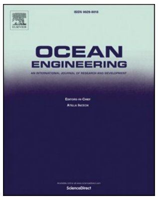
Ocean Engineering 279 (2023) 114420

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng



A framework for the economic-environmental feasibility assessment of short-sea shipping autonomous vessels

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ARTICLE INFO

Handling Editor: Prof. A.I. Incecik

Keywords:
Maritime autonomous surface ships
Short-sea shipping
MASS Outlook
Economic analysis
Environmental analysis
Feasibility assessment framework

ABSTRACT

Despite the pursued autonomous ships initiatives, the lack of information on emerging technologies and their costs along with the limited investigations of the autonomy effects on logistics render these vessels feasibility assessment challenging. This study aims at developing an overarching framework to support decisions for the transition to autonomous shipping. The ship lifetime capital, operational and voyage expenditures are estimated to quantify the economic-environmental impact and required investments. Several scenarios are defined to address the input data uncertainty. The case of a short-sea shipping cargo vessel operating in the Norwegian waters is studied, considering its conversion to operate autonomously, as well as the next generation crewless ship design. The derived results demonstrate that the converted autonomous ships can reduce the lifetime present value by 1–12% and the carbon emissions by 4%, whereas the next-generation autonomous ships design leads to their further reductions by 3–4% and 4–7%, respectively. These savings can further increase by 6–7% by reducing the autonomous ships sailing speed, as crew replacement periods are not required. The estimated economic margin indicates that the next-generation autonomous ships can adopt greener technologies, such as hydrogen or green ammonia, to achieve the targeted carbon emissions reduction.

1. Introduction

The Maritime Autonomous Surface Ships (MASS) have demonstrated a prolific progress that led to recent full-scale demonstrations in the framework of industrial projects, including the cargo vessel Yara Birkeland (Yara, 2022), the scientific Mayflower Autonomous Ship (Mayflower, 2022) and the six demonstrators from Meguri 2040 project (Suzuki, 2021; The Nippon Foundation, 2022). Several research projects have been pursued, including the MUNIN project (MUNIN, 2015; Burmeister et al., 2014, Kretschmann et al., 2015; Kretschmann et al., 2017), the ReVolt project (DNV, 2014) and the AAWA project (Rolls-Royce, 2016). More recently, the AUTOSHIP project (AUTOSHIP, 2022) has been investigating the impact for the MASS on several aspects to pave the development of key enabling technologies as well as to build and test two full-scale demonstrators.

The fast uptake of MASSs must be supported by the emerging technologies development and is driven by economic, environmental and societal needs for enhancing the shipping operations sustainability, the supply chain resilience, reducing accidents, and providing better working conditions shifting jobs from sea to shore (Munim, 2019; Iannaccone et al., 2020; Li and Yuen, 2022). The recent advancements in robotics, machine learning, deep learning, artificial intelligence (Li and Yuen, 2022; Nielsen et al., 2022), communications and cyber-security (Bolbot et al., 2020; Weaver et al., 2022) enable the development of the required technologies for safe autonomous and remote navigation (Heffner and Rødseth, 2019; Negenborn et al., 2023). The principal economic motivation is related to the reduction of the ship's operational costs, which is achieved by an increase in the ship sailing efficiency (Kretschmann et al., 2017; Munim, 2019), lower maintenance cost (Cullum et al., 2018; Cheliotis et al., 2020), higher operational efficiency (Shaw and Lin, 2021; Yuan et al., 2021), as well as by transfer of crew from sea to shore (Kooij et al., 2021; Jovanović et al., 2022a). The economic impact can be even higher when considering a MASS fleet (Akbar et al., 2021; Barzegari et al., 2023), which can render smaller ships more attractive.

Although measures (technical and operational) resulting from the higher ship efficiency positively impact environmental footprint (Munim, 2019), they are not adequate to address the International Maritime Organisation (IMO) targets for the shipping industry decarbonisation, which include the total annual reduction in greenhouse gas

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https://doi.org/10.1016/j.oceaneng.2023.114420
Received 9 February 2023; Received in revised form 19 March 2023; Accepted 1 April 2023

(GHG) emissions from international shipping of at least 50% by 2050 compared to 2008 (IMO, 2018, 2020; Joung et al., 2020). To reach this target, additional investments on greener technologies are required (Horvath et al., 2018), such as alternative fuels, electrification/hybridisation (Geertsma et al., 2017; Allal et al., 2019; Perčić et al., 2021), and energy-saving devices (Stark et al., 2022). For the next-generation MASS, the higher economic margin can be used to overcome the barriers for such investments (Rødseth et al., 2023).

Autonomous shipping is expected to offer more attractive and inclusive jobs on shore supported by technology (van den Broek and van der Waa, 2022), thus addressing the crew shortage attributed to the seafarers aging (de Vos et al., 2021). For example, Japan currently has the world's highest percentage of seafarers close to retirement, at 28.7%, which is forecasted to exceed 30% in 2030 and reach 40% in 2055. This reflects in the shipping workforce, 35% of which is around 60-year-old, reaching the retirement age within a few years, introducing challenges for future shipping industry operations (Suzuki, 2021; Kamata, 2021). Other significant benefits from MASS commercialisation include the safety enhancement (Kim et al., 2022; Rødseth et al., 2023), improve working conditions (Rødseth et al., 2023), reducing the maritime accidents related to human-error (Coraddu et al., 2020; Baumler et al., 2021; Porathe et al., 2018).

The MASS economic feasibility is rarely studied in the pertinent literature, which however investigated some autonomous vessels under varying assumptions. Kretschmann et al. (2017) investigated the impact of the unmanned operation for a bulk carrier (MUNIN, 2022), concluding that autonomy can reduce the ship present value (PV), for 25 years operations, about 4.3%, which are not enough to change to a lower carbon fuel. Santos and Guedes Soares (2018) compared the transition from conventional to autonomous operations for a small container ship sailing in the Portugal coast, concluding that similar return rates compared to conventional ships can be achieved at the expense of 32% higher investment. Ghaderi (2019) investigated a large container ship operating in the Short Sea Shipping (SSS), verifying that the unmanned ships feasibility depends on the demand and scale of operations, being more favourable in scenarios with fluctuating demand. Kooij et al. (2021) investigated the gradual replacement of the crew by autonomous systems in a SSS scenario, concluding that autonomous operations are advantageous. Jovanović et al. (2022a) studied the autonomy impact for three ferries sizes/routes with alternative fuels, identifying that the autonomous ships have a higher present value (PV), with better results achieved for smaller ships. Kooij et al. (2021) and Jovanović et al. (2022a) investigated the adoption of fuel cells, concluding that their current cost makes them unfeasible, despite the positive environmental footprint. Jovanović et al. (2022b) investigated different carbon tax scenarios in the feasibility analysis of a container ships, demonstrating the economic advantages of MASSs compared to conventional vessels.

The preceding literature review reveals the following research gaps and challenges: (a) lack of studies on the autonomous ships feasibility, (b) lack of available data required to assess feasibility for both conventional and autonomous ships, (c) addressing market instability requires methods for decision support under uncertainty, (d) autonomy impact on voyage alteration was not considered.

This study aims at developing an overarching framework to support decisions pertinent to MASSs feasibility, analysing the transition from conventional to autonomous shipping. This framework is implemented for the case study of a SSS autonomous cargo vessel, the main characteristics of which are derived based on an existing conventional vessel (baseline). The autonomy impact on the vessel design and operation is studied considering two stages: (i) conversion of the baseline ship to operate autonomously, representing the technological transition from the conventional to autonomous ships, denoted as Transition Autonomous Ship (TAS) and (ii) new autonomous ship design without crew accommodation compartments, denoted as Next Generation of Autonomous Ship (NGAS). Both TAS and NGAS are assumed compatible to the IMO autonomy degree of three or four (IMO, 2021), where the ships operate autonomously supervised by a remote operator. Four scenarios are investigated for each vessel to consider the uncertainty in operational and capital costs of technologies to enable autonomous operation and the fuel prices.

The novelty of this study stands from: (i) the developed framework to assess the autonomous ships feasibility, (ii) the framework implementation based on actual data to estimate the operational costs for the present value (PV) analysis; (iii) the consideration of voyage alterations due to autonomy; (iv) the consideration of the data uncertainty through investigation of different scenarios.

The remaining of this study is organised as follows. Section 2 provides the details of the methodological approach. Section 3 presents the operation data for the baseline vessel. Section 4 details the considered outlook for the MASS model adopted. Section 5 describes the environmental analysis results. Section 6 reports the economic analysis results. Section 7 discusses the derived results, whereas Section 8 summarises the main findings and provides recommendations for future studies.

2. Methodological approach

This study develops a framework to provide decision support for the economic-environmental sustainability of short sea shipping autonomous vessels. This framework consists of the following phases, which are also illustrated in the flowchart shown in Fig. 1.

Phase 1	This phase develops the operating profile for the baseline ship by employing as input its characteristics along with operational data, sea trials and prevailing weather conditions.
Phase 2	This phase deals with the outlook for MASS developments pertinent to the evolution of the baseline ship considering both the design and operations modifications due to the introduction of autonomy. The output of Phases 1 and 2 result in the definition of the operating profile for autonomous operations (MASS operating profile), which considers the voyage alteration due to autonomy (reducing the port staying periods for crew support, correspondingly increasing the sailing periods lowering the sailing speed).
Phase 3	This phase includes the environmental and economic analyses for both the conventional and autonomous operations (baseline ship, TAS and NGAS). The former is based on the calculated fuel consumption and the use of emission factors. The economic analysis employs the capital, operational, and voyage expenditure models to calculate the present value (PV).
Phase 4	This phase includes the definition of the scenarios for the sensitivity and uncertainty studies as well as the market analysis, which provides input to the economic analysis (Phase 3). The market analysis provides the prices and input parameters required for the economic analysis. The scenarios are defined to address the sensitivity and uncertainty in these prices, studying their impact on the MASS operation.
Phase 5	This phase aggregates and visualises the information (output parameters) from the previous phases, thus supporting decisions on the design and operation of the TAS and NGAS.

2.1. Case study vessel description

The case study considered herein refers to a cargo vessel that delivers fish feed from a factory to floating fish farms across the Norwegian coast with her main particulars presented in Table 1. Wennersberg et al. (2019) provides detailed description of this ship and her operational phases.

The vessel operates in a weekly pattern, sailing on short and long routes. Fig. 2 illustrates an example of the long route along with the ship calls at several farms and ports. The farms, ports and routes are different every week; however, these voyages commence and conclude at the fish

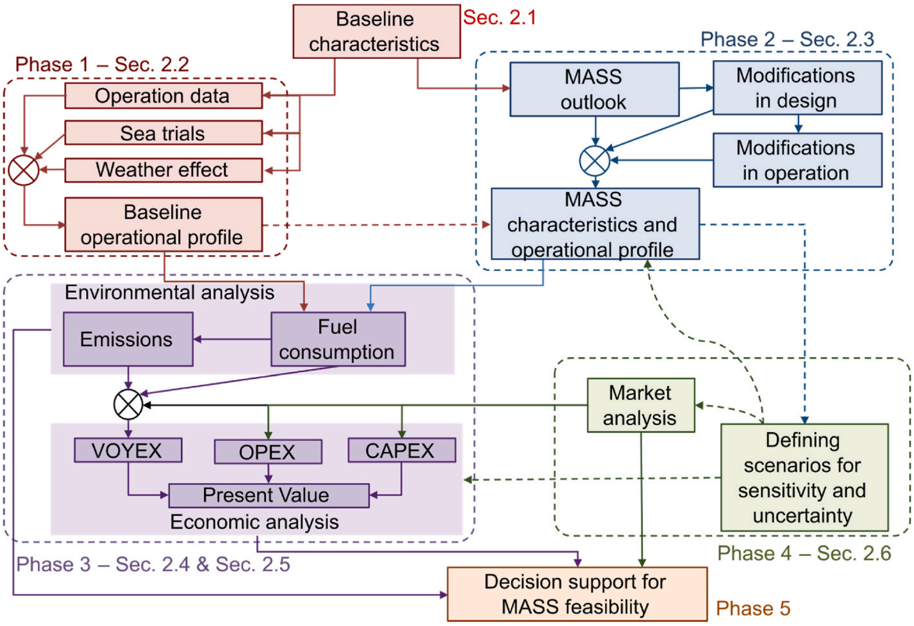

Fig. 1. Framework flowchart (Sections corresponding to each phase are provided).

Table 1
Main particulars of the study vessel.

Properties	Value
Length of waterline	74.7 m
Breadth moulded	13.6 m
Draft max.	5.1 m
Gross tonnage	2,145
Deadweight	1,450 mt
Lightship weight	1507 mt
Crew	2 officers 2 engineers 3 ratings

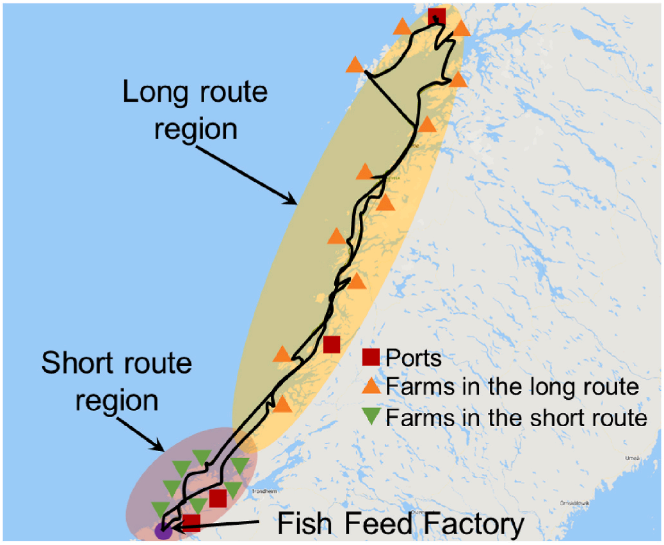

Fig. 2. Example of a long route pathway, and operational regions for the short and long routes. Approximated data showing typical ports and farms. Source of background image: www.myshiptracking.com; map data from OpenStreetMap (openstreetmap.org/copyright).

Table 2
Average and standard deviation of the voyages (short and long routes) characteristics.

Parameter	Short route	Long route
Duration	2 ± 0.2 days	5 ± 0.6 days
Distance	390 ± 50 km	1,400 ± 275 km
Farms no.	8 ± 2	10 ± 2
Ports no.	2 ± 1	1
Factory no.	1	1

feed factory (FFF). Table 2 shows the characteristics of each route. The ship operates year-round, except for two to four weeks allocated to maintenance. Crew rotation is used to compensate for leave and vacation. To address the ship stability concerns, the vessel draft is adjusted by using ballast water to an almost constant value for the entire vessel operation. The ship power plant layout and technical characteristics are presented in Fig. 3.

The ship controllable-pitch propeller (CPP) is used as propulsor during sailing, whereas during slow speed and Dynamic Position (DP) manoeuvres (berthing), both the CPP and the Tunnel-Thrusters (TT) (bow and stern) are used. The vessel power plant includes a Power Take-Off/Power Take-In (PTO/PTI) system; the auxiliary electric power demand is covered by the main engine (PTO mode), or the ship auxiliary engines energy is used to support the ship propulsion (PTI mode). An

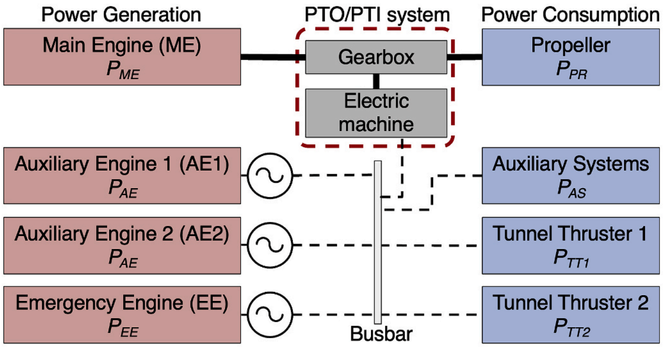

Fig. 3. Layout of the baseline vessel’s power plant.

emergency engine (EE) provides power the ship critical systems at emergencies. These engines main particulars are listed in Table 3.

2.2. Operation/mission definition

The baseline vessel operation was analysed using the method developed in Dantas and Theotokatos (2023), the flowchart of which is presented in Fig. 4. This method employs data from operation, sea trials and weather conditions to estimate the ship operating profiles (power demand) for each operational mode (sailing, berthing, loading at the FFF and unloading at the farms). This method uses the following modules:

- **Operational data** – The voyage characteristics are calculated by analysing data acquired via the Automatic Identification System (AIS). The collected datasets are classified based on the pertaining operational mode and are used to calculate the distributions of the sailed distance, time, speed, and destination for every voyage.
- **Power data** – The power and energy demand for each operational mode is derived using the sampled voyage data and the ship sea trials measurements. The sea trials provide the propulsion power versus ship speed for calm and rough sea conditions in each operational mode.
- **Weather data** – The annual energy profile is estimated by correlating the averaged historical weather data to the power at the prevailing sea conditions and sailing speed. The annual profiles (distributions) for the wind speed and wave height are employed to estimate the average power due to added resistance.

2.3. MASS outlook

This section investigates how crewless operations affect the baseline ship design, and how the design modifications impact the economic aspects. The effects from reduced crew are not analysed herein, as previous studies demonstrated that the highest impact is achieved by crewless operations (Kooij et al., 2021). This study assumes that both TAS and NGAS are capable to operate autonomously in normal conditions, whereas supervision by an operator is required under emergencies. This is compatible to the IMO autonomy degree three or four (IMO, 2021). Moreover, modifications to the vessel's design are identified to study the technical advantages of ships without deckhouse and crew accommodation spaces, whereas voyage alterations for autonomous operations are considered.

The Transition Autonomous Ship (TAS) is assumed to be the conventional ship retrofit (same structure; installation of the required systems and equipment), whereas the NGAS represents a redesigned vessel not restricted by structures for crew accommodation. The TAS can be hybrid, being operated either conventionally (with crew onboard) or from the remote control centre (RCC). Fig. 5 highlights the modifications for TAS and NGAS.

Future ships are expected to utilise technologies and designs for improving navigation efficiency and safety. Examples of these technologies include routing optimisation based on speed (Psaraftis and Kontovas, 2014), weather and logistic factors (Zaccone et al., 2018; Krata and Szlapczynska. 2018; Li et al., 2022); traffic at sea and in confined water (Zhou et al., 2019), use of energy-saving devices (Stark et al., 2022); adoption of hybrid power plants (Geertsma et al., 2017); alternative fuels and electrification (Perčić et al., 2021; Jovanović et al., 2022a); or fleet size optimisation (Sheng et al., 2019; Akbar et al., 2021; Barzegari et al., 2023). However, this study disregards these technologies effects, only focusing on the impact from autonomous operations.

Table 3
Baseline vessel energy producers.

Engines	No.	Power [kW]	Fuel
Main (ME)	1	2,430	NG
Auxiliary (AE)	2	2 × 469	MDO
Emergency (EE)	1	99	MDO

NG: natural gas; MDO: marine diesel oil.

2.4. Environmental analysis

The fuel consumption as well as the carbon dioxide (CO_2) and nitrogen oxides (NOx) emissions during operation are calculated by Eq. (1), and Eq. (2), respectively, as recommended by IMO (2020).

$$FC_{en} = \sum_{op} SFC_{en}\, E_{en,op} \tag{1}$$

$$EM_{en} = \sum_{op} EF_{en}\, FC_{en,op} \tag{2}$$

Where, E denotes the energy demand obtained from Phase 2 (Sec. 2.2), SFC is the Specific Fuel Consumption, and EF is the fuel-based Emissions Factors, whereas op and en denote the operation mode and engine, respectively.

2.5. Economic analysis

The economic analysis employs the Present Value (PV) method (Kretschmann et al., 2017; Jovanović et al., 2022a), according to which all future expenditures for owning and operating a vessel are brought to today's values, considering a discount rate. The following expenditures are considered in this study:

- Capital expenditure (**CAPEX**): costs related to investment need for acquiring or upgrading a fixed asset for the owner, such as the vessel, equipment, or systems.
- Operational expenditure (**OPEX**): regular costs required for the vessel operation during a typical year, such as the staff, regular maintenance, and administration. This expenditure is considered as a fixed cost.
- Voyage expenditure (**VOYEX**): costs related to the vessel's voyage that are proportional to its use, such as the consumed fuel; these costs are considered varying.

The discount rate (r) and the lifetime (n) were considered 8% and 25 years, respectively, as these values are typically used in studies pertinent to maritime industry (Kretschmann et al., 2017; Iannaccone et al., 2020). The revenue and the decommissioning expenditure (DECEX) were not considered herein. The Present Value (PV) is calculated according to the following equation:

$$PV = CAPEX + \sum_{i=1}^{n=25} \frac{OPEX_i + VOYEX_i}{(1+r)^i} \tag{3}$$

As commercial autonomous vessels in operation are not available, this study estimated the costs for TAS and NGAS based on the baseline vessel, considering the corresponding costs variations according to the pertinent literature.

The costs are corrected for 2024, using the database from the Organisation for Economic Co-operation and Development (OECD) for Norway up to 2022 and the forecasts for 2024. The Producer Price Indices (PPI) (OECD, 2022a) were employed to correct the prices for materials, equipment, and services from the industry, whereas the Consumer Price Index (CPI) (OECD, 2022b) was used to correct the staff costs (e.g., salary).

The economic analysis is carried out considering the following parameters:

- The **economic margin** is the PV difference between the baseline and the MASS; a positive margin indicates a better investment or a profit opportunity (Potter and Sanders, 2012).

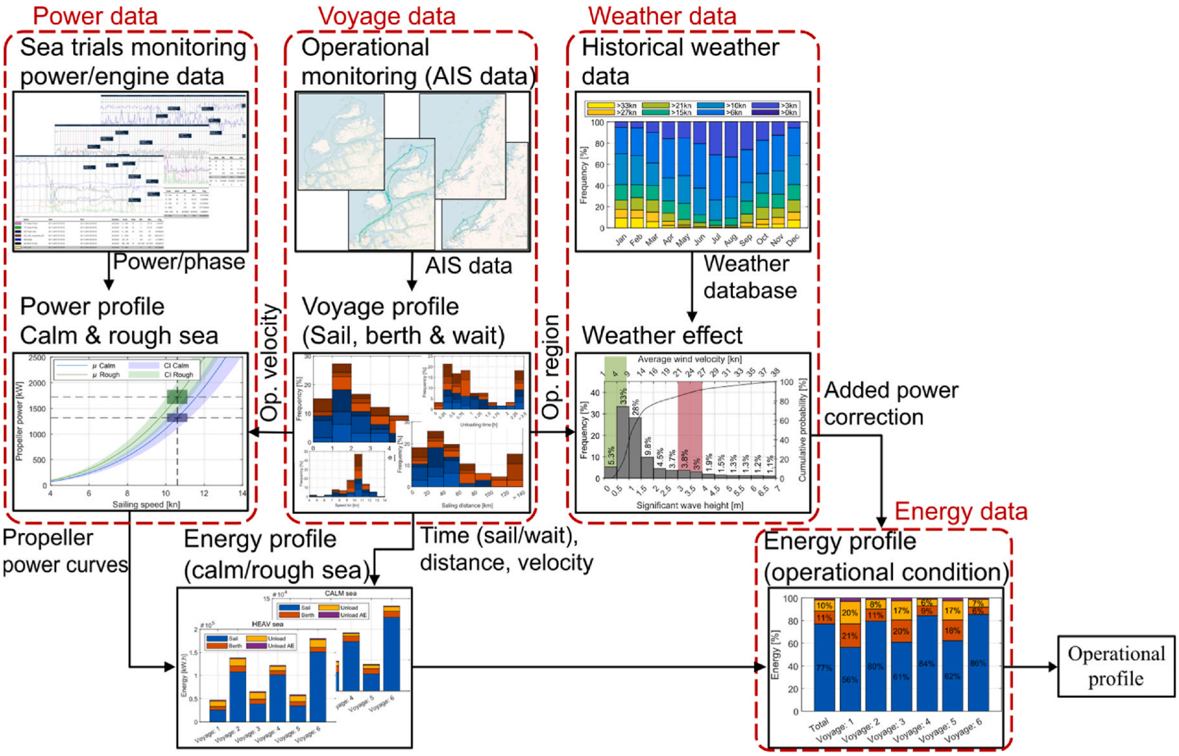

Fig. 4. Method for estimating vessels annual operating profile. Adapted from Dantas and Theotokatos (2023).

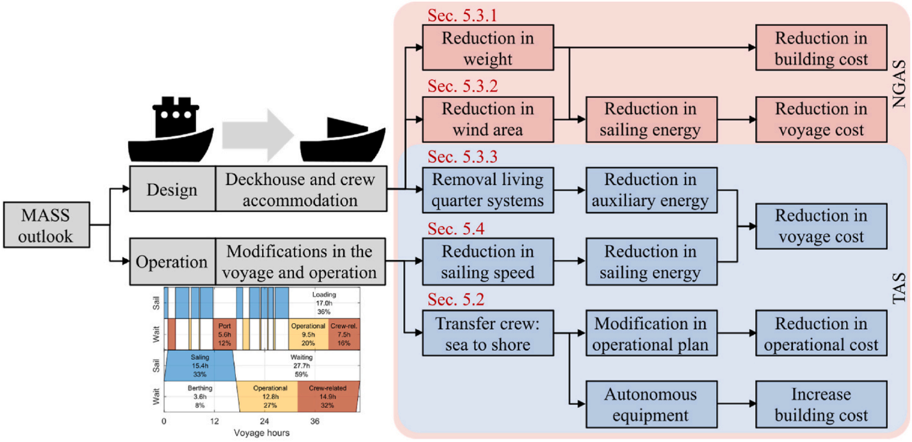

Fig. 5. Outline of the MASS outlook, showing the considered modifications and their outcome (modifications are elaborated in the indicated sections).

- The **economic robustness** is the ability of a financial system to resist in the market disturbances, demonstrating responsiveness and robustness (Bianco et al., 2023). This study investigates scenarios that are more dependent on a type of expense, thus, being more sensitive to specific market variations.

2.6. Exploratory scenarios for uncertainty and sensitivity

To address the uncertainty of the available data (technical and economic) and the considered assumptions, the following four scenarios were considered: (i) L-CO/L-V denoting low CAPEX and OPEX (corresponding to the best scenario) along with low VOYEX (corresponding to optimistic scenario pertinent to the fuels market uncertainty); (ii) H–CO/L-V denoting high CAPEX and OPEX (corresponding to the worst scenario) along with low VOYEX (corresponding to optimistic scenario); (iii) L-CO/H–V denoting low CAPEX and OPEX (corresponding to the best scenario) along with high VOYEX (corresponding to pessimistic scenario); (iv) H–CO/H–V denoting high CAPEX and OPEX (corresponding to the worst scenario) along with high VOYEX (corresponding to pessimistic scenario). These scenarios are summarised in Table 4.

Table 4
Definition of the scenarios for the sensitivity and uncertainty analysis.

		Scenario	
		Best Low CAPEX & OPEX (L-CO)	Worst High CAPEX & OPEX (H–CO)
Scenario	**Optimistic Low VOYEX (L–V)**	L-CO/L-V	H–CO/L-V
	Pessimistic High-VOYEX (H–V)	L-CO/H–V	H–CO/H–V

3. Operational profile

This section presents the main parameters of the baseline vessel's mission/operation, along with the estimation of the power demand, required energy, fuel consumption, and emissions for each operational mode. Detailed results are reported in Dantas and Theotokatos (2023).

3.1. Power demand

The baseline ship power demand for each operational mode was measured during the contacted sea trials in calm and rough sea conditions. The average annual power was estimated considering the weather along a typical year, using datasets retrieved by Meteoblue (2022). The average power for each mode and voyage type was calculated by employing the detailed power demand as reported in by Dantas and Theotokatos (2023) and is illustrated in Fig. 6(b). The ship Main Engines (ME) operate at all modes (apart from port staying and anchorage). The ship Auxiliary Engines (AE) typically operate at manoeuvring and cargo unloading at the farms.

3.2. Energy profile

The energy consumed during the baseline vessel operation was estimated multiplying the time spent and the power demand at each operational mode. This study used the weather-averaged power from the sea trials, correcting the sailing power by using the measured vessel speed, according to the method adopted in IMO (2020) and Olmer et al. (2017). The available AIS datasets for six voyages are employed to estimate the operational time at each mode. The datasets were separated in several voyage' legs, i.e., operation during two stops, providing an estimation for the time spent for each operational mode (sailing, unloading at the fish farms, and loading in the factory). The berthing time were considered constant due to the low temporal resolution of the AIS data (1–2 min), whereas the average value from the sea trials was used for the berthing speed. Assuming that this profile repeats along the year, the operational time, the annual average power demand, and the consumed energy profiles are estimated for the short and long voyages. These results are presented in Fig. 6.

4. MASS outlook

This section presents the assumptions considered in this study (Sec. 4.1), the overall operation modification (Sec. 4.2), the design modifications (Sec. 4.3) and the voyage plan alteration (Sec. 4.4).

4.1. Assumptions

This study adopts the following assumptions for the TAS and NGAS:

- The autonomous operations are constrained (Rødseth et al., 2022), which implies that the ship's operating systems can make decisions and determine actions, however human supervision is required. This is equivalent to three IMO autonomy degree (IMO, 2021).
- The human supervision is carried out by a remote control centre (RCC) operator with sporadically intervention. This condition is compatible to three or four IMO autonomy degree (IMO, 2021).
- The required autonomous technologies are established for commercial use and certified for safe operation, including the autonomous navigation, as well as operations at ports, fish feed factory (FFF) and farms.
- The investigated MASSs operate at the same routes as the baseline ship.

4.2. Operations modification

The following sections present the expected modifications for the TAS and NGAS operations.

4.2.1. Transfer seafarers from sea to shore

Crew is not expected to be onboard autonomous ships to perform activities required for the navigation, machinery monitoring, and periodic maintenance. These activities must be handled by the vessel autonomous systems, the RCC operators and the ports staff.

This study assumes that the RCC personnel are responsible for overseeing the operation of the autonomous ship, actively aiding with more complex tasks, such as high traffic, berthing, navigating in adverse conditions and operating the cargo equipment (Hoem et al., 2022). The RCC's organisation follows the recommendations of the MUNIN project (Kretschmann et al., 2015). An RCC operator with first or second officer qualifications supervises navigation of up to six ships. A floor supervisor and a backup operator are required for five RCC operators. The RCC also requires one engineer to supervise the engine room operation for up to 30 vessels. Additionally, it is assumed that the unloading procedure can be performed remotely by the RCC operator.

4.2.2. Regular maintenance

The maintenance activities of conventional ships are normally carried out onboard by the crew. However, autonomous ships must rely on prognostics and health management (PHM) technologies and use predictive maintenance (PM), instead of corrective or planned maintenance. This study assumes that the PM activities will be carried out at

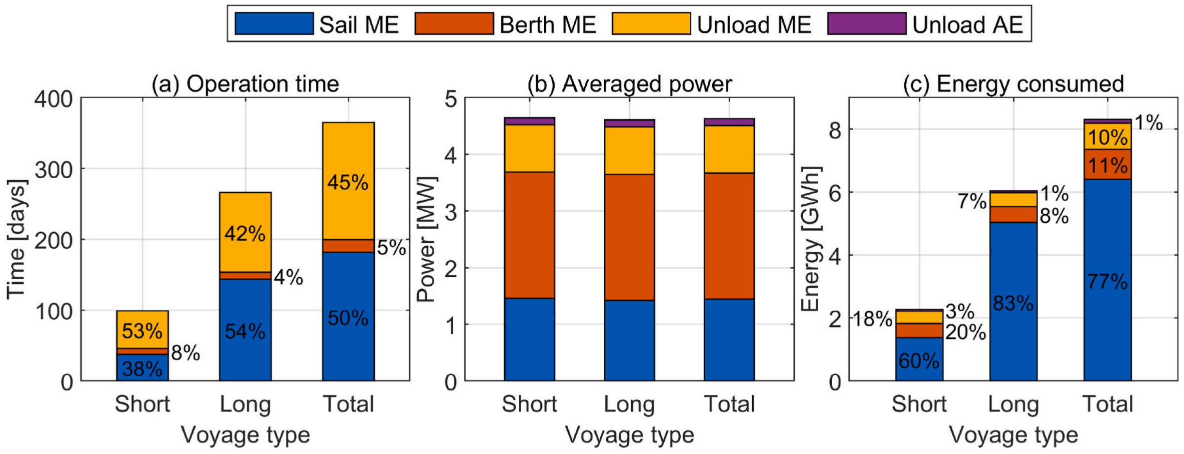

Fig. 6. Baseline vessel operational modes for short and long voyages: (a) annual time, (b) average power demand, and (c) consumed energy (ME: Main Engine; AE: Auxiliary Engine).

ports and quays (every 3–4 days) by using dedicated maintenance teams. Two maintenance groups are expected; one is responsible for the ship berthing and cargo loading/unloading, consisting of a first officer and able seaman; the other is responsible for the ship cleaning, machinery, and systems maintenance, as well as bunkering, consisting of engineers, bosun and able seaman.

4.2.3. Periodic maintenance and repairs

The PM and PHM technologies directly and indirectly impact the maintenance and repairs related costs. A risk-based maintenance scheduling can reduce the maintenance cost (Cullum et al., 2018) and fault detection can allow for maintenance actions and planning increasing the ship availability (Cheliotis et al., 2020). The real-time monitoring with data-driven models can improve energy efficiency operational indicators and estimate the ship requirements for future maintenance (Shaw and Lin, 2021), as well as optimise their fuel consumption (Yuan et al., 2021). This concept can be extended to the hull coating maintenance and drydocking, using stochastic methods to predict the coating failure (Davies et al., 2021) and using economic and environmental metrics to enable evidence-based decisions on the optimal vessel availability (Oliveira et al., 2022). In this study, these methods benefits are considered as an overall reduction in maintenance costs, adding the necessary equipment investment and analytics costs related to data management for these technologies. Despite the expected benefits from the increased availability, the proposed economic analysis does not consider them, as this is beyond this study scope.

4.3. NGAS design modifications

This section outlines the NGAS design modifications considering that accommodation spaces are not required, whereas bridge visibility restrictions do not exist. Due to the uncertainties related to these modifications and their effect in the ship efficiency, the identified best and worst scenarios are considered.

4.3.1. Reduction in lightship weight

As deckhouse and accommodation spaces are not required in NGASs, lighter ship with lower wind area is expected, with a consequent resistance decrease. These weights are assumed to be proportional to the whole ship volume, i.e., same structural density. The baseline ship characteristics were used to estimate these weights. This ship deckhouse and crew accommodation volume is 996 m^3, accounting for about 10% of total ship volume. Hence, the NGAS design exhibits a weight reduction of 151 mt. This estimation represents the worst scenario.

For the best scenario, it was considered that the ship water-related systems and tanks are also removed. These systems include the fresh, grey and black water systems and tanks, as well as other miscellaneous systems, such as, air conditioning, life rafts and their mountings. These systems weight in the baseline ship was approximated to 72 mt.

It must be noted that the removed weight can be used to increase the cargo capacity, resulting in increased ship energy efficiency. However, this modification implies variations in the fleet logistics and the assumed operational profile, which renders the comparative assessment with other vessels versions challenging. Therefore, this study considers that the reduced weight results in the NGAS draft reduction.

The relation between the ship draft and sailing power is estimated by the method reported in Olmer et al. (2017) and IMO (2020), assuming the admiralty coefficient constant. It was assumed that the ship block coefficient (C_b), moulded breadth (B) and length (L) do not vary with the draft (t), resulting in the propeller sailing power ($P_{PR\text{-}Sail}$) being proportional to the displacement to the power of two third ($\Delta^{2/3}$) and, consequently, to the draft at same power ($t^{2/3}$), according to Eq. (4). Table 5 summarises the reductions in the NGAS weight, draft, and propulsion power compared to the baseline ship along with the respective percentages.

Table 5
Lightship weight reduction impact on propulsion power.

Parameter	Baseline parameters	Parameter reduction/Percentage reduction	
		Worst scenario	Best scenario
Lightweight	1,507 mt	151 mt/10.0%	223 mt/14.8%
Draft	5.0 m	0.26 m/5.1%	0.38 m/7.5%
Power[a]	1,459 kW	59 kW/3.4%	88 kW/5.1%

[a] Propeller power at 10.6 kn, with 1450 t of cargo (total displacement of 2957 t).

$$P_{PR-Sail} \propto (\Delta)^{\frac{2}{3}} \propto (L\ \ B\ \ t\ \ C_b\ \ \rho_{sw})^{\frac{2}{3}} \propto (t)^{\frac{2}{3}} \tag{4}$$

Without the deckhouse, the ship centre of gravity lowers, which can potentially reduce the required ballast water volume, consequently, further increasing the ship efficiency and positively impact safety (Tvete, 2014; Ghaderi, 2019). The NGAS design can further reduce the ship's lightweight considering the fuel storage requirements for the intended ship operating profile, as crewless operation may result in less demanding safety requirements and more effective compartmentalisation.

4.3.2. Reduction in wind area

The NGAS concepts (Royce, 2016) and prototypes (Yara, 2022) take advantage of the lack of deckhouse to use a streamlined design, reducing the wind/air drag and, consequently, increasing the sailing efficiency. Although the air resistance represents about 2% of the total sailing power, in adverse weather conditions, the wind resistance can become significant (MAN Energy Solutions, 2018).

The frontal area regions of the baseline vessel are presented in Fig. 7. The worst scenario assumes that the entire deckhouse area is removed, whereas the hull area above the waterline is reduced proportionally to the draft reduction. In the best scenario, additionally, 50% of antenna area is reduced, considering newer and more compact equipment. Due lack of available data, the drag coefficient (C_D) values reported by Kretschmann et al. (2017) and Blendermann (1996) were considered; hence, $C_D = 0.68$ for the baseline ship, TAS and the worst scenario of NGAS; $C_D = 0.45$ for the best scenario of the NGAS. The power reduction is estimated considering the ship average speed (10.6 kn) and the mean wind speed (5 kn and 24 kn) for calm and rough sea conditions, respectively. The estimated parameters are presented in Table 6.

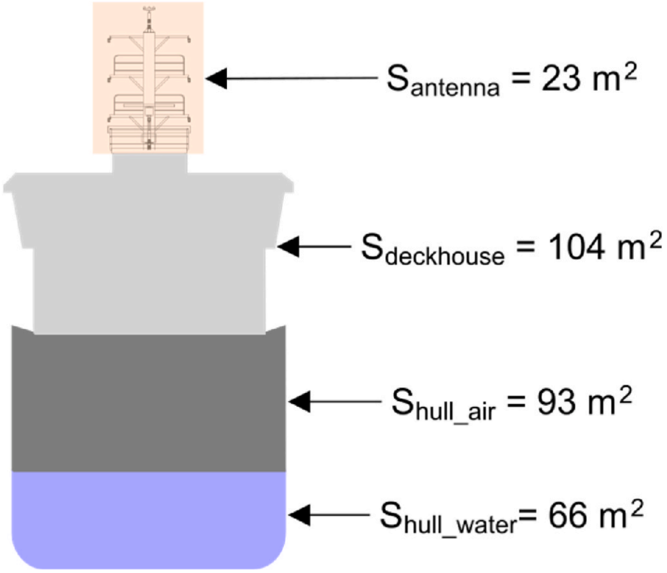

Fig. 7. Frontal areas estimated for the baseline vessel.

Table 6
Results from the wind area reduction study.

Parameter		Parameter/Percentage reduction[a]		
		Baseline ship	Worst scenario	Best scenario
Area (m^2)		221	113/49%	100/55%
Drag coefficient (–)		0.68	0.68/0%	0.45/34%
Power (kW)	Calm sea conditions	1,320	1,301/1.5%	1,292/2.1%
	Average sea conditions	1,459	1,409/2.7%	1,385/3.8%
	Rough sea conditions	1,724	1,665/5.5%	1,636/7.9%

[a] The percentage values indicate the reduction compared to the baseline ship.

4.3.3. *Auxiliary systems energy*

The crewless vessels do not require energy (electric and thermal) for the living quarters, thus resulting in reduced auxiliary energy demand. The auxiliary systems of the baseline vessel use about 170 kW during sailing and berthing, and about 300 kW during unloading (Dantas and Theotokatos, 2023). This study adopts the reduction levels reported in Kretschmann et al. (2017) and Allal et al. (2018), corresponding to 40% and 37% for the best and worst scenarios, respectively. These values are estimated considering the reduction for heating, ventilation, galley, laundry, lighting (partial), sewage and ballast, as it is expected that the NGAS have a ballast-free design (Tvete, 2014). This value was applied only for the 170 kW, as it is assumed that the additional energy during unloading is related to the cargo management.

For the TAS, the same values are considered, disregarding the reduction in ballast, mooring and lights electric energy demand, which required for the ship operation, resulting in a difference of about 5% in both scenarios, i.e., 35% and 32% reduction for the best and worst scenarios, respectively.

4.4. *Voyage modification due to autonomy*

In a typical operation, the baseline vessel spends time in ports and quays that are not directly related to the cargo transport. These periods are related to the crew shift changes, loading the consumables and crew rest. However, for crewless vessels, these waiting time periods are not required; hence, TAS and NGAS operating profile can be modified to increase the sailing mode period by reducing the sailing speed, which reduces the ship propulsion power demand. On average, the baseline ship spends about 15% ± 7% of its weekly operation time at ports.

At the FFF, the shore equipment is used for the cargo loading that lasts about 10 h. The time needed to berth the vessel and prepare the cargo hold is assumed to be 2 h. Simultaneously with the loading procedure, the crew carries out the bunkering, routine maintenance, cleaning, and machinery checking (Fan et al., 2022). However, it was deduced from the acquired AIS data that the baseline ship stays in the FFF about 21 h ± 17 h on average per call, or 43 h ± 10 h per week, indicating that the vessel also waits for supplies; the latter is not pertinent to the ship operation.

Using this information, the maximum required time for loading and bunkering the baseline ship during its stays in the FFF was estimated as function of the delivered cargo, considering the time spend in the farms. On average, considering all voyages, the ship stays in the FFF about 24% ± 5% of the weekly operation time (sum of the short and long routes), in which 9% ± 5% is related to the loading/bunkering procedure and 15% ± 13% is related to waiting for supplies. This behaviour was observed for all long routes and several short routes, indicating periods when the vessel further stays at the FFF, instead of ports. Examples with and without port staying are presented in Fig. 8(a) and Fig. 8(b), respectively, showing the time percentage for each operational mode (sailing, waiting and berthing) compared to the entire voyage duration, identifying the periods of the normal operation and crew logistics. The percentages presented in Fig. 8 are calculated considering the total voyage time. By adding the time spent at ports and the waiting time at the FFF for the short and long routes, the baseline ship non-operational time ($t_{non\text{-}op}$) was calculated as about 29% ± 5% of the entire voyage time.

This study considers that the $t_{non\text{-}op}$ can be reduced increasing the sailing time at a lower speed. However, as this modification can involve other issues, such as, the FFF loading queue, additional time for maintenance, and weather conditions, it is assumed that only part of $t_{non\text{-}op}$ can be used. Therefore, this study investigates five cases of progressive reduction factors, starting from the reference case (no reduction) to the maximum (100% of $t_{non\text{-}op}$). These cases are presented in Table 7 considering the average operational weekly period.

As it is challenging to reach the 100% reduction factor (case IV), the reduction factor of 50% (case II) was considered a more realistic and achievable. It must be noted that the speed reduction for the unmanned vessels can potentially enhance the overall navigation safety (Tvete, 2014; Ghaderi, 2019), as the autonomous navigation system will have additional time to identify obstacles and make collision avoidance decisions (either by the autonomous navigation system or the RCC's operator for the most demanding scenarios).

5. Environmental analysis: consumed fuel and emissions

The environmental analysis used the average parameters and emissions factors (EF) as reported in IMO (2020), considering the main and auxiliary engines. These parameters are presented in Table 8. This study focused on the CO$_2$ and NOx emissions, as their social cost (taxation) is considered in the economic analysis (Sec. 6.4). The environmental analysis results are presented in Fig. 9 for the best (L-CO) and worst scenarios (H–CO), adding the four cases of sailing speed reduction shown in Table 7 for each scenario, represented by the percentage of the non-operating time related to the crew ($t_{non\text{-}op}$) reduction on the horizontal axis.

The derived results show that the MASS will have considerable

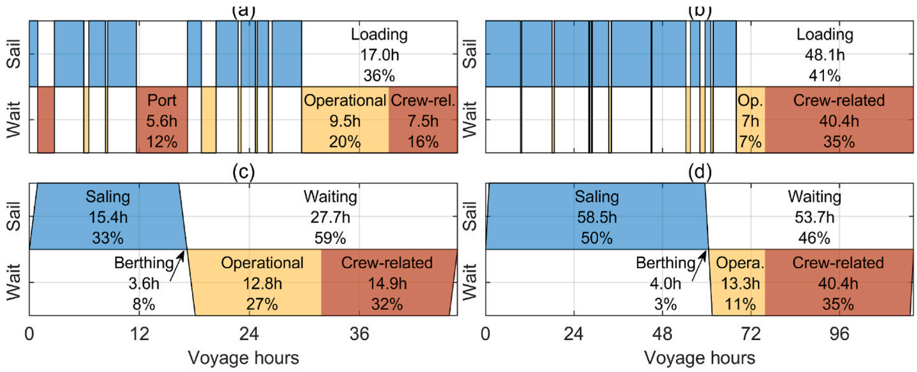

Fig. 8. Example of the waiting time study, (a) with port stay in a short route and (b) without port stay in a long route. Blue denotes the sailing time, yellow denotes the waiting time related to essential operation, and red denotes the waiting time related to the ship crew. The berthing time is considered in the transition between sailing and waiting periods. Plots (a) and (b) provide the operations in chronological order; Plots (c) and (d) provide aggregated results for each operational mode for the plots (a) and (b), respectively.

Table 7
Results from the four cases of the waiting time reduction (corresponding to sailing time increase).

Cases	Reduction factor	Sail time increase	Wait time reduction	Total	Sailing	Berthing	Waiting	Waiting	
								Operational	Crew-related
				[h]	[h]/[%]	[h]/[%]	[h]/[%]	[h]/[%]	[h]/[%]
Ref.[a]	0%	0%	0%	168	83/50%	8.4/5%	76/45%	27/16%	49/29%
I	25%	15%	16%	168	96/57%	8.4/5%	64/38%	27/16%	37/22%
II	50%	29%	32%	168	108/64%	8.4/5%	52/31%	27/16%	25/15%
III	75%	44%	48%	168	120/72%	8.4/5%	39/23%	27/16%	12/7%
IV[b]	100%	59%	65%	168	133/79%	8.4/5%	27/16%	27/16%	0/0%

[a] Case without modification in the $t_{non\text{-}op}$.
[b] Case considering that all $t_{non\text{-}op}$ is employed to increase the sailing time.

Table 8
SFC and EF for the ME and AE of the baseline vessel (Dantas and Theotokatos, 2023).

Parameters	Main Engine	Auxiliary Engine
Engine type	Lean Burn Spark-Ignited	diesel
Fuel	LNG	MDO
SFC	156 g NG/kWh	185 g MDO/kWh
EF CO_2	2,750 g CO_2/kg LNG	3,206 g CO_2/kg MDO
EF NOx	8.3 g NOx/kg LNG	60.5 g NOx/kg MDO

NG: natural gas; LNG: liquified natural gas; MDO: marine diesel oil.

positive environmental impact. The TAS CO_2 emissions reduce between 3.6% and 3.9%, whereas the NOx emissions reduce between 3.9% and 4.2%, due to the lower auxiliary power. The NGAS exhibits CO_2 and NO_X emissions reduction by 8.3–11% and 8.2–10%, respectively attributed to the lower sailing power related to the vessel's lower weight/draft and wind area.

The emissions are further reduced by reducing the ship non-operational time ($t_{non\text{-}op}$), which, consequently, reduces the navigation speed (Sec. 4.4). This effect has great impact on the emissions reduction compared to the design changes; e.g., considering the case with 50% of $t_{non\text{-}op}$ reduction (case II in Table 7), the CO_2 and NOx emissions exhibit reductions of 28–33% and 26–31%, respectively.

6. Expenditures evaluation

The following sections present the assumptions and limitations considered (Sec. 6.1) and the summarised results for the CAPEX (Sec. 6.2), OPEX (Sec. 6.3), VOYEX (Sec. 6.4) and PV (Sec. 6.5) for the baseline ship, TAS and NGAS. The breakdown and justification for each cost are presented in Appendix A, B and C, respectively. Sec. 6.5

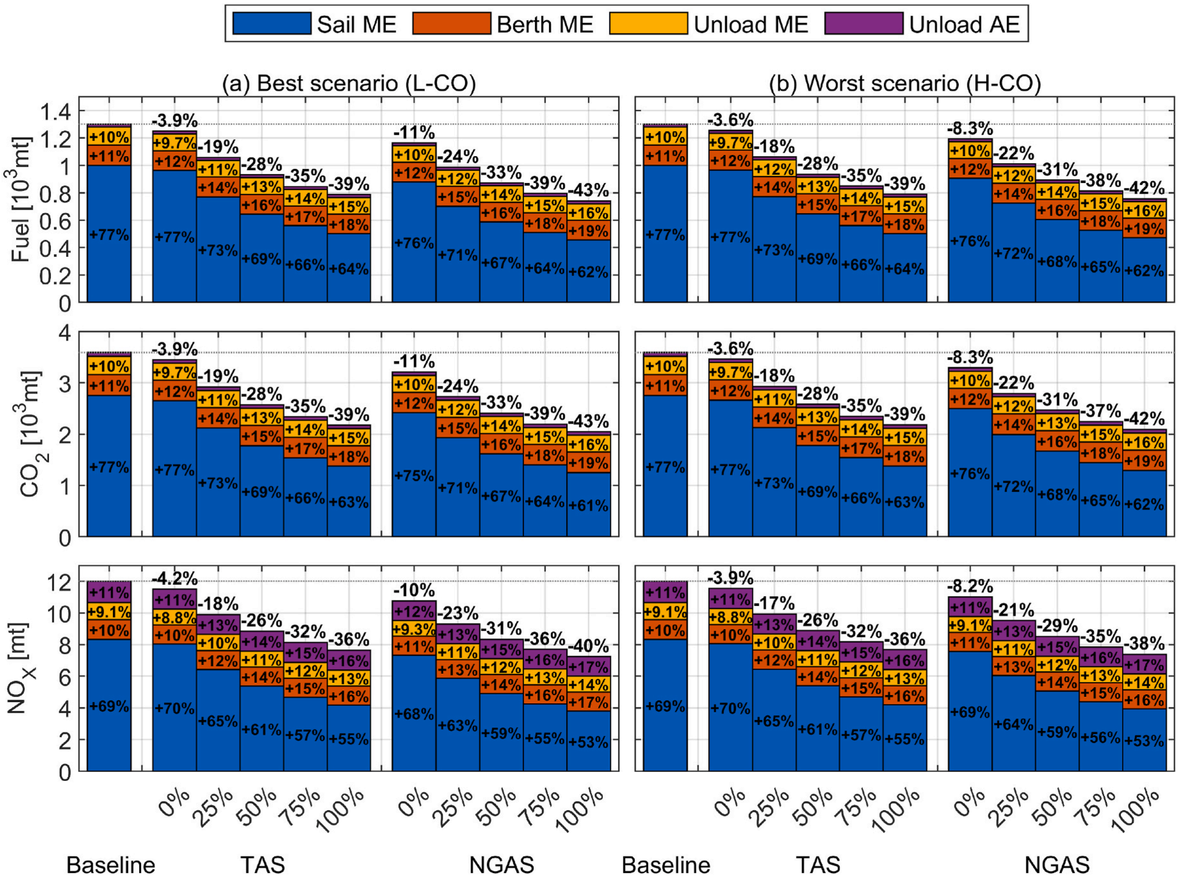

Fig. 9. Annual fuel consumption and emissions (CO_2 and NOx) for: (a) best (L-CO) and (b) worst (H–CO) scenarios. The numbers above bars denote variations against the baseline ship; numbers inside bars correspond to each category cost percentage; and the percentages in the horizontal axis indicate the reduction of the non-operating time related to the crew logistics ($t_{non\text{-}op}$) shown in Table 7.

summarises all the costs using the PV method (Sec. 2.4).

6.1. Assumptions and limitations

This study considered the following assumptions and limitations for the expenditure evaluation:

- Likewise other studies (Kretschmann et al., 2017; Ghaderi, 2019; Kooij et al., 2021; Jovanović et al., 2022a), the certification cost (part of CAPEX) was not considered, as its estimation is greatly uncertain.
- The RCC was considered service with its cost being part of the OPEX (Nordahl et al., 2022) (details are provided in Appendix B.2). This approach was investigated in Kretschmann et al. (2015), suiting operators/owners with few ships, as it requires lower initial investments.
- It is considered that the vessels and their equipment is fully depreciated at the end of the 25-year lifespan, i.e., having insignificant economic value.
- The ship operation as presented in Sec. 3 (Dantas and Theotokatos, 2023) repeats every year, i.e., without modifications in routes, cargo and energy due to seasonal demand.
- The costs of port calls (VOYEX) were not considered in this study, as they are negligible compared to the other considered costs.
- VOYEX and OPEX do not change over the 25-year lifespan of ships, not considering the increase in maintenance costs and the increase in fuel consumption due to aging equipment.

This study assumes that the revenues and the decommissioning expenditure for the TAS and NGAS are similar to the baseline ship, and hence are not considered.

6.2. CAPEX

The estimated CAPEX along with the cost contributors for each investigated vessel for the best and worst scenarios is presented in Table 9. The graphical representation of these results is shown in Fig. 10.

The derived results presented in Fig. 10 and Table 9 demonstrate that the autonomous crewless vessels require a higher initial investment compared to their conventional alternatives (baseline versions). For the TAS, the CAPEX increases between 8% and 17% (for the best and worst scenarios respectively), which are mainly attributed to the autonomous systems (Sec. A.4) and the use of required equipment (Sec. A.3 and A.5) and engine (Sec. A.2). The NGAS CAPEX was estimated 3–5% less compared to the TAS, attributed to the steel and manufacturing costs reductions, corresponding to non-existence of the deckhouse and crew-related structures (Sec. A.1). However, the NGAS' CAPEX is expected to be 3%–14% higher than the baseline, indicating a higher initial investment for future MASSs.

6.3. OPEX

The derived results for the annual OPEX and its contributors are presented in Table 10, whereas their graphical representation is illustrated in Fig. 11. The OPEX for the investigated autonomous ships greatly varies, as the crew costs are substituted by the RCC and maintenance related costs, which are generally lower that the expected ones for conventional ships (Kretschmann et al., 2017; Ghaderi, 2019; Iannaccone et al., 2020; Kooij et al., 2021).

For the baseline vessel, about 50% of the OPEX are directly related to the crew (salaries and consumables, Sec. B.1), 32% are related to management (insurance, Sec. B.7, and administration, Sec. B.8), and 18% are pertinent to maintenance and repairs (Sec. B.5 and B.6). The conversion to the autonomous operation reduces the crew cost, as the ship functions are expected to be carried out by the RCC operators (Sec. 4.2), which leads to a lower cost (60–80% reduction, Sec. B.2 and B.3). However, the shore tasks, such as maintenance, bunkering and loading, need to be carried out by raiding teams (Sec. B.4) during the ports or FFF calls, largely increasing the maintenance related costs (43–62%). Management costs are the least affected, changing only due to the insurance cost, which is assumed to be proportional to the vessel CAPEX.

Considering the OPEX variations presented in Table 10 and Fig. 11, the TAS OPEX was estimated 12–34% less than the baseline ship (for the best and worst scenarios respectively), whereas the NGAS OPEX was estimated about 1% lower than TAS due to the insurance cost. These results shows that the MASS are expected to have a higher operating economic margin than the manned vessels, increasing their economic attractiveness, as the logistics of the new staff can be optimised to handle more ships with a smaller crew number.

6.4. VOYEX

The estimated annual VOYEX and its contributors are presented in Table 11, for the four investigated cases considering combinations of the best (L-CO) and worst (H–CO) scenarios in the CAPEX and OPEX, as well as the pessimistic (H–V) and optimistic (L-V) voyage-related costs. Fig. 12 provides the graphical representation of the derived VOYEX results, adding the four cases of sailing speed reduction shown in Table 7 for each scenario, which are represented by the percentage reduction of the non-operating time related to the crew logistics ($t_{non\text{-}op}$) on the horizontal axis. The total VOYEX reduction percentages compared to the baseline ship are indicated on top of each bar.

The derived results indicate that the consumed fuel cost is the greatest contributor to the VOYEX for the baseline ship, ranging from 72% in the optimistic scenarios (L-V) to 77% in the pessimistic scenarios (H–V); the emissions taxation is the next contributor (13–23% of the VOYEX), whereas the engine maintenance contributes about 4%. The TAS VOYEX was estimated 3.5–3.9% lower compared to the baseline vessel, which is attributed to the reduction of the auxiliary energy for the crew accommodation spaces. For the NGAS, reduction in the range

Table 9

CAPEX for the investigated vessels considering the best and worst cost scenarios.

Categories			Best scenario						Worst scenario					
	Baseline		TAS			NGAS			TAS			NGAS		
	k€[b]	%[c]	↑↓[a]	k€[b]	%[c]	↑↓[a]	k€[b]	%[c]	↑↓[a]	k€[b]	%[c]	↑↓[a]	k€[b]	%[c]
Hull/structure	7,464	36	0%	7,464	33	−15%	6,360	30	0%	7,464	31	−10%	6718	28
Engines	6,501	31	5.0%	6,826	30	5.0%	6,826	32	10%	7,151	29	10%	7151	30
DP system	3,126	15	5.0%	3,283	15	5.0%	3,283	15	10%	3,439	14	10%	3439	15
Electronics	625	3.0	150%	1,563	6.9	150%	1,563	7.3	317%	2,605	11	317%	2605	11
Cargo	3,126	15	10%	3,439	15	10%	3,439	16	20%	3,752	15	20%	3752	16
Total	20,843	100	8.3%	22,575	100	3.0%	21,471	100	17%	24,411	100	14%	23,665	100

[a] Cost variation from the baseline.

[b] Cost in thousand euros.

[c] Cost ratio for the vessel/scenario.

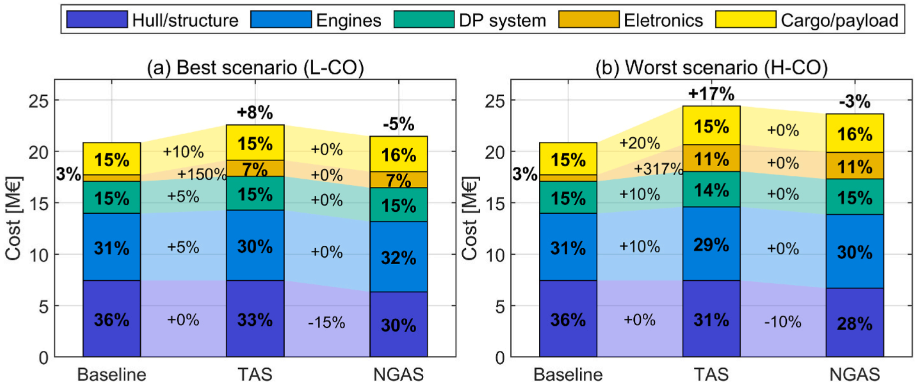

Fig. 10. CAPEX results for the (a) best and (b) worst cost scenarios. Numbers above bars denote variations against the baseline ship; numbers between bars denote variations for each category; numbers inside bars correspond to each category cost percentage.

Table 10
Annual OPEX for the investigated vessels considering the best and worst cost scenarios.

Categories	Baseline		Best scenario						Worst scenario					
			TAS			NGAS			TAS			NGAS		
	k€[b]	%[c]	↑↓[a]	k€[b]	%[3]	↑↓[a]	k€[b]	%[c]	↑↓[a]	k€[b]	%[c]	↑↓[a]	k€[b]	%[c]
Crew salary	1,036	41	RC	0	0	RC	0	0	RC	0	0	RC	0	0
Crew consumables	192	8	RC	0	0	RC	0	0	RC	0	0	RC	0	0
RCC	0	0	NC	192	12	NC	192	12	NC	289	13	NC	289	13
Software/Analytics	26	1	262%	94	6	262%	94	6	623%	188	9	623%	188	9
Regular mainten.	50	2	485%	292	18	485%	292	18	606%	353	16	606%	353	16
Periodic mainten.	300	12	0%	300	18	0%	300	18	0%	300	14	0%	300	14
Repairs	100	4	−50%	50	3	−50%	50	3	−25%	75	3	−25%	75	3
Insurance	417	17	−19%	339	21	−23%	322	20	46%	610	28	42%	592	27
General costs	380	15	0%	380	23	0%	380	23	0%	380	17	0%	380	17
Total	2,501	100	−34%	1,647	100	−35%	1,630	100	−12%	2,195	100	−13%	2,176	100

NC: new contributor; RC: removed contributor.

[a] Cost variation compared to the baseline.

[b] Cost in thousand euros.

[c] Cost ratio for the vessel/scenario.

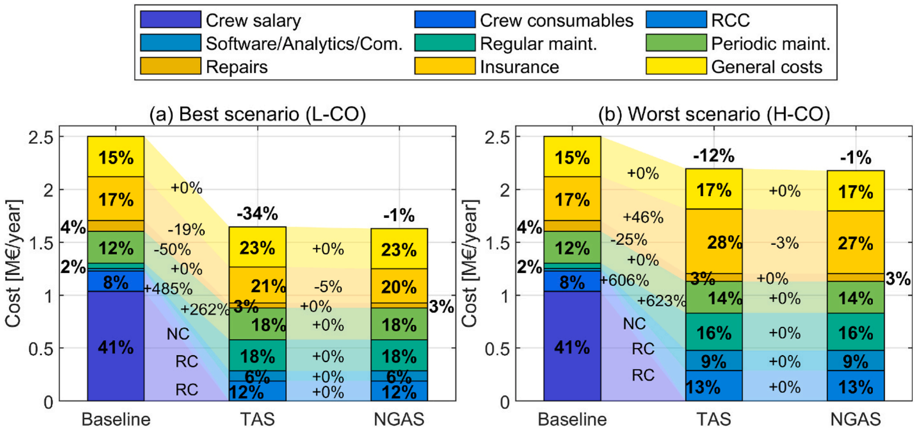

Fig. 11. Annual OPEX results for the (a) best and (b) worst scenarios. Numbers above bars denote variations against the baseline ship; numbers between bars denote variations for each category; numbers inside bars correspond to each category cost percentage; NC: new contributor; RC: removed contributor.

8–11% compared to the baseline vessel was estimated, which is attributed to the increased navigation efficiency, related to lower structural weight and wind area (Sec. 4.3).

According to the results presented in Fig. 12, the autonomous ships VOYEX can be further reduced by reducing the time periods spent in ports and factories (not related to the ship sailing – $t_{non\text{-}op}$) and increasing the navigation time, reducing the sailing speed (Sec. 4.4). Considering 100% reduction of the crew-related time (theoretical case IV in Table 7), the VOYEX can be reduced by 40% for the TAS and 44% to the NGAS, compared to the baseline ship. However, in practice this reduction should be lower. Considering a more conservative modification according to which half time spent by the crew can be converted to navigation time (case II in Table 7), the VOYEX reductions were estimated to 28% and 33% for the TAS and NGAS, respectively. This indicates that for the investigated ships, the VOYEX is more affected the operational modes changes rather than the ship design modifications.

Table 11
Annual VOYEX costs for the baseline, TAS and NGAS vessels, for the best (lower CAPEX and OPEX) and worst (higher CAPEX and OPEX) scenarios with the pessimistic and optimistic voyage-related costs.

				L-CO (best)						H–CO (worst)					
	Categories	Baseline		TAS			NGAS			TAS			NGAS		
		k€[b]	%[c]	↑↓[a]	k€[b]	%[c]	↑↓[a]	k€[b]	%[c]	↑↓[a]	k€[b]	%[c]	↑↓[a]	k€[b]	%[c]
L-V	Fuel	1238	72	−3.9%	1190	72	−11%	1106	72	−3.6%	1194	72	−8.3%	1135	72
	CO$_2$ tax	380	22	−3.9%	366	22	−11%	340	22	−3.6%	367	22	−8.3%	349	22
	NOx tax	32	2	−4.2%	30	2	−10%	28	2	−3.9%	30	2	−8.2%	29	2
	Engine maint.	71	4	−4.0%	68	4	−11%	63	4	−3.6%	68	4	−8.3%	65	4
	Total	1721	100	−3.9%	1654	100	−11%	1538	100	−3.6%	1659	100	−8.3%	1577	100
H–V	Fuel	2952	77	−3.9%	2838	77	−11%	2638	77	−3.5%	2848	77	−8.3%	2706	77
	CO$_2$ tax	682	18	−3.9%	655	18	−11%	610	18	−3.6%	658	18	−8.3%	625	18
	NOx tax	37	1	−4.2%	35	1	−10%	33	1	−3.9%	36	1	−8.2%	34	1
	Engine maint.	168	4	−3.9%	161	4	−11%	150	4	−3.6%	162	4	−8.3%	154	4
	Total	3839	100	−3.9%	3690	100	−11%	3431	100	−3.6%	3703	100	−8.3%	3519	100

[a] Cost variation related to the baseline.
[b] Cost in thousand euros.
[c] Cost percentage for the vessel/scenario.

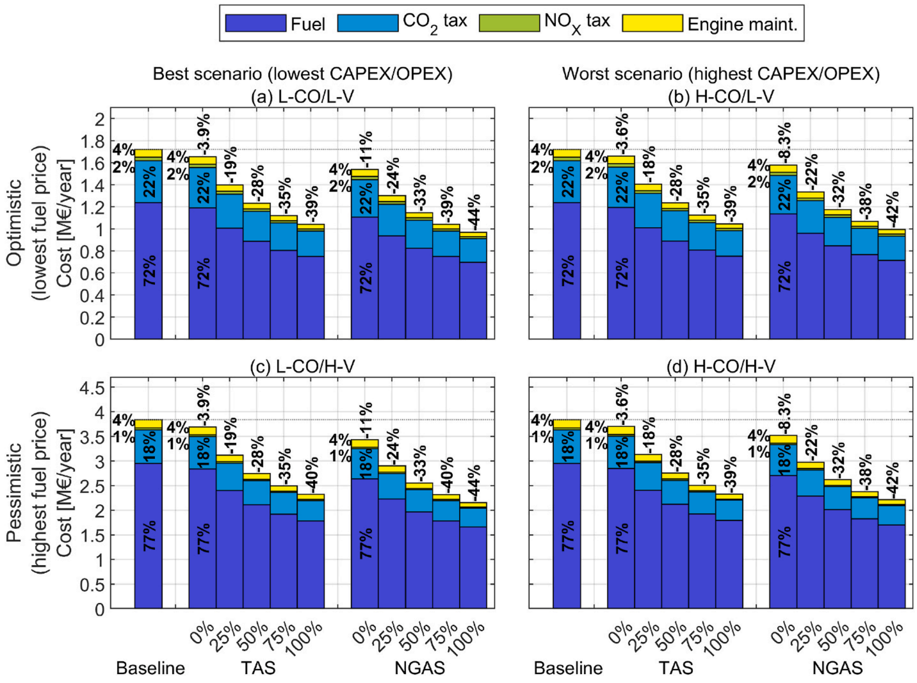

Fig. 12. Annual VOYEX results for the (a) best CAPEX & OPEX and optimistic VOYEX (L-CO/L-V), (b) worst CAPEX & OPEX and optimistic VOYEX (H–CO/L-V), (c) best CAPEX & OPEX and pessimistic VOYEX (L-CO/H–V) and (d) worst CAPEX & OPEX and pessimistic VOYEX (H–CO/H–V). Numbers above bars denote variations against the baseline ship; numbers inside bars correspond to each category cost percentage; and the percentages in the horizontal axis indicate the reduction in the reduction in the non-operating time ($t_{non\text{-}op}$) shown in Table 7.

Table 12
PV study results for the baseline, TAS and NGAS vessels, for the scenarios in Table 4.

				L-CO (best)						H–CO (worst)					
	Categories	Baseline		TAS			NGAS			TAS			NGAS		
		M€[b]	%[c]	↑↓[a]	M€[b]	%[c]	↑↓[a]	M€[b]	%[c]	↑↓[a]	M€[b]	%[c]	↑↓[a]	M€[b]	%[c]
L-V	CAPEX	20.8	32	8.3%	22.6	39	3.0%	21.5	39	17%	24.4	37	14%	23.7	37
	OPEX	26.7	41	−34%	17.6	30	−35%	17.4	31	−12%	23.4	36	−13%	23.2	36
	VOYEX	18.4	28	−3.9%	17.7	31	−11%	16.4	30	−3.6%	17.7	27	−8.3%	16.8	26
	Total	65.9	100	−12%	57.8	100	−16%	55.3	100	−0.5%	65.6	100	−3.3%	63.7	100
H–V	CAPEX	20.8	24	8.3%	22.6	28	3.0%	21.5	28	17%	24.4	28	14%	23.7	28
	OPEX	26.7	30	−34%	17.6	22	−35%	17.4	23	−12%	23.4	27	−13%	23.2	28
	VOYEX	41.0	46	−3.9%	39.4	50	−11%	36.6	49	−3.6%	39.5	45	−8.3%	37.6	44
	Total	88.5	100	−10%	79.5	100	−15%	75.5	100	−1.3%	87.4	100	−4.6%	84.5	100

[a] Cost variation related to the baseline ship.
[b] Cost in million euros.
[c] Cost ratio in percentage for the vessel/scenario.

A lower VOYEX due to lower sailing speeds indicates that modifications in the supplies logistics (as changes in the cargo amount and number of supplies) have less impact in the operation cost. This can be used to increase the supply chain robustness, as higher ship speed can be employed to accommodate a seasonal increase in the cargo delivery demand or to address a fleet emergency (e.g., longer maintenance periods).

6.5. *Present value*

The results from the PV study for four cases, considering the combinations of the best (lower) and worst (higher) scenarios for the CAPEX and OPEX as well as the pessimistic (higher) and optimistic (lower) scenarios for VOYEX, are presented in Table 12. Fig. 13 shows these results in a graphical format. For each scenario and ship type in Fig. 13, the horizontal axis indicates the four cases of sailing speed reduction shown in Table 7, represented by the percentage of the reduction in the non-operating time ($t_{non\text{-}op}$).

The TAS can reduce the PV between 0.5% (H–CO/L-V) and 10% (L-CO/H–V) compared to the baseline, whereas the NGAS can achieve a PV reduction between 3.3% (H–CO/L-V) and 15% (L-CO/H–V). The lower PV for the TAS and NGAS compared to the baseline represent a positive economic margin, demonstrating their economic feasibility.

According to the results presented in Fig. 13, the TAS and NGAS PVs are further reduced by reducing the vessel non-operational time ($t_{non\text{-}op}$), which increases the navigation time (reducing the sailing speed) (Sec. 4.4). Considering the conservative case, 50% of reduction in $t_{non\text{-}op}$ (case II in Table 7), the TAS can achieve a reduction between 7.4% (H–CO/L-V) and 22% (L-CO/H–V) in comparison to the baseline PV, and the NGAS a reduction between 10% (H–CO/L-V) and 25% (L-CO/H–V).

7. Discussion

The environmental and economic analyses showed that for all scenarios the investigated MASSs exhibit a higher operational margin (Fig. 13) with a lower carbon and NOx emissions (Fig. 9) compared to the baseline ship. Fig. 14 shows the relation between the PV and CO_2 emissions, for the uncertainty scenarios presented in Table 4 and the waiting time reduction cases (Table 7), represented by the percentage of $t_{non\text{-}op}$.

The regions shown in Fig. 14 represent the boundaries of the PV and CO_2 emissions for the TAS and NGAS, considering the data and modelling uncertainty included in the investigated scenarios. These regions indicate that the MASS adoption can reduce the lifetime costs and the emissions for all scenarios, demonstrating a positive economic margin aligned to a lower environmental impact. However, the large uncertainty (size of the regions) undermines the results accuracy, indicating a need to improve the available data confidence. This uncertainty is mostly attributed to the fuel prices (difference between L-V and H–V), however the OPEX and CAPEX also significantly contribute to it.

The economic robustness is analysed comparing the percentages of each expenditure for all scenarios and vessels, which are presented in Table 12. The L-V (optimistic VOYEX) scenarios are more balanced compared to the H–V (pessimistic VOYEX) ones. For the L-V scenarios, the PV major contributor is the OPEX (about 40%) for the baseline ship, and the CAPEX (about 40%) for the TAS and NGAS. For the H–V scenarios, the VOYEX is the main PV contributor (45–50%) for all ships. This indicates that the economics of operation in H–V scenarios are more sensitive to fluctuations in fuel prices compared to the L-V scenarios.

A similar economic robustness analysis was applied to the difference of the baseline and MASS costs, to investigate the impact of the prices variation on the transition from conventional to autonomous shipping. Table 13 summarises the absolute and relative values for the differences between the PV (economic margin) of each type of expenditure presented in Table 12 compared to the baseline. Table 13 cells are coloured to show the OPEX to VOYEX ratio (green: less than 2; yellow: 2–3; red: greater than 3). Lower ratios indicate that the economic margin has a balanced composition between expenditures and is more robust due to individual price fluctuations. On the contrary, higher ratios indicate significant dependency of the economic margin on one expenditure and, consequently, the economic margin can be significantly affected by fluctuations in the contributors' prices/costs of this expenditure.

This analysis indicates that without operational modes alteration (case Ref. in Table 7), the TAS and NGAS feasibility greatly depends on a considerable OPEX reduction; better economic margin is exhibited for the H–V scenarios and the NGAS. In the case with 50% less waiting time (case II in Table 7), the considerable savings in VOYEX balance the composition of the economic margin and, consequently, contribute to

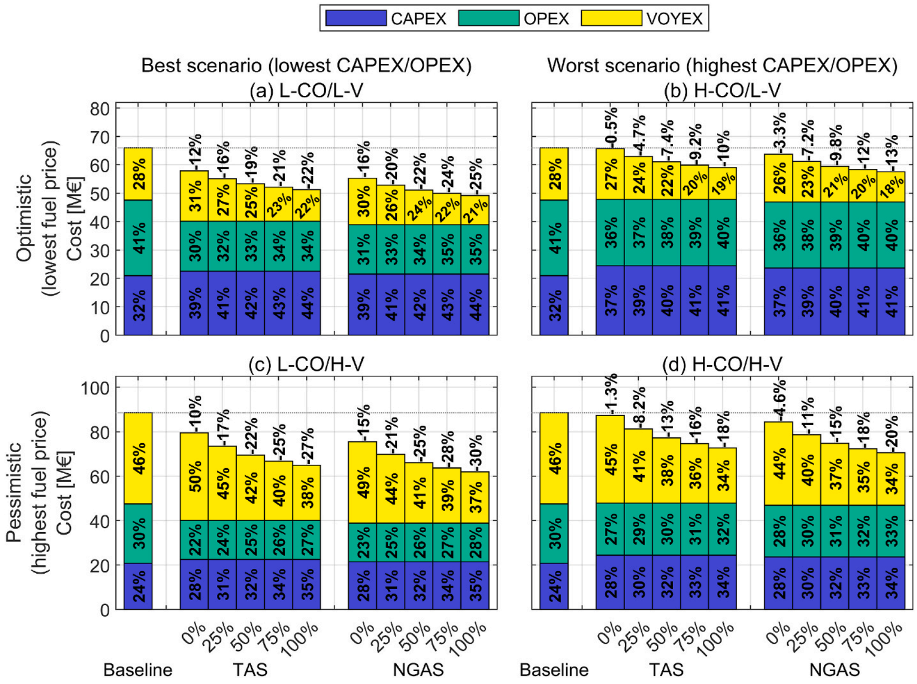

Fig. 13. PV analysis results aggregating CAPEX, OPEX and VOYEX. The percentages shown in the horizontal axes indicate reduction in the non-operating time ($t_{non\text{-}op}$) presented in Table 7; (a) low CAPEX/OPEX & low VOYEX (best scenario with optimistic VOYEX) – L-CO/L-V; (b) high CAPEX/OPEX & low VOYEX (worst scenario with optimistic VOYEX) – H–CO/L-V; (c) low CAPEX/OPEX & high VOYEX (best scenario with pessimistic VOYEX) – L-CO/H–V; (d) high CAPEX/OPEX & high VOYEX (worst scenario with pessimistic VOYEX) – H–CO/H–V. Percentages above bars indicate the total cost reductions compared to the baseline ship.

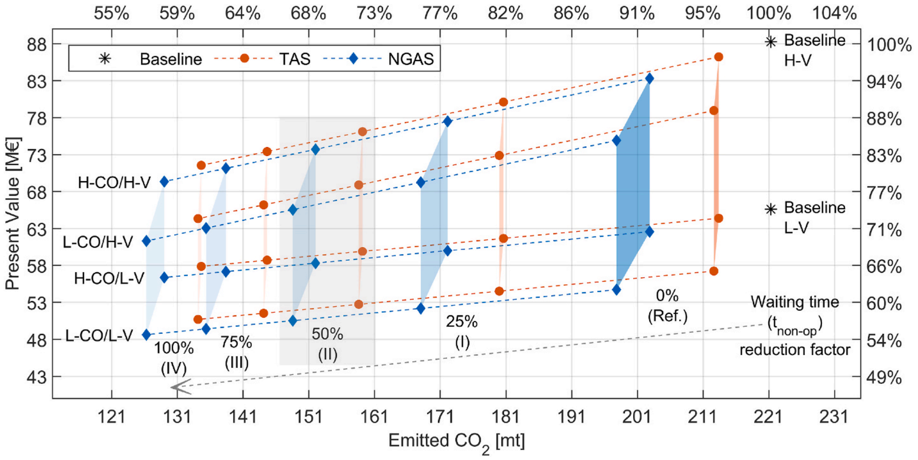

Fig. 14. Present Value versus emitted CO_2 emissions for all scenarios and reduced factors, highlighting the conservative case (II). The scenarios are defined in Table 4 and the waiting time reduction factors are defined in Table 7. The right vertical and top horizontal axes provide the PV and CO_2 emissions differences (in percentage) from the respective values of the baseline ship and H–V scenario.

Table 13
Differences in the PV from the baseline ship for the TAS and NGAS for the scenarios presented in Table 4.

	Scenarios		L-CO (best)				H-CO (worst)			
			TAS		NGAS		TAS		NGAS	
		Costs	M€[a]	%[b]	M€[a]	%[b]	M€[a]	%[b]	M€[a]	%[b]
Without operational modes modification	L-V (optimistic)	CAPEX	1.7	−21	0.6	−6	3.6	−1013	2.8	−130
		OPEX	−9.1	113	−9.3	88	−3.3	926	−3.5	159
		VOYEX	−0.7	9	−1.9	18	−0.7	186	−1.5	70
		Total	−8.1	100	−10.6	100	−0.4	100	−2.2	100
	H-V (pessimistic)	CAPEX	1.7	−19	0.6	−5	3.6	−309	2.8	−69
		OPEX	−9.1	102	−9.3	71	−3.3	283	−3.5	85
		VOYEX	−1.6	18	−4.4	33	−1.5	126	−3.4	84
		Total	−9.0	100	−13.0	100	−1.2	100	−4.1	100
50% less waiting time compared to baseline	L-V (optimistic)	CAPEX	1.7	−13	0.6	−4	3.6	−59	2.8	−37
		OPEX	−9.1	66	−9.3	58	−3.3	54	−3.5	46
		VOYEX	−6.4	46	−7.3	46	−6.4	105	−7.0	92
		Total	−14	100	−15.9	100	−6.1	100	−7.6	100
	H-V (pessimistic)	CAPEX	1.7	−8	0.6	−3	3.6	−26	2.8	−17
		OPEX	−9.1	42	−9.3	37	−3.3	23	−3.5	21
		VOYEX	−14	66	−16.2	65	−14	102	−15.6	96
		Total	−22	100	−24.9	100	−14	100	−16.2	100

[a] Cost difference (in M€) between the TAS or NGAS and the baseline ship (Table 12).
[b] Cost difference percentage (CAPEX, OPEX or VOYEX over Total) for each vessel/scenario.

this scenario economic robustness. However, in the H–CO/H–V scenario, the high savings on VOYEX render the achieved economic margin very dependent on VOYEX, hence, less robust.

The achieved margins can support the higher investment cost (CAPEX) for the autonomous systems, key enabling technologies and other related equipment, which exhibits great uncertainty, in addition to the investment needed to automate the unloading process (not considered in this study). A complementary pathway is the investment on greener technologies to further reduce the emissions considering the IMO targets for 2030 and 2050 (IMO, 2018). The considered herein sailing efficiency increase for the NGAS (Sec. 4.3) and the speed reduction (Sec. 4.4) are not adequate to achieve the emissions targets for 2050 (IMO, 2018), as shown in Fig. 14.

The results revealed PV differences between the TAS and NGAS in the range of 3–5%. This is attributed to very similar OPEX (around 1% difference) and CAPEX (between 3% and 4%), as well as the slight improvement in the sailing efficiency (between 5% and 8%). Hence, the use of autonomous vessels with shipboard crew (in smaller number compared to conventional ships) can be attractive in the transition period, to build confidence in autonomous operations.

This study only considered the weight reduction for the NGAS (Sec. 4.3). However, autonomous ships and fleet design optimisation must be investigated in future studies to identify the optimal parameters in terms of cargo capacity and ships number, targeting the OPEX and VOYEX reduction along with the supply chain resilience enhancement. This study did not consider direct social benefits; these were indirectly considered by using the environmental impact on the VOYEX cost via the CO_2 and NOx emissions taxation. However, it must be noted that the transition of jobs from sea to shore is expected to provide social benefits pertinent to job satisfaction, inclusivity and resilience, as reported in Baumler et al. (2021), de Vos et al. (2021), Suzuki (2021), Kamata (2021) and Rødseth et al. (2023). These outcomes can enhance the attractiveness of autonomous shipping and encourage governments to financially support investments for developing the required autonomous systems, technologies, and infrastructure.

8. Conclusions

This study presented an overarching framework to assess the economic feasibility of autonomous ships considering the transition and next generation phases. This framework (Sec. 2) combines operational information from a baseline ship (Sec. 3) and the autonomous ships outlook (Sec. 4) to estimate the environmental (Sec. 5) and economic (Sec. 6) characteristics for the baseline ship, as well as the transition (TAS) and next generation (NGAS) autonomous ships. The economic analysis considered the best and worst combinations of CAPEX and OPEX, along with pessimistic and optimistic expectations for the VOYEX. The main findings of this study are summarised as follows.

- The TAS and NGAS exhibit lower PV compared to the baseline ship, mainly attributed to the crew cost reduction (OPEX) and fuel savings (VOYEX) at the expense of requiring higher initial investments.
- For the TAS, the ship PV lifetime expenses reduce in the range 1–12% compared, whereas the NGAS can reach savings in the range of 3–16% (both compared to the baseline ship).
- The reduction of the non-operation time ($t_{non\text{-}op}$) can further increase the savings from autonomous operations. The conservative case (50% reduction in the $t_{non\text{-}op}$, case II in Table 7) can additionally reduce 6–7% the PV for the scenarios with lower fuel prices (L-V), and about 11–22% for the scenarios with higher fuel prices (H–V). This finding demonstrates the importance of the logistics on the autonomous ships feasibility.
- The CO_2 emissions can be reduced by about 4% for the TAS and 8–11% for the NGAS; hence the MASS adoption can contribute to sustainable shipping operation.

The estimated savings shows that the MASS can be used to enable the investment on greener technologies and reach the IMO GHG reduction targets (IMO, 2018), without impacting the supply chain economics. The MASS adoption is expected to exhibit greater economic margin for SSS routes with frequent port calls, such as, the ones investigated herein, compared to other shipping types, like ocean-going.

It should be noted that this study relied on several assumptions, due to the lack of information on the costs for autonomous systems, novel equipment, and technologies as well as services, such as, RCC and communications. Future studies must consider data from commercial MASSs operations to verify this study outcomes. However, this study results provide guidance of assessing the feasibility of future MASSs, as several extreme scenarios were investigated. Nonetheless, future studies could investigate the entire fleet, focusing on optimal and sustainable operations and logistics, as well as replacing larger size conventional vessels with smaller size MASSs.

CRediT authorship contribution statement

Joao L.D. Dantas: Conceptualization, Methodology, Software, Validation, Visualization, Resources Writing - Original Draft, Writing. **Gerasimos Theotokatos:** Conceptualization, Methodology, Validation, Supervision, Visualization, Writing – review & editing, Funding acquisition.

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

Data will be made available on request.

Acknowledgments

The study was carried out in the framework of the AUTOSHIP project (AUTOSHIP, 2022), which is funded by the European Union's Horizon 2020 research and innovation programme under agreement No 815012. The authors affiliated with the MSRC greatly acknowledge the funding from DNV AS and RCCL for the MSRC establishment and operation. The opinions expressed herein are those of the authors and should not be construed to reflect the views of EU, DNV AS, RCCL, and the AUTOSHIP partners.

Appendix A. CAPEX breakdown

This appendix presents the CAPEX breakdown shown in Table 9 and Fig. 10, justifying and detailing the values considered in this study.

Hull/structure

The cost for the hull's structure for the baseline vessel was estimated by the method adopted in Kooij et al. (2021), which used the empirical formulation from Martínez-López (2013) to calculate the SSS vessel cost as function of gross tonnage (GT), and subsequently correcting it for 2024 using the Producer Price Indices (PPI) (OECD, 2022a). The latter resulted in 262% increase of the ship structure cost compared to 2005. The TAS was considered to have the same cost as the baseline, no significant changes were assumed for its structure. For the NGAS, a proportional reduction to the lightship weight decrease (Sec. 4.3.1) was considered, leading to this cost reduction by about 15% and 10% (for the considered best and worst scenarios, respectively).

Engines

The costs for the engines and auxiliary equipment purchase, installation, and certification were calculated by using their installed power and used fuel type. This study assumed the following cost factors of 2,302 €/kW for the ship ME (operating with NG), and 873 €/kW for the AE and EE (operating with MDO). These values were calculated by using 1,300 €/kW for the ME (Iannaccone et al., 2020; Faber et al., 2017) and 493 €/kW for the AE and EE (Trivyza et al., 2018), and considering 77% increase to correct these values for 2024 using the PPI (OECD, 2022a).

The autonomous vessels will require equipment with higher reliability and robustness than the baseline, enduring a voyage of up to 4 days without manual checks, and ready-to-use PHM technologies. This study assumed additional costs between 5% and 10% for this equipment, which is similar to the values adopted in Kretschmann et al. (2017) and Jovanović et al. (2022a).

Dynamic Positioning System

The baseline's Dynamic Positioning (DP) System uses a sophisticated Class 2 control system, and is employed to approach the farms in slow speed and maintain the vessels position and orientation during the unloading procedure. It uses a bridge operator station to control the bow and stern tunnel-thrusters speed, the speed and pitch angle of the ship controllable-pitch propeller, and the power management. Its cost was assumed to be 15% of the vessel's CAPEX. For the autonomous vessels, the additional investment is considered between 5% and 10%, similarly to the engines cost.

Electronics and autonomous systems

This cost refers to hardware and software needed for the vessels' safe navigation. The baseline vessel uses the standard equipment required by current legislation, such as Radar, AIS, supervisory system, communications, position system (GPS) and others. This study considers that this cost corresponds to 3% of the ship CAPEX.

The autonomous vessels require key enabling technologies (Heffner and Rødseth, 2019; ABS, 2022) to achieve secure and safe operation, such as situational awareness, collision avoidance, autonomous navigation (manoeuvre/berthing), connectivity and cybersecurity, intelligent machinery, power management system, and shipboard robotics systems. The investment for these technologies is estimated to be between 7.5% and 12.5% of the baseline vesesl's CAPEX; this corresponds to ±2.5% from the value assumed in Kretschmann et al. (2017).

Cargo/payload

The baseline ship consists of several cargo holds and uses a system to unload the fish feed to the farm through a specialised crane. This study adopted the same cost used for the cargo vessel in the MUNIN project (Shetelig, 2013), i.e., 15% of the baseline vessel's CAPEX. The baseline vessel uses a supervisory system to manage the cargo and its conditioning but needs the crew to operate the crane. An additional investment between 10% and 20% was estimated to integrate this system into the autonomous vessels system and transfer the operation to the RCC.

Appendix B. OPEX breakdown

This appendix presents the OPEX breakdown shown in Table 10 and Fig. 11, justifying and detailing the values considered herein.

Crew salary and tax

The baseline vessel uses a crew of seven seafarers, consisting of a captain, officers, engineers, and ratings (listed in Table 1). The seafarers' salaries presented in Kooij et al. (2021) were adopted in this study, using the Consumer Price Index (CPI) (OECD, 2022b) to correct the wages to the Norway market. Similarly to Ghaderi (2019), this study considered the additional costs for: crew annual leave compensation (12%); crew rotation (8.3%), and; the employer payroll contributions (14.1%) for social security. The annual cost of the baseline ship-related to crew salaries was estimated to €1,036k.

Additionally, the costs to maintain the crew during the sailing, such as subsistence, personal protective equipment (PPE), transport (when needed), and medical expenses were considered. For the baseline ship, this cost was estimated at €75 per day and person for every weekday, resulting in an annual cost of €191.6k.

RCC service cost

Kretschmann et al. (2015) argues that the shipping companies can build their own RCC (building and personnel), use the RCC service (contracting), or rent the infrastructure and use their own RCC operators. This study considered that the RCC service for the TAS and NGAS; hence, the RCC costs is part of the OPEX.

The best scenario (L-CO) assumed an RCC service annual cost of €195k, considering an increase of 38% from figures reported in Kretschmann et al. (2015, 2017) to correct to 2024 by using the CPI (OECD, 2022b). The worst scenario (H–CO) assumed €290k for the RCC service, based in the higher estimation proposed by Kooij et al. (2021) increased by 24% to correct for 2024. The difference in these values is due to the assumptions in the RCC model. Kretschmann et al. (2015, 2017) assumed the RCC service for 90 ships instead of 30 ships considered by Kooij et al. (2021); however both studies assumed the same ships number per operator.

The future cost of the RCC service remains uncertain. Ghaderi (2019) argues that at the beginning of technology adoption, personnel costs can be 20% higher to attract a more skilled workforce. However, with the RCCs widespread, the more attractive working conditions and the staff training can reduce this cost by 20%. Additionally, assessing actual conditions can lead to different ships-per-operator arrangement, affecting this cost (van den Broek and van der Waa, 2022).

Software update, data analytics, and communications

As the continuous connectivity render autonomous ships potential targets from different attack groups (Bolbot et al., 2020), with minor and major economic impact (Weaver et al., 2022), an annual investment is anticipated to address cybersecurity for the vessel and the RCC, as well as to update the hardware and software. Additionally, it is assumed that data analytics is required to maintain/store the amount of data generated for the navigation and health monitoring systems (Coraddu et al., 2019; Yuan et al., 2021; Nielsen et al., 2022). For the TAS and NGAS, these costs were assumed between €40k and €80k for the best (L-CO) and worst (H–CO) scenarios, respectively.

Robust and reliable communications between the ship and RCC are needed for autonomous operations (MUNIN, 2015; Munim, 2019; Heffner and Rødseth, 2019; Negenborn et al., 2023), with more demanding requirements for data transfer and connectivity links bandwidth compared to conventional ships. This is expected to considerably increase the communications cost (Santos and Guedes Soares, 2018). However, new technologies (Koo et al., 2023) and novel methods for data management (Jurdana et al., 2021) can reduce this cost.

This study assumed an annual communication cost of €26 k for the baseline ship €18 k for operation, and €8k is for the crew) (Santos and Guedes

Soares, 2018). For the TAS and NGAS, the worst scenario considers an additional cost of €108k (six times the operation cost), whereas the best scenario considers an additional cost of €54k (three times the operation cost); the latter is justified by cost reductions from new communication technologies.

Regular maintenance, mooring, and bunkering

Regular maintenance involves activities to check, lubricate and clean ship machinery, deck cleaning and other minor tasks. It is typically carried out by the crew during sailing or berthed at ports. For the baseline vessel, a cost of €50k was assumed for consumables (oil, cleaning materials and others), as the crew cost was considered in Sec. B.1.

It was assumed that these tasks will be performed for the TAS and NGAS during their staying at the FFF, which has a typical frequency twice per week (each lasting around 12 h). It is also assumed that thee shore teams are required, whereas each team composition and tasks were derived employing the considerations reported in Fan et al. (2022) and presented in Table 14.

Table 14
Shore teams for mooring, loading, maintenance and bunkering for TAS and NGAS

Team	Tasks	Team	Frequency (times per week)
Mooring and loading	Mooring Loading cargo Communications with FFF	Chief officer Able seaman Ordinary seaman	2
Maintenance and cleaning	Machinery check Cleaning/wiping Oiling	Chief engineer* Second engineer* Bosun (1st oiler) Ordinary seaman	2
Bunkering	Engine and piping checks Bunkering Systems monitoring	Chief engineer* Second engineer* Able seaman (1st oiler) Ordinary seaman	1

*Staff are shared between both teams.

Using the salaries and tax rates reported in Sec. B.1, and considering that these teams will support the whole fleet (TAS or NG AS), whereas the consumables cost is same to the baseline ship, an annual cost of about €350k is estimated for the worst scenario (H–CO). The best scenario (L-CO) considered a 20% reduction of this cost (€300k).

The mooring team can be reduced by employing automated mooring devices, such as, MoorMaster (Cavotech, 2022), AutoMoor (Trelleborg, 2022) or Docklock (Mampaey, 2022). However, as these systems viability requires a high use (Díaz et al., 2016).

Periodic maintenance

The periodic maintenance refers to a long-term and complex maintenance carried out at dry-docking. This cost can be broken down into hull/structure and engines/machines. The periodic maintenance cost only considers the hull maintenance, as the engines maintenance cost depends on their annual usage was added to VOYEX (Sec. C.3).

For the baseline vessel, it is assumed that the drydocking is the most significant periodic cost. This maintenance is typically performed annually lasting two weeks, and costs €200k (considering manning, infrastructure, material, and others). This is equivalent to 10% of the baseline vessel's OPEX.

Davies et al. (2021) and Oliveira et al. (2022) argue that the hull maintenance management by PHM methods can optimise maintenance planning, increasing the ship availability and reduce this cost. However, as it is challenging to quantify this reduction, the TAS and NGAS periodic maintenance cost was considered the same as the baseline ship.

Repairs

Repair expenses refer to minor unexpected or emergency maintenance carried out while sailing or waiting in port. This cost pertains to minor incidents in the ship's machinery, such as equipment failure or misuse, with a value that depends on the equipment usage, crew training, preventive maintenance and others. It is estimated at €70k for the baseline ship, corresponding to 5% of the OPEX.

The inclusion of intelligent machinery and PHM in the autonomous system will allow the use of effective predictive maintenance, which is expected to reduce the overall maintenance cost related to repairs (Cullum et al., 2018), and increase the vessel availability (Cheliotis et al., 2020; Shaw and Lin, 2021). As no data was available, this study assumed a reduction between 50% (best scenario – L-CO) and 25% (worst scenario – H–CO) for the TAS and NGAS repairs cost.

Insurance

The insurance covers all operations, equipment and infrastructure used during the shipping operation. As the literature does not provide pertinent data, the insurance cost was assumed 2% of the baseline ship CAPEX, as reported in Ros Chaos et al. (2021).

The insurance cost for autonomous ships may be higher or lower. Higher cost pertains to the new technology, at least in the transition mode (conventional to autonomous). Lower cost may reflect the fact that most insurance costs are associated with crew injuries (Dybvik et al., 2020). Nonetheless, this cost variation is assumed ±0.5% for the best and worst scenarios, resulting in an OPEX of 1.5% and 2.5% of the CAPEX, respectively.

General costs

This OPEX includes the expenses associated to the ship administration and management (order requests, logistics, payments), and other minor costs. This study assumes this cost being equal to 15% of the baseline ship OPEX, which was estimated considering the average of the values reported in the literature (13% in Kretschmann et al. (2017); 12% in Ros Chaos et al. (2021); 17% in Kooij et al. (2021)). The same cost is also expected for the autonomous vessels.

Appendix C. VOYEX breakdown

This appendix presents the breakdown of the VOYEX shown in Table 11 and Fig. 12.

Fuel price

The fuel price upsurged in 2022 due to the reduction in the supply of raw material, motivated by the other externalities, rendering accurate fuel prices forecasts challenging. This study considered an optimistic (L-V) considering a recovery in the fuel market, and a pessimistic (H–V), where the fuel prices were assumed in the 2022 levels (disregarding peaks). The pessimistic scenario (H–V) considered: 2404 €/mt for LNG, and 1036 €/mt for MGO. The optimistic scenario (L-V) employed: 957.5 €/mt for LNG, and 580.7 €/mt for MGO. These prices were obtained from Ship & Bunker (2022) for the Rotterdam port.

Emissions (CO_2 and NOx) taxation

Governments use emission taxation to encourage a shift to less-polluting fuels and greener technologies to curtail the emissions generated in several industrial sectors. As this taxation is progressive, this study uses the estimates for 2030. The VOYEX in this study only accounts for the CO_2 and NOx emissions taxation, which is already enforced in Norway.

For estimating the low and high levels for the CO_2 emissions taxation, the recommendation of Sartori et al. (2014) and the proposed taxation reported in NMCE (2021) were employed whilst considering an annual increase rate of 5% (corresponding to the optimistic and pessimistic scenarios, respectively). The NOx emissions tax was estimated as in The Norwegian Tax Administration (2022) with the average annual increase of 2% and 5.9% (for the optimistic and pessimistic scenarios, respectively). Table 15 summarises the employed values for the considered scenarios.

Table 15
CO_2 and NO_X emissions tax considered for the optimistic and pessimistic scenarios

Emission	Optimistic scenario (L-V)			Pessimistic scenario (H–V)		
	Tax cost	Annual increase	Reference	Tax cost	Annual increase	Reference
CO_2	106 €/mt	5%	Sartori et al. (2014)	190 €/mt	5.0%	NMCE (2021)
NOx	2,640 €/mt	2%	The Norwegian Tax Administration (2022)	3,080 €/mt	5.9%	estimated

Engine maintenance

The specific maintenance cost for marine engines is estimated as function of the annual vessel energy consumption and the cost factors, which depend on the engine type. The cost factors employed herein are presented in Table 16, correcting their values for 2024 using the Producer Price Indices (PPI) from Norway for 2022 and the forecast for 2024 (OECD, 2022a). The same cost factors are used for all the investigated vessel configurations, as the cost reduction due to the autonomous operations are related to the reduced energy consumption.

Table 16
Maintenance cost for the investigated vessels

Engine	Fuel	Optimistic scenario (L-V)		Pessimistic scenario (H–V)	
		Cost [€/kWh][1]	Reference	Cost [€/kWh][1]	Reference
ME	LNG	0.008	Trivyza et al. (2018)	0.020	Faber et al. (2017) Danish Maritime Authority (2012)
AE & EE	MGO	0.025	Kooij et al. (2021) Hekkenberg (2013)	0.034	Trivyza et al. (2018) Pelet et al. (2005)

[1] The Producer Price Indices (PPI) from Norway (OECD, 2022a) were used to correct these costs for 2022 and to forecast for 2024.

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