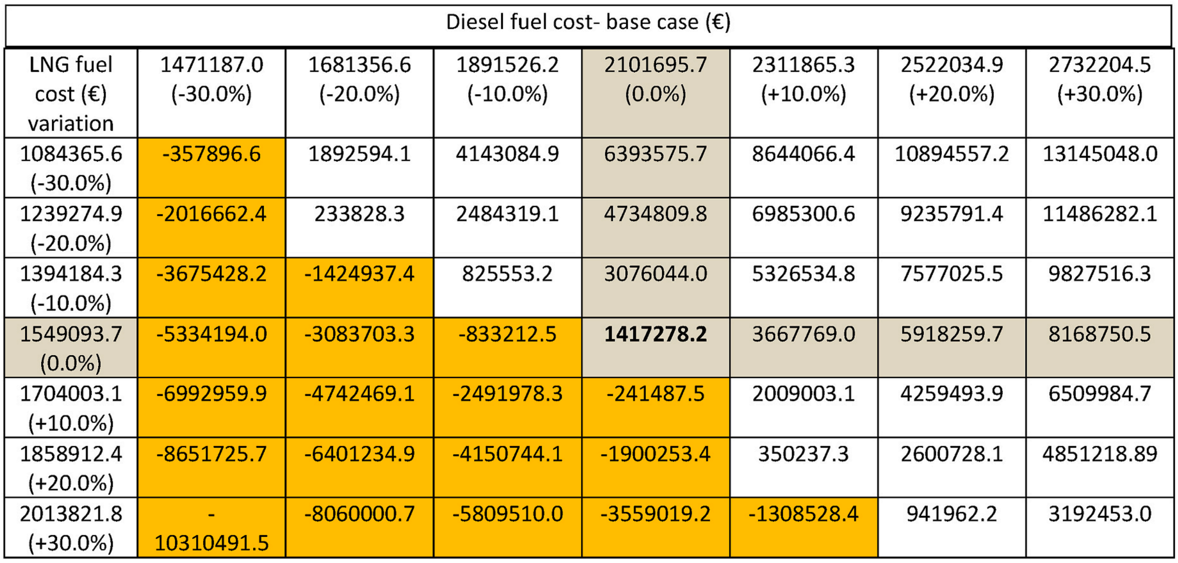
Fig. 10. The NPV variation matrix with the base case fuel (diesel) cost and the proposed LNG fuel cost for (a) case 1, (b) case 2, (c) case 3, and (d) case 4.

(c) case50%



Diesel fuel cost- base case (€)							
LNG fuel cost (€) variation	1538563.15 (-30.0%)	1758357.8 (-20.0%)	1978152.6 (-10.0%)	2197947.3 (0.0%)	2417742.1 (+10.0%)	2637536.8 (+20.0%)	2857331.5 (+30.0%)
1099419.83 (-30.0%)	374258.35	2727815.0	5081371.7	7434928.5	9788485.2	12142041.9	14495598.6
1256479.80 (-20.0%)	-1307536.0	1046020.6	3399577.3	5753134.1	8106690.8	10460247.5	12813804.2
1413539.78 (-10.0%)	-2989330.4	-635773.7	1717782.9	4071339.6	6424896.4	8778453.1	11132009.8
1570599.76 (0.0%)	-4671124.9	-2317568.1	35988.5	**2389545.2**	4743101.9	7096658.7	9450215.4
1727659.73 (+10.0%)	-6352919.3	-3999362.6	-1645805.8	707750.8	3061307.5	5414864.2	7768421.0
1884719.71 (+20.0%)	-8034713.7	-5681157.0	-3327600.3	-974043.5	1379513.1	3733069.8	6086626.5
2041779.68 (+30.0%)	-9716508.1	-7362951.4	-5009394.7	-2655838.0	-302281.2	2051275.4	4404832.1

(d) case85%



Diesel fuel cost- base case (€)							
LNG fuel cost (€) variation	1471187.0 (-30.0%)	1681356.6 (-20.0%)	1891526.2 (-10.0%)	2101695.7 (0.0%)	2311865.3 (+10.0%)	2522034.9 (+20.0%)	2732204.5 (+30.0%)
1084365.6 (-30.0%)	-357896.6	1892594.1	4143084.9	6393575.7	8644066.4	10894557.2	13145048.0
1239274.9 (-20.0%)	-2016662.4	233828.3	2484319.1	4734809.8	6985300.6	9235791.4	11486282.1
1394184.3 (-10.0%)	-3675428.2	-1424937.4	825553.2	3076044.0	5326534.8	7577025.5	9827516.3
1549093.7 (0.0%)	-5334194.0	-3083703.3	-833212.5	**1417278.2**	3667769.0	5918259.7	8168750.5
1704003.1 (+10.0%)	-6992959.9	-4742469.1	-2491978.3	-241487.5	2009003.1	4259493.9	6509984.7
1858912.4 (+20.0%)	-8651725.7	-6401234.9	-4150744.1	-1900253.4	350237.3	2600728.1	4851218.89
2013821.8 (+30.0%)	-10310491.5	-8060000.7	-5809510.0	-3559019.2	-1308528.4	941962.2	3192453.0

Fig. 10. (*continued*).

(2%), discount rate (2%), debt ratio (75%), and debt term (5 years). The inflation rate and discount rate are decided according to the normal economic and fiscal situation in Norway context. The debt ratio reflects the financial leverage created for a project, the higher the debt ratio, the larger the financial leverage. The yearly variations in the cash flow for different under investigation cases are graphed in Fig. 8 over the lifetime of the project. The lowest flow pertains to case 1 which represents the unprofitable state of fuel substitution from diesel to LNG. Meanwhile, the profitable case (case 2) by changing low quality (low energy density) to high quality LNG (higher WI index) gives the highest cash flow and sooner raises to a positive amount. The equity for all cases starts from -€600 K and the plunge of the flow for all cases is because the debt term has been finished after 5 years and then the income raises again. The yearly cash flow trend for cases 3 and 4 are close to each other. Following the fuel consumption efficiency at 50% load results in 22% increase of the obtained cash at the end of project (year = 20) compared to that of vessel operation in 85% load i.e. case 4.

The cumulative cashflow graphs are exhibited in Fig. 9a for Scenario1 (fuel property) and Fig. 9b for Scenario2 (load condition). The accumulated flow after year 0 is shown where the shift from negative values to positive gives the equity payback. The more profitable the project (more income and inflow), the sooner the project balances the debt. As observed in Fig. 6a, the difference between cases regarding the fuel properties is considerable when LNG-powered vessel is adopted over the diesel-powered ship, since the equity payback of 8.2 years can be shortened to 1.3 years by using the high quality and high calorific rich LNG. Moreover, the accumulated flow after 20 years of the project span for case 2 more than tripled in comparison to case 1. Case 3 and 4 equity paybacks without modification of the fuel property at different fuel consumption rates of 50% (max) and 85% (min) are 5 and 6.6 years. This confirms that when the vessel manages to be operated at the maximum fuel consumption, the LNG use instead of diesel brings about sooner payback in the project and the accumulated cash from €5.27 M of case 3 at the end of the project reaches to €7.45 M. This is mainly because the gas fuel efficiency (LNG-fueled engine) from 85% to 50% does not increase evidently.

Table 6 summarizes the prominent key financial indicators as output based on the calculations and cashflow of the project. The NPV of the case 2 is considerably higher than case 1 and it goes back to 3 factors of fuel cost difference (489 K→570 K), GHG reduction revenue (88 K→224 K), and maintenance cost saving (14 K→53 K). The increase of income or financial gain in case 2 is considerable that leads to a larger NPV of the LNG-retrofitted vessel with a desirable LNG specification. The simple payback is characterized as the length of time for a proposed retrofitted LNG-operated facility in ships to recoup its own initial cost, out of the GHG revenue or fuel cost or maintenance savings it generates. The basic principle of the simple payback (SP) method is that the faster the cost of an investment can be recovered, the more attractive is the investment. The SP is not the primary criteria to assess a project. It can be regarded, however, as an ancillary criterion to forecast the level of risk of an investment. The SP method does not factor in the time value of money, therefore NPV comparison as the prime indicator of the cases is more noteworthy. The desirable fuel changing scheme of case 2 (even with the consideration of fuel quality price) leads to 4.5 years shorter duration of the investment payback rather than case 1 which is undesirable change of fuel at constant 100% load. This signifies the role of used diesel and LNG quality and their respective density and heating value on the long run of the project lifetime. The simple payback method is not a measure of how profitable one project is compared to another, but rather how quick the initial cost can be retained along the project. Considering the total initial cost, annual costs, savings, and revenue the project of case 3 pays back the initial investment compared to case 4. This can be translated to better fuel efficiency of the SeaTech engine on gas mode at 50% load.

The modified internal rate of return (MIRR) evaluator calculates the true interest yield provided by the project assets over its life (in the modified IRR the gained income flow is used for the reinvestment on the project). It is calculated using the pre-tax yearly cash flows, the project life, the discount rate, and the reinvestment rate. Since the discount rate for all the cases of the project are identical, the more profitable financial situation with higher NPV results in the higher rate of investment return. The MIRR of case 2 in Scenario1 and case 3 in Scenario2 are dominant in the categories of fuel property and load operation condition with 14% and 10.2%. This shows that by replacing the better-quality LNG with diesel, the investment success is more secure to the case of the LNG utilization under different operating condition by the load management.

The BCR estimates the ratio of the net benefits (annual saving and revenue) to the cost as the project equity. This ratio can be considered as the profitability index and Ratios greater than 1 are indicative of profitable projects. The BCR values provided in Table 6 indicate that the LNG replacement as a clean technology even in the worst-case scenario (case 1) would result in BCR >1 (i.e., 2.3). The yearly saving by the proposed case project of the LNG-powered vessel represented by the ALCS shows that a great benefit is expected by adopting case 2 therein the fuel saving potential and fuel pricing unit has the utmost role. Handling the vessel at 50% load where the maximum diesel and LNG SFC occurs leads to 40.6% more annual saving compared to vessel operation close to full load operation (85%).

3.4. Sensitivity and risk analysis

The sensitivity of the underlying economic indicators with respect to technical and financial input parameters are surveyed in this study. A broad band of the sensitivity range is considered (30%) to cover the whole possible scenarios especially when it comes to the topic of fuel pricing (both diesel and LNG). The sensitivity analysis allows to see the impact of financial input (independent variables) on the key project feasibility indicators. The sensitivity analysis is performed on the NPV with threshold of zero since the viable projects (economic wise) have NPV >0 and the rest fail in fulfilling the economic objectives of the study. The fuel cost (diesel and LNG) is chosen for the sensitivity analysis since according to the impact graph introduced in the next section, they have the most significance impact on the overall financial performance of the project.

According to Fig. 10 that is a collection of sensitivity charts, the effect of both fuels' changes in the −30% to +30% interval on the NPV has been analyzed. The unfeasible states are marked orange and the status quo (0% or unchanged rows and columns) is marked grey. The white-colored spots mean the project is safer to be investigated and is more price-fluctuated proof and the security of the investigation on the LNG-infrastructure and engine-retrofitting is guaranteed. In scenario1, the desirable fuel quality change can only jeopardize the viability of the plan

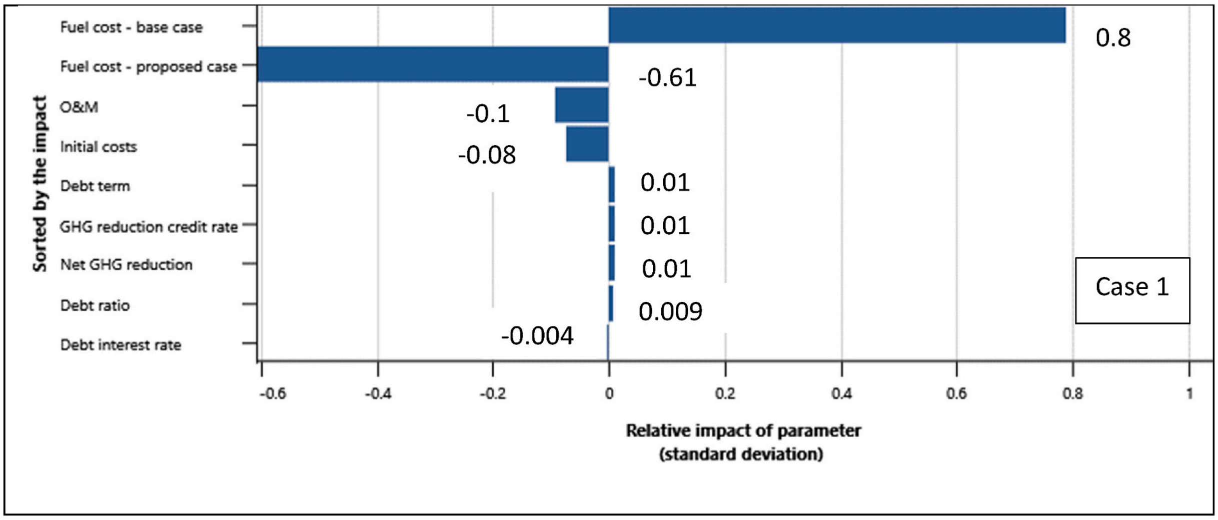


Fig. 11. The sensitivity chart based on the impact assessment of the project NPV indicator for (a) case 1, (b) case 2, (c) case 3, and (d) case 4.

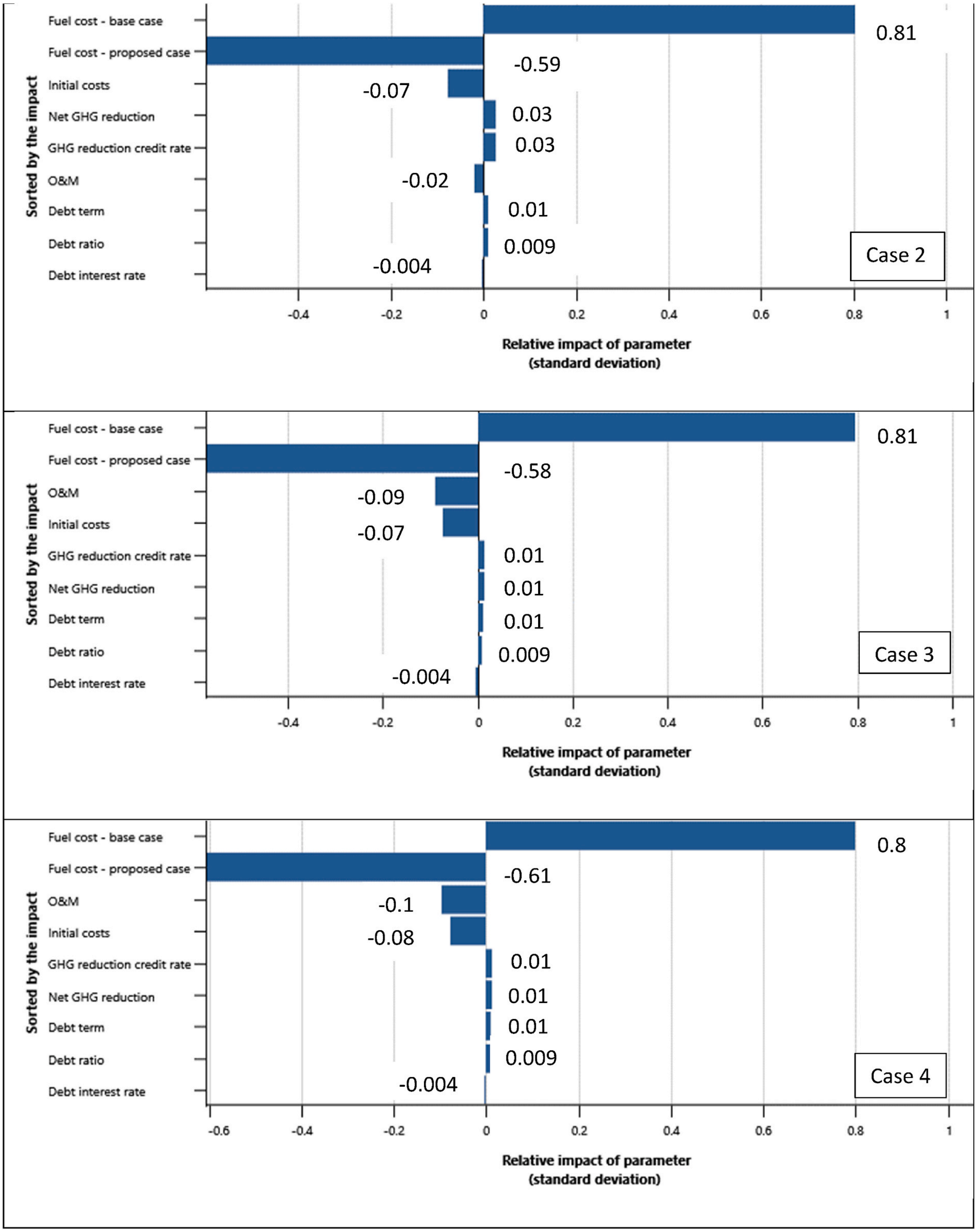


Fig. 11. (*continued*).

only at extreme cases of simultaneous LNG price soaring (up to 30%) and diesel fuel plummeted by 10–30% which is a rare occasion since the fuel and LNG follow the same oil market. Cases 1 and 4 at the central position are close and adjacent to the orange-marked danger region and are very sensitive to the fuel pricing such that any 10% change of either diesel (decrement or moving left) or LNG (increment or moving down) can make unfeasible investment with negative NPV. On the other hand, cases 2 and 3 have respectively 2 and 1 buffer layer with the danger zone, so they are resilient to the fluctuations of the pricing changes and market instabilities in the long run.

In order to undertake the risk assessment, the Monte Carlo technique is implemented. The Monte Carlo simulation is an approach whereby the distribution of possible financial indicator outcomes is produced by taking randomly chosen sets of values as input parameters, within a predefined interval, to simulate possible outputs (Emblemsvåg, 2003). The simulation procedure follows the below steps (HYDRO, 2001).

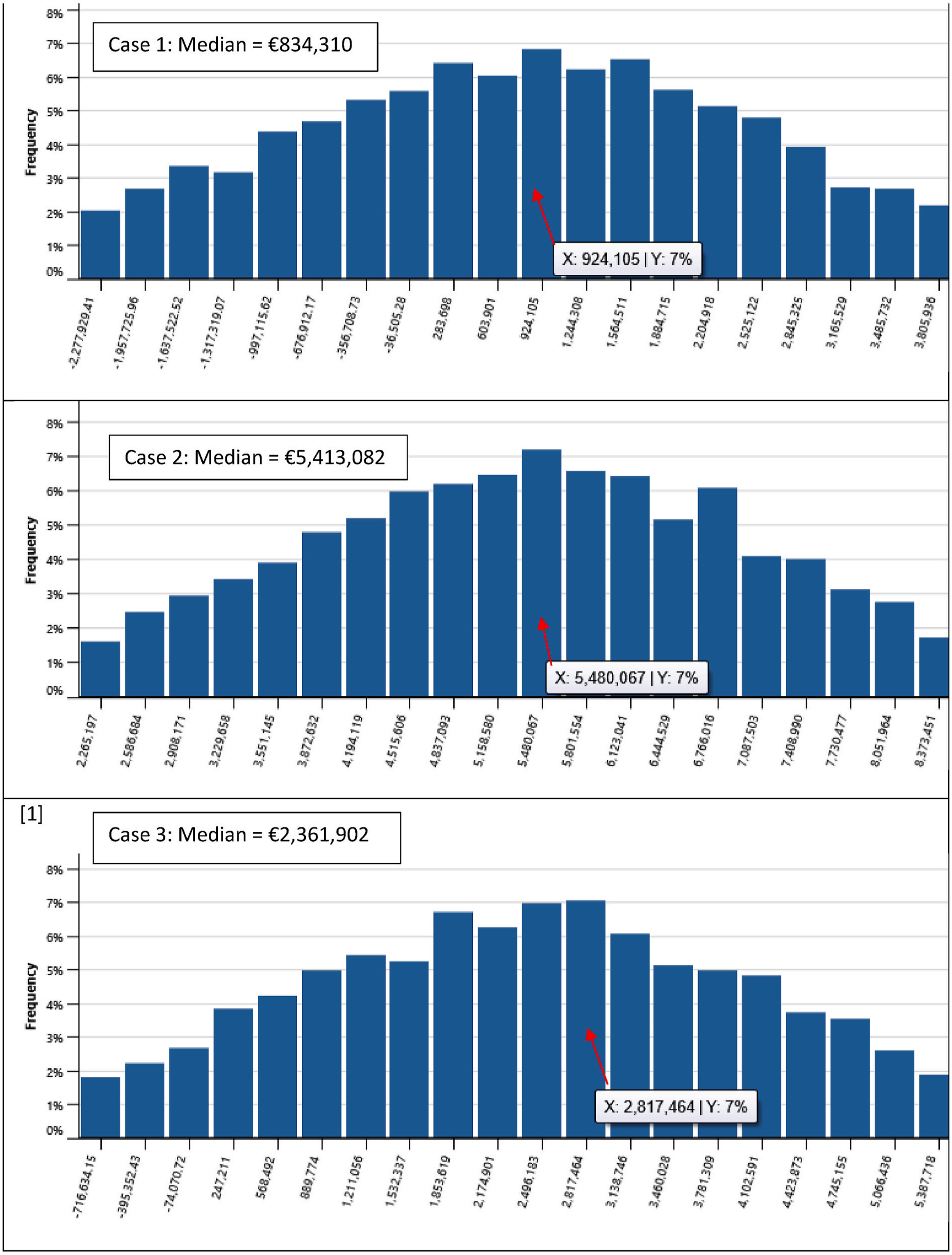


Fig. 12. Uncertainty distribution of NPV values as histogram chart with extreme 10% risk level for (a) case 1, (b) case 2, (c) case 3, and (d) case 4.

1. For every input parameter, 4000 random values are produced via a normal (Gaussian) distribution with a mean of 0 and a standard deviation of 0.33 using the Random Number Generation function in the worksheet. Upon generation, these arbitrary numbers are fixed.
2. Each random value is then multiplied by 20% of variability (range). The result is a 4000 × 9 matrix containing 20% of the variations that will be applied to the initial values of input parameters in order to obtain 4000 results for the NPV as the output financial indicators.

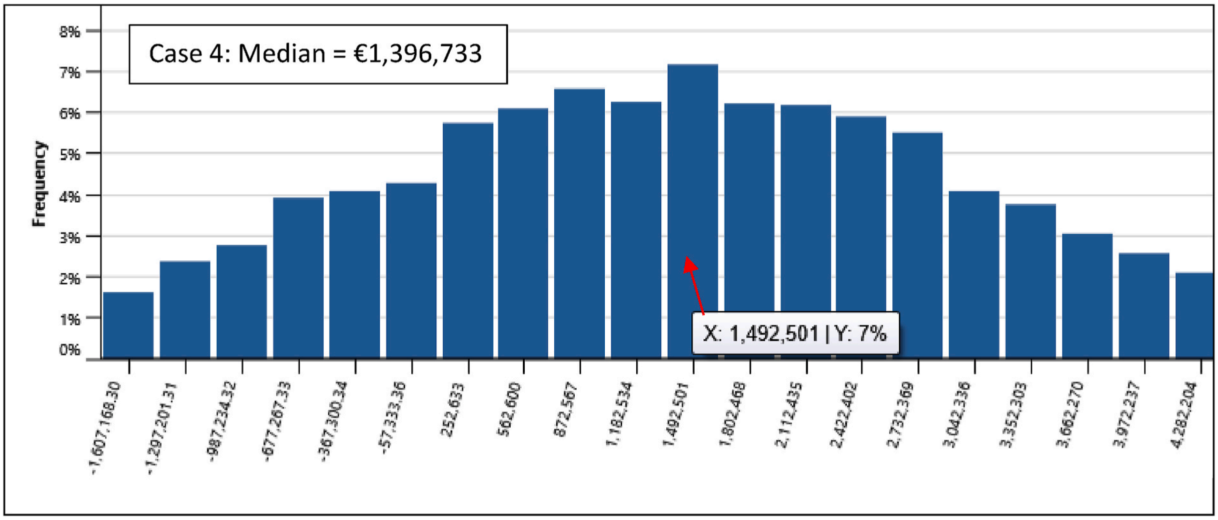


Fig. 12. (*continued*).

In the impact graph (Tomado Graph) of Fig. 8, the effect of each input parameter on NPV is obtained by applying a standardized multiple linear regression (Neter et al., 1996) on the financial indicator. The input parameters' weight on the impact graph is calculated using the method of least squares.

Let Y to be the dependent variable, NPV, while the independent variables X are: X_1: initial cost; X_2: O&M; X_3: LNG fuel cost; X_4: diesel fuel cost; X_5: net GHG reduction; X_6: GHG reduction credit rate; X_7: debt ratio; X_8: debt interest rate; and X_9: debt term. Then the multiple linear regression model is:

$$Y = \alpha_1 X_1 + \alpha_2 X_2 + \alpha_3 X_3 + \alpha_4 X_4 + \alpha_5 X_5 + \alpha_6 X_6 + \alpha_7 X_7 + \alpha_8 X_8 + \alpha_9 X_9 + \varepsilon \tag{14}$$

where αk is the coefficient or weights of each input factor (k) and ε is the model error. The model functions with the produced data from the Monte Carlo simulation. The total of 4000 values exists for Y that corresponds with 4000 values of each X. Having completed the values of Y vector and X matrix, the coefficients are obtained by using the least squares method. The resulted coefficients are subsequently standardized by the following equation:

$$a_k = \frac{s_k}{s_Y} \alpha_k \tag{15}$$

where s_k is the standard deviation of the 4000th X_k values and s_Y is the standard deviation of the 4000th Y values. The obtained a_k values are the final coefficients that are plotted in the impact graph.

The resulted impact graphs on 4 cases are illustrated in Fig. 11. As seen for all cases the base (diesel) and the proposed (LNG) fuels cost rank first and second with almost 0.8 and −0.6 relative impact factor and these parameters can be considered game changers. It means that changing diesel fuel cost either as amount (fuel or system efficiency) and the market volatility is the key in the NPV of the entire project. The next parameters' position in terms of significance changes per case and their coefficient varies accordingly. About case 2, since the maintenance cost leverage for LNG is considerably higher than other cases, as a result it will be offset with operating costs so the O&M position in case 2 drops from third place to sixth and initial cost takes over the third place. The initial investment cost and O&M decrease the NPV value by impact factor of ~10%, while the banking loan parameter (debt parameters) have negligible influence on the feasibility index of the project. The observation of the trend affirms that in each scenario, the successful cases (i.e., case 2 and 3) have higher impact coefficient of diesel cost and lower coefficient of the LNG cost.

The level of risk of 10% (confidence interval of 90%) is chosen for the risk assessment through Monte Carlo histogram plots in Fig. 12 therein all cases have normal unimodal distribution showing the systematic data generation. The level of risk is used to establish a confidence interval within which the financial indicator is expected to fall. The level of risk represents the probability that the financial indicator will fall outside this confidence interval. It means that there is a 10% risk that NPV falls outside the defined interval. The height of each bar represents the frequency (%) of values that fall in the range defined by the width of each bar. The highest frequency is 7% and based on the generated Monte Carlo data, the probability of NPV for the case 1 falling within €924,105 is the highest that is more than the median and the actual NPV. The same trend can also be observed for the case 2 where the $NPV_{act} < NPV_{med} < NPV_{max,his}$. This shows that the generated data from 4000 combinations resulted in 4000 NPV values from random X1 to X9 data slightly overestimates the actual NPV. The variability of NPV for case 2 does not include negative amounts even in the minimum level of confidence. The probability of acquiring negative NPV for case 3 is low since few of the generated output (with $Y < 3\%$) may fall into infeasible financial plan. For case 3 which is a bit left-skewed, the occurrence probability of higher NPV is higher so that is a good sign of the project feasibility. However, in case 4 the possibility of falling the data lower than −1.29 M€ is less than 5% and the most likely NPV are between 872 K€ to 1.8 M€.

The variability of the generated NPV by Monte Carlo shows that the lowest NPV in the border of 5% confidence is assigned to case 1 where the good quality diesel is replaced by the poor-quality LNG. On the other side, using a rich LNG fuel can assure the feasibility of the LNG-retrofitting investment to a great deal since the 4000 data of different combinations of financial variables have the confidence of lower than 5% to be lower than 2.26 M€ of NPV.

4. Conclusion

The present study is developed based on the LCA and the LCC of the LNG-retrofitting process of diesel-fueled vessel in dual-fuel engine mode. The LCA considers the vessel voyage in a short and long distance with the HFO, LSD, and the LNG in fuel production and consumption lifecycle pathway. The LCC investigation is coupled with the green technology analysis tool which provides the sensitivity analysis and risk assessment in addition to financial viability indicators. The summary of the obtained results from this research is outlined as.

- The LNG's GHG release amount during WtT is on average 29.2% more than TtP, which implies that more controlling measures in the LNG production must be taken.
- The NOx amount for the HFO is comparatively higher in TtP phase versus WtT and the NOx for the HFO (unlike other fuels) is dependent on the vessel's traveled distance (from 36.7 g for R1 to 51.4 g for R2).
- The LNG-retrofitted project is especially advisable for an upgraded rich LNG use (in case 2) instead of the lean LNG in case 1 since under the identical operation condition at full load, 11.1 more fuel efficiency and 6.9-years sooner positive cash flow in equity can be reached.
- The MIRR for case 2 from Scenario1 and case 3 from Scenario2 are the highest with 14% and 10.2%. Overall, case2, which suggests using the rich-LNG instead of poor diesel is the ideal situation with $\text{NPV} = 5.32$ M€, $\text{SP} = 2.8$ years, and $\text{BCR} = 9.9$.
- According to the sensitivity analysis, the diesel fuel price is more important ($a_1 \approx 0.8$) than the LNG fuel price ($a_2 \approx -0.6$) in the NPV indicator determination.
- For all cases except case 2, the O&M ranks after fuel pricing among the financial parameters impact on the NPV.
- The sensitivity analysis demonstrates that case 1 and case 4 have more instability against the fuel pricing.
- The range of developed histogram for case 2 indicates that 95% of the generated data for NPV by the Monte Carlo falls above 2.26 M€, hence exploiting an upgraded rich LNG even with the higher price is recommended for having a highly probable successful investment.

CRediT authorship contribution statement

Hadi Taghavifar: Data curation, Formal analysis, Investigation, Methodology, Software, Writing – original draft, Visualization. **Lokukaluge P. Perera:** Conceptualization, Writing – review & editing, Supervision, Investigation.

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 data that has been used is confidential.

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Nomenclature

a	Ash content (% mass), standardized impact coefficient
a(f)	Amount of an energy source
ALCS	Annual life cycle saving (€/yr)
AWP	Average weighted power (kW)
AWS	Average weighted speed (km/h)
BOG	Boil-off gas
C	Total initial cost of the project, fixed energy system coefficient (km/kWh)
C_n	Cash flow for year n
CP	Current carbon policy
DF	Dual fuel
E	Energy vector
E_m	Emission vector
$E_{up}(f)$	Energy vector associated with upstream energy to produce f
ec(f)	Energy consumption by fuel
EF	Emission factor(g/MJ or kg/GJ)
f	Fuel or energy source
f_d	Debt ratio (%)
ft	Transported fuel or the energy source
GHG	Greenhouse gas (tCO_2-eq)
GRR	GHG reduction revenue
GWP	Global warming potential
HFO	Heavy fuel oil
hp	Horse power (kW)
IG	Incentives and grants (€)
IMO	International marine organization
IRR	Internal rate of return (%)
LCA	Life cycle assessment
LCC/LCCA	Life cycle cost assessment
LCFC	Life cycle fuel cost
LCI	Life cycle inventory
LCMC	Life cycle maintenance cost
LSD	Low-sulfur diesel
LTC	Low-temperature combustion
MGO	Marine gas oil
MIRR	Modified internal rate of return (%)
N	Project lifetime
NNA	Non-north American
NPV	Net present value (€)
NZP	Non-zero emission carbon policy
r	Discount rate (%)
R1/R2	Short shipping route/long shipping route
s	Share of energy source (%), diesel sulfur content (% mass)
S_G	Special gravity
SDG	Sustainable development goals
SFC	Specific fuel consumption (g/kWh)
SP	Simple payback (yr), stated policies carbon scenario
TtP	Tank to propeller
w	Water content (% mass)
WtP	Well to tank
X:1 to 9	Financial input matrices
Y	Financial indicator (here NPV) vector
α	Coefficient of financial impact factor
ε	Regression model error
δ	Small change in fuel efficiency by property change: good diesel → poor LNG
Δ	Big change in fuel efficiency by property change: poor diesel → good LNG

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