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# Techno-Economic and Regulatory Assessment of Onboard Carbon Capture Systems in LNG Carriers Toward the 2050 Decarbonization Horizon

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**Abstract**

Carbon capture and storage technologies are widely adopted, primarily in conventional power plants. Maritime transport must align with the 2050 targets and sharply reduce its environmental footprint. Onboard Carbon Capture and Storage (OCCS) appear to be an immediately feasible solution until alternative fuels are adopted and fully implemented. This study presents a regulatory compliance assessment and a techno-economic analysis of the implementation of OCCS. An LNG tanker was selected as a case study due to the inherent compatibility between LNG storage systems and $CO_2$ storage on board. The examined regulation includes the calculation of the corresponding penalties arising from the enforcement of the EU ETS, FuelEU Maritime, and the IMO NZF framework. The cost of installing the OCCS is also considered when evaluating the proposal's sustainability. The results demonstrate that OCCS shows real promise in the fight against maritime transport emissions, but at present, it is not economically viable. Its viability depends mainly on clear regulatory guidelines and effective incentives that encourage its adoption, while offsetting investment and operating costs. Finally, the current study also seeks to resolve an ambiguity in the existing legislation that renders the OCCS a viable option.

**Keywords:** onboard carbon capture and storage (OCCS); LNG carrier; techno-economic analysis; EU ETS; FuelEU Maritime; IMO NZF framework; greenhouse gas intensity; shipping decarbonization

## 1. Introduction

The maritime industry is on the verge of significant changes that will transform the sector in the coming years. Driven by an increasingly pressing regulatory environment aimed at reducing greenhouse gas (GHG) emissions, the transition to a net-zero emissions framework is underway. The revised IMO GHG Strategy adopted in July 2023 (Resolution MEPC.377(80)) introduced a target whereby zero- and near-zero-emission fuels, energy sources, and technologies should contribute at least 5–10% of the total energy demand of international shipping by 2030. The strategy sets an objective of achieving net-zero GHG emissions from international shipping by or around 2050. In addition, it recalls the 2018 Strategy and may be replaced in the future by an updated IMO GHG Strategy in 2028 [1,2]. Key mechanisms, including the EU Emissions Trading System (EU ETS), FuelEU Maritime, and the IMO's Net-Zero Framework (NZF), have emerged as policy instruments.

Among the various alternatives and solutions, Onboard Carbon Capture and Storage (OCCS) appears to be a vital option for reducing emissions and promoting the development

Check for updates

Academic Editor: Alberto Pettinau

Received: 21 February 2026
Revised: 18 March 2026
Accepted: 23 March 2026
Published: 25 March 2026

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of a green supply chain within the shipping industry. It is expected that fossil-based fuel vessels will remain in use until the net-zero target is achieved in 2050 [3]. OCCS seems to be one of the most promising short-term solutions for reducing emissions from the existing fleet of ships that run on conventional marine fuels. Although studies indicate that the technology can be safely applied to ships, it still requires further development and optimization before it can be used and integrated into shipping. Furthermore, wider application also depends on its commercial competitiveness compared to other decarbonization options. In general, OCCS might be a commercially attractive solution in cases of high capture rates, low fuel costs, and low $CO_2$ storage costs [4]. Even though carbon capture technology is advanced, there are still significant risks that need to be dealt with before a large-scale commercial application on board a vessel. The main risks include additional energy demand onboard, potential cargo loss, delays in developing a regulatory framework or market for acquiring credits for $CO_2$ reduction, and a lag in onshore infrastructure development [3].

Although the integration of an OCCS system alters the ship's energy balance, its impact should be assessed in terms of overall carbon efficiency per unit of transport work, not just fuel consumption. Despite the fact that the process of capturing and managing $CO_2$ entails additional energy demand, the substantial reduction in net emissions leads to an improvement in carbon intensity indicators, shifting the focus from fuel efficiency to carbon efficiency. The possibility of thermodynamic integration with heat recovery and boil-off gas management systems in LNG carriers allows for partial compensation of the energy load, thereby enhancing the ship's overall exergy utilization. Under this approach, OCCS is not simply an additional emission control technology, but a mechanism for reorganizing energy and environmental performance, where optimization is defined in terms of net $CO_2$ emissions per transport service and not exclusively in terms of specific fuel consumption.

Despite the obvious environmental benefits, the sustainability of implementing OCCS solutions on ships, taking into account the quantification of all current legislation in economic terms, has not been adequately evaluated in existing literature. The aim of this research study is to conduct a comparative techno-economic and regulatory compliance assessment of an LNG carrier operating with and without OCCS. A technical analysis is carried out for both cases, based on calculations of fuel consumption and emissions. The existing legislation for the EU ETS, FuelEU Maritime, and the IMO NZF framework has been reviewed, and the corresponding penalties for each case are calculated in accordance with the respective consumption and emission profiles. In order to assess the economic viability of the OCCS investment, key financial indicators are calculated, including the discounted payback period, Net Present Value (NPV) and Internal Rate of Return (IRR).

The rest of this paper is organized as follows: Section 2 outlines the current legislation at the international and European levels. Section 3 provides a brief description of the onboard carbon capture system and summarizes relevant case studies from the literature. The examined case study and the methodological approach are presented in Section 4. The results of the economic evaluation are set out in Section 5, with the conclusions coming in Section 6.

## 2. Regulations Background

Since 2018, the International Maritime Organization (IMO) has been contributing to the global effort to address climate change by adopting strategies to reduce GHG emissions from ships. The latest, 2023 IMO GHG Strategy, includes the use of zero- or near-zero GHG-emission technologies, fuels, and energy sources for at least 5–10% of the energy consumed by international shipping by 2030. GHG emissions from international shipping should become net 0 by or around 2050. By 2030, the international shipping sector must set

an average reduction in carbon intensity by at least 40%. These targets were operationalized by introducing short-term measures, effective from January 2023, including the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII) rating system. All ships that are subject to the IMO's Data Collection System (DCS) must develop and maintain a detailed energy efficiency plan that is tailored to their CII performance. In general, the 2023 Strategy outlines the timeline for adopting the package of measures and the updated IMO GHG Strategy for 2028 [5].

As part of its wider decarbonization programme, the IMO has introduced the Net-Zero Framework (NZF), which includes two key regulatory instruments: the Global Fuel Standard (GFS) and the Global Economic Measure (GEM). The GFS requires ships to progressively reduce their annual GFI, defined as the amount of greenhouse gas emissions generated per unit of energy consumed, using a well-to-wake accounting approach. Vessels that exceed their allowable GFI thresholds will be required to purchase 'remedial units' to offset their excess emissions. Conversely, ships operating below the Direct Compliance Target will be eligible to generate 'surplus units'. In order to facilitate this credit-based mechanism, the IMO intends to set up the IMO Net-Zero Fund [6].

The MEPC (Marine Environment Protection Committee) is the IMO's main body responsible for dealing with the environmental impact of international shipping, particularly with regard to pollution control and climate change mitigation. At MEPC 83, amendments to MARPOL (MARitime POLlution Convention) Annex VI were agreed to strengthen regulatory flexibility for the implementation of fuel- and technology-based emission reduction strategies. As part of the efforts to reduce carbon intensity, MEPC 83 set annual CII reduction factors for the period 2027–2030. These factors apply to liquefied natural gas (LNG) carriers with a Gross Register Tonnage (GRT) above 5000, and the targets will gradually increase from 13.625% in 2027 to 21.500% in 2030. The overall objective of the NZF package is to facilitate the progressive reduction of GHG emissions from international shipping at the earliest possible time, and this objective aligns with the emission reduction pathways set out in the IMO's 2023 strategy [7].

Furthermore, in 2021, the European Commission (EC) introduced the 'Fit for 55' legislative package, which affects the shipping sector through the EU ETS. According to the EU ETS, shipping companies are required to Monitor, Report, and Verify (MRV) the carbon dioxide ($CO_2$) emissions produced by their vessels during designated voyages [8]. The FuelEU Maritime Regulation operates as a central pillar of the Fit for 55 package. The main objective for vessels exceeding 5000 GT is to control their emissions by setting progressive limits on GHG intensity in ship energy use, effective from 1 January 2025. A penalty (FuelEU Penalty) is calculated based on the amount of non-compliant VLSFO, in grams of $CO_2$ equivalent ($gCO_2eq$) [9].

## 3. Onboard Carbon Capture and Storage (OCCS)

### *3.1. OCCS Technology*

Recently, there has been growing popularity in implementing $CO_2$ capture technologies in fossil fuel power plants and commercial vessels. Carbon capture and storage (CCS) is an integrated system developed to prevent carbon dioxide emissions from the source. CCS forms part of a wider chain of energy processes that involve the capture, transportation, and final storage of $CO_2$. It involves separating $CO_2$ from industrial or combustion processes and storing it permanently in geological deposits or using it for industrial applications. In addition to the capture technologies themselves, the processes relating to the behaviour of the geological formations in which $CO_2$ can be stored also play an important role. In this context, recent studies examine the mechanical behavior of underground formations and the fracturing phenomena associated with $CO_2$ injection processes in energy systems, con-

tributing to an understanding of the parameters that influence the geological management of carbon dioxide. Currently, CCS at onshore facilities has attained remarkable technical maturity after decades of implementation [10,11].

Instead, marine CCS is still in the development phase, moving from theoretical research to validation on a pilot scale. In the shipping sector, the OCCS provides a roadmap for the decarbonization of conventional ships powered by fossil fuels, offering an alternative to switching to fuels such as LNG. Comparative studies show that ships equipped with OCCS can attain lower greenhouse gas emissions and operating costs compared to several low-carbon alternatives [10].

Implementing OCCS systems improves alignment with the United Nations' Sustainable Development Goals (SDGs). SDG 13: "Climate Action" is directly supported through the reduction of greenhouse gas emissions in shipping. Meanwhile, integrating innovative carbon capture technologies strengthens innovation and industrial infrastructure, SDG 9, by promoting the development of new, low-emission systems and processes for commercial ships. Furthermore, efficiently managing captured $CO_2$ and optimizing capture system operations contributes to SDG 12: "Responsible Consumption and Production" by reducing emissions per unit of cargo transported and promoting sustainable shipping practices.

OCCS is not only a way of reducing emissions from individual ships, but also part of a broader effort to reshape the maritime supply chain and transition to a low-carbon, circular economy. The OCCS facility creates new flows of material and energy resources. Captured $CO_2$ becomes a manageable product that must be transported, stored or utilized. This requires the ship to be connected to port infrastructure, land transport networks and industrial applications for utilization or geological storage. In this way, shipping is transformed from a mere emitter to an active part of a carbon value chain. Here, $CO_2$ can be reintroduced into the production process for use in synthetic fuels or industrial applications. This contributes to the transition from linear 'emission-diffusion' models to circular 'capture-utilization-reuse' models. Therefore, the integration of OCCS affects not only the energy efficiency of the ship, but also the interconnections between shipping, industrial ecosystems and port supply structures. This makes it a critical component in the formation of integrated, cross-sectoral decarbonization chains.

There are three primary categories of $CO_2$ capture technologies: post-combustion, pre-combustion, and oxyfuel combustion. The pre-combustion and oxyfuel approaches involve significant modifications to the fuel supply and power generation systems, which makes them less suitable for retrofitting. In contrast, post-combustion capture extracts $CO_2$ directly from the exhaust gases after combustion has occurred. Pre-combustion capture achieves high $CO_2$ capture rates of 92–93%, but efficiency is reduced by the water–gas shift section. Although its capital cost is lower than that of the other systems, the complexity of this system and the required upgrades increase the total cost. With oxyfuel combustion, true $NO_x$ emissions can be decreased by 60–70% compared to other methods; however, a large amount of oxygen is needed for the process, which is costly [12].

A range of post-combustion carbon capture technologies and $CO_2$ storage approaches have been developed and could potentially be adapted for shipboard applications. In general, post-combustion carbon capture is applied to exhaust gas, and the separated $CO_2$ is stored on board, unloaded at ports for final geological storage or utilization. Commercial applications of post-combustion carbon capture include chemical absorption, membrane and cryogenic separations or calcium looping methods [13].

Solvent-based chemical absorption appears to dominate among other OCCS technologies, although it requires high energy consumption for $CO_2$ separation and solvent regeneration. Furthermore, it has a high Technology Readiness Level (TRL) 7–9 [14] and has already been tested in land-based applications. Monoethanolamine (MEA) was selected

as the solvent for this study because of its high reactivity and low cost. These characteristics are key to its widespread use across various flue gas conditions and make it a suitable choice for the present analysis. MEA-based OCCS system can achieve a capture rate of 73% [15]. In addition to chemical absorption-based OCCS, calcium looping has proven to be another viable option with a TRL of 5–7. It is based on the cyclic calcination and carbonation of limestone, which acts as a sorbent. Apart from these two options, membrane and cryogenic separation systems are also promising alternatives, though they are less popular and have TRLs of 3–7 [16]. Recent advances in $CO_2$ capture materials and methods have led to the development of innovative catalysts and functional adsorbents, inspiring future improvements [17].

The OCCS system also includes the $CO_2$ liquefaction process, in which captured $CO_2$ is compressed, dehydrated, cooled, and transferred to a storage tank. One of the reasons an LNG carrier was selected as the case study is the inherent compatibility between LNG storage systems and onboard $CO_2$ storage. LNG carriers are already equipped with large-scale cryogenic containment systems, which can be adapted for the storage of captured $CO_2$. This makes the integration of an OCCS particularly attractive, as it minimizes additional space requirements and avoids many of the layout constraints that other vessel types would face [18].

In addition to these advantages, the integration of an OCCS on an LNG carrier is further supported by the significant loss of cargo capacity observed when such systems are retrofitted on bulk carriers. This aligns with Maersk's observation that the most favourable business case for onboard carbon capture is found in large tankers, particularly those fueled by LNG, due to their lower baseline $CO_2$ emissions, reduced additional energy demand and ample space for system integration. In contrast, the practicality of such retrofits is hindered by the considerable spatial and capacity limitations of conventional cargo vessels, especially smaller ones [3].

### *3.2. Literature Overview*

A targeted literature review was carried out to examine the existing research on scientific developments in the field of OCCS. The search focused on techno-economic assessments, environmental evaluations, and feasibility studies related to the integration of OCCS in commercial vessels. Particular attention was paid to the case studies examined for different ship types. As the availability of publications was limited, the most relevant ones were selected for further analysis and were organized into two subcategories:

#### 3.2.1. Applications in Different Ship Types

A group of researchers is focusing on applying OCCS to different types of real ships and evaluating the operational, economic and environmental constraints.

Feenstra et al. [19] performed a technical and economic assessment of ship-based carbon capture (SBCC) on both diesel and LNG vessels. Two ships were selected as case studies: an inland ship with a 1280 kW engine and a general cargo vessel with a 3000 kW engine and an 8000-deadweight tonnage. Calculated $CO_2$ capture costs varied from €98 to €389 per tonne of $CO_2$, depending on engine size, fuel type, chosen capture rate and selected solvent.

Visonà et al. [20] examined the feasibility and economic implications of implementing a solvent-based carbon capture system on an ultra-large container ship equipped with two dual-fuel engines that operate using either heavy fuel oil (HFO) or LNG. The paper examines multiple configurations for supplying the heat and electricity required for carbon capture, and the authors examined an innovative configuration based on an electric heat pump. They observed that the increase in fuel consumption due to OCCS varies depending

on the type of fuel and the design of the process and the estimated carbon abatement cost ranges between EUR 64 and EUR 149 per ton of $CO_2$ captured.

Tavakoli et al. [14] assessed the technical feasibility of OCCS for both a newbuild and a retrofit bulk carrier. Results indicated that a 70–90% $CO_2$ reduction can be achieved. However, the limited onboard space remains a key factor, as does the higher energy consumption of the newbuild compared with the existing vessel, which poses a significant operational challenge.

Zanobetti et al. [13] studied OCCS as a practical short-term solution for a fossil-fuel-powered cruise ship. Considering onboard energy requirements, chemical absorption by amine scrubbing and advanced cryogenic carbon capture appeared to be the only feasible solutions. They also extended their evaluation to other zero-carbon alternatives and concluded that all of these options were more sustainable and environmentally friendly than the baseline fossil-fuel-based engine.

Wohlthan et al. [21] explored ways to improve the thermal integration of a post-combustion carbon capture system based on MEA by conducting research on a 10000 twenty-foot equivalent unit (TEU) container ship. Their options included installing a bypass for the main turbine engine, reducing the steam working pressure and implementing a waste heat recovery system from the auxiliary engines. The results showed that it was feasible to reduce additional fuel consumption from 55% to 23% and raise the avoided carbon dioxide rate from 76% to 81%.

Malukas and Lebedevas [22] investigated the integration of cryogenic carbon capture in Floating Storage and Regasification Units (FSRUs). They conducted a technical analysis to evaluate energy efficiency and optimize system performance. The study concludes with the potential for a 22% reduction in fuel consumption and a 100% $CO_2$ capture rate.

#### 3.2.2. Evaluation Within Regulatory Frameworks

The literature incorporating regulatory frameworks is found to be extremely limited and without application in ship case studies.

Oh et al. [23] calculated the well-to-wake (WtW) GHG intensity under the FuelEU Maritime framework. Nine scenarios for ship propulsion based on combinations of fossil fuels (HFO, MGO and LNG) and marine engines were assessed. Notably, the OCCS reduces the WtW GHG intensity by 54–68%, depending on the scenario, and oil-fuelled ships were found to be less GHG-intensive and more cost-effective than ships powered by LNG.

Jeong et al. [15] explored ways to enhance the efficiency of OCCS systems, given the high energy requirements for solvent regeneration. By integrating heat recovery from $CO_2$ liquefaction compression and employing a hybrid solvent system using amino methyl propanol–piperazine (AMP-PZ) alongside a heat pump, the proposed model significantly lowers additional heat demand by 45.2% in diesel mode and 73.7% in LNG mode compared to traditional MEA setups. Despite these improvements, long-term compliance with future greenhouse gas targets beyond 2045 will not be achieved, and further measures are required.

Although interest in OCCS is growing rapidly, the available literature remains limited and relatively recent, with most studies published after 2019. The main focus is on techno-economic and energy assessments of specific ship types, including container, cargo, and cruise ships. It is observed that there is a lack of comprehensive studies on the implementation of all applicable legislation and its economic and environmental assessment, which this study attempts to address by applying it to an LNG carrier.

## 4. Materials and Methods

### 4.1. Case Study

The implementation of OCCS is considered for a 174,000 $m^3$ LNG carrier that operates continuously for 358 days per year, over a period of 26 years until 2050. Technical analysis is carried out for both cases, resulting in the calculation of fuel consumption and emissions for Case 1 (without OCCS) and Case 2 (with OCCS).

#### 4.1.1. Operating Profile

The vessel operates for 358 days of the year, with the remaining 2% allocated for off-hire, typically for repairs and dry docking. Its operational profile is a round trip between Freeport, Texas, and Rotterdam, the Netherlands (a distance of 5044 nautical miles) at an average speed of 15 knots. The vessel is equipped with a typical configuration of main engines and generators, found on comparable vessels: two HYUNDAI-MAN B&W 5G70ME-C9.5-GI (11,756 kW), two Wärtsilä 6L34DFC-ER2&ER3 G6_XAAB721239 S (2877 kW), and two Wärtsilä 8L34DFC-ER2&ER3 G6_XAAB721239 S (3836 kW). Data regarding engine power, Specific Fuel Gas Consumption (SFGC), Specific Fuel Oil Consumption (SFOC) and Specific Pilot Oil Consumption (SPOC) under all operating conditions were obtained from the company's records for the specific vessel and from the manufacturer. Table 1 shows the vessel's annual operating profile based on real operational data obtained from the vessel's voyages during the last year.

**Table 1.** Annual operating profile of the LNG carrier.

| Annual Operating Profile | At Sea (2 ME [1] & 2 GE [2] 6L) | Maneuvering (2 ME & 2 GE 6L & 1 GE 8L) | At Berth (2 GE 6L & 1 GE 8L) |
|---|---|---|---|
| Operating time | 93% | 2% | 5% |
| Operating days | 333 | 7 | 18 |
| Operating hours | 7984 | 172 | 429 |
| **Fuel Consumptions (t/year)** | | | |
| Natural gas (NG) | 16,387 | 180 | 572 |
| Low-Sulphur Marine Gas Oil (LSMGO) | 0 | 129 | 0 |
| Pilot LSMGO | 900 | 2.7 | 7.3 |
| Total Consumption | | 18,178 | |

[1] ME—Main Engine; [2] GE—Generator.

#### 4.1.2. Emissions Calculations

For the 1st Case (without OCCS), the $CO_2$ emissions are calculated by multiplying the emissions factors of each fuel by the corresponding consumption. The result is $CO_2$ emissions of 50,465 t/year (or 141 t/day). The estimated emissions were verified against those reported by the ship during the last operational year, showing agreement between the calculated and actual data.

In the 2nd Case (with OCCS), the additional consumption required for the OCCS to operate must be included. In this case, it is assumed that the vessel will be equipped with Wärtsilä's OCCS. Figure 1 shows the process flow diagram of the system with 5 main stages: pre-conditioning, absorption, desorption (or stripping), liquefaction, and storage [24]. During preconditioning, depending on the fuel used, the exhaust gas is cleaned of NOx, SOx and particulate matter, and cooled down. In the 2nd stage, the exhaust gas is mixed with a liquid solvent. This process captures the $CO_2$ in the solvent. The cleaned exhaust gas then exits the system. During the stripping stage, the $CO_2$-saturated solvent is heated, releasing the $CO_2$. The lean solvent is then reused in the system. The process of liquefaction

involves compressing, drying and cooling the CO2 to a liquid state, where it is then stored. The final stage is storage. Liquid $CO_2$ is pumped through pipes to an onboard tank, where it is stored until it can be offloaded.

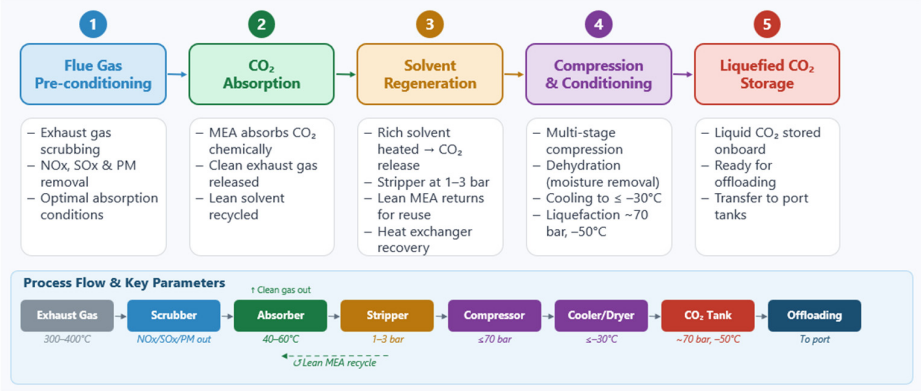



**Figure 1.** Process flow diagram for the examined OCCS.

This is a chemical absorption carbon capture system, which uses a 30% MEA solution as the lean solvent, a technology that has been in development since 2019. In January 2025, Wärtsilä introduced the first ship to be outfitted with a full-scale CCS system following a turnkey retrofit by the Singaporean shipbuilding group Seatrium. This system is capable of reducing a ship's carbon dioxide ($CO_2$) emissions by up to 70%. The conservative $CO_2$ capture rate of 60% will be used in the analysis, which reflects realistic operational conditions and design choices. The literature [25] indicates that the actual performance of OCCS systems is significantly influenced by energy requirements and varying load conditions rather than the maximum capture efficiency cited by manufacturers. The system can also be integrated into newbuilds using all types of carbon-based fuels, including heavy fuel oil (HFO), methanol, liquefied natural gas (LNG), and marine gas oil (MGO) [26].

The energy required to operate the OCCS unit is categorized as follows:

(a) The electric load, which is provided by the generators requires them to burn more fuel to provide this load; and

(b) The boiler, which produces more steam and heat for absorption, pumping, stripping and solvent treatment by burning fuel oil.

Based on the manufacturer's data, the total electrical load required for OCCS operations is 989 kW. A 5% margin is also incorporated into the total electric load—a common practice among shipowners for improving the accuracy of consumption estimations—and as a result, the total energy needed for operating the OCCS is calculated to be 8,290,844 kWh per year. This increased energy requirement leads to a 16% rise in total fuel consumption: 20,996 t/year in 2nd Case compared to 18,178 t/year in the 1st Case.

The exhaust gas flow rate for the system was defined using the operational profiles of the two selected main engines and four generator engines. A representative exhaust gas flow rate of 150,000 kg/h was adopted (calculated from the manufacturer's load–exhaust gas flow diagram) to cover all possible loads below 75% of the main engine and generators. With a $CO_2$ capture rate of 60%, the total amount of $CO_2$ captured is calculated to be 32,047 t$CO_2$ per year. Correspondingly, the total $CO_2$ emissions in the 2nd Case are calculated at 24,223 t/year (or 68 t/day) from LNG and 1409 t/year from LSMGO.

### *4.2. Methodology Approach*

This research aimed to conduct a comparative techno-economic and regulatory compliance assessment of an LNG carrier operating with and without an OCCS. The analysis evaluates supplementary costs arising from the implementation of the OCCS, including

capital expenditure (CAPEX) and operational expenditure (OPEX). The study includes EU Emissions Trading System (EU ETS) charges, FuelEU compliance costs, and International Maritime Organization (IMO) Market-Based Measures.

#### 4.2.1. Fuel EU

As stated in the FuelEU [27], the GHG intensity of the energy used on a ship is measured using the following formula:

$$\text{GHG intensity}\left[\frac{\text{gCO}_2\text{eq}}{\text{MJ}}\right] = f_{\text{wind}} \times (WtT + TtW) \quad (1)$$

where $f_{\text{wind}}$ is the wind propulsion factor (here, there is no wind assisted propulsion).

According to Annex I $WtT$ is measured from the type:

$$WtT = \frac{\sum_i^{n_fuel} M_i \times CO_{2\,eq_{WtW\,i}} \times LCV_i + \sum_k^c E_k \times CO_{2\,eq\,electricity,k}}{\sum_i^{n_fuel} M_i \times LCV_i \times RWD_i + \sum_k^c E_k} \quad (2)$$

where:

$M_i$ is the Mass of fuel i consumed by fuel consumer unit j [g fuel)];

$CO_{2\,eq_{WtWi}}$ is the WtT GHG emission factor of fuel i [g $CO_2$eq/MJ];

$LCV_i$ is the lower calorific value of fuel i [MJ/g fuel];

$\sum_k^c E_k$ is the sum of electricity delivered to the ship per onshore power supply (OPS) connection point k in [MJ];

$RWD_i$ is the reward factor of 2 that can be applied from 1 January 2025 to 31 December 2033 for the use of Renewable Fuels of Non-Biological Origin (RFNBO).

The other main component used to calculate Well to Wake GHG Intensity, is calculated as follows:

$$TtW = \frac{\sum_i^{n_fuel} \sum_j^{m_engine} M_{i,j} \times \left[\left(1 - \frac{1}{100} C_{\text{slip}\,j}\right) \times (CO_{2\,eq,TtW,i,j}) + \left(\frac{1}{100} C_{\text{slip}\,j} \times CO_{2\,eq\,TtW,slip,i,j}\right)\right]}{\sum_i^{n_fuel} M_i \times LCV_i \times RWD_i + \sum_k^c E_k} \quad (3)$$

where:

$C_{slip\,j}$ is the non-combusted fuel coefficient as a percentage of the mass of the fuel i consumed by fuel unit j. $C_{slip}$ includes fugitive and slipped emissions;

$CO_{2\,eq,TtW,i,j}$ is the TtW $CO_2$ equivalent emissions of combusted fuel i in fuel consumer unit j [g $CO_2$eq/g Fuel];

$CO_{2\,eq\,TtW,slip,i,j}$ is the TtW CO2 equivalent emissions of slipped fuel i towards fuel consumer unit j [g $CO_2$eq/g Fuel].

These factors are required to calculate the $CO_{2\,eq,TtW_{i,j}}$ which is defined in FuelEU Annex I as:

$$CO_{2\,eq,TtW_{i,j}} = \left(C_{fCO_{2,j}} \times GWP_{CO_2} + C_{fCH_{4,j}} \times GWP_{CH_4} + C_{fN_2O_j} \times GWP_{N_2O}\right)_i \quad (4)$$

The TtW $CO_2$ equivalent emission intensity includes $CH_4$ and $N_2O$ emissions from fuels. FuelEU Annex II provides default $CH_4$ and $N_2O$ emission factors (in g $CH_4$/g fuel and g $N_2O$/g fuel, respectively).

The GHG intensity is calculated separately for the two cases. In the 2nd case, the mass consumption due to the OCCS system is also considered. Table 2 shows the values.

**Table 2.** GHG intensity values for both cases.

| | 1st Case | | 2nd Case | |
|---|---|---|---|---|
| **Consumption** | **Actual** [1] | **FuelEU-Compliant** [1] | **Actual** | **FuelEU-Compliant** |
| **ME NG (t/year)** | 11,661 | 5830 | 11,661 | 5830 |
| **ME LSMGO (t/year)** | 954 | 477 | 954 | 477 |
| **GE NG (t/year)** | 5478 | 2739 | 8255 | 4128 |
| **GE LSMGO (t/year)** | 86 | 43 | 127 | 63 |
| **WtT GHG intensity** | 18.295 [$gCO_2eq/MJ$] | | 18.315 [$gCO_2eq/MJ$] | |
| **TtW GHG intensity** | 61.848 [$gCO_2eq/MJ$] | | 63.052 [$gCO_2eq/MJ$] | |
| **$GHG_I$** | 80.1 [$gCO_2eq/MJ$] | | 81.37 [$gCO_2eq/MJ$] | |

[1] To comply with the FuelEU Maritime Regulation, a distinction is made between total fuel consumption (Actual) and consumption used in calculations. For voyages between EU and non-EU ports, 50% of the energy consumed is included [28].

Finally, to determine whether there is a compliance deficit or surplus, the compliance balance must be calculated:

$$\text{Compliance Balance } [gCO_{2eq}] = (GHGIE_{target} - GHGIE_{actual})[\frac{gCO_{2eq}}{MJ}] \times \text{Energy } [MJ] \quad (5)$$

where: Energy = $\sum_i^{n_{fuel}} M_i \times LCV_i$.

The required intensity is defined in relation to the fleet's average well-to-wake fuel GHG intensity of 91.16 $gCO_2eq$ per megajoule (MJ) in 2020. The requirements begin with a 2% reduction in GHG intensity relative to the 2020 average, from 2025 to 2029. This increases to 6% from 2030 to 2034, accelerating from 2035 to reach an 80% reduction by 2050. [29]. In both cases examined, the vessel does not meet the target from 2035 onwards, with its level of non-compliance gradually increasing in line with the upper limits set.

If there is non-compliance, the FuelEU Penalty must be determined. The energy associated with non-compliance, referred to as 'non-compliant energy', should be determined and converted into the equivalent mass of non-compliant Very Low Sulphur Fuel Oil (VLSFO) in metric tonnes (MT). If a ship has a compliance deficit for two or more consecutive reporting periods, this amount will be multiplied by a penalty escalation factor. The type for calculating the FuelEU Penalty is as follows:

$$\text{FuelEU Penalty} = \frac{\text{Compliance Balance } [gCO_2eq] \times 2400 \text{ [EUR/ MT VLSFO]}}{GHGI_{actual} [gCO_2/ MJ] \times 41,000 \text{ [MJ/ MT VLSFO]}} \quad (6)$$

Based on Hecla Emissions Management's new Compliance Market Indicator (CMI), the price per tonne $CO_2eq$ varied from 268 in late 2024/early 2025 to €470 in March 2025 [30]. For the current analysis, a value of USD 300/$tCO_2eq$ was adopted to reflect a conservative (pessimistic) case. In this case study, the FUEL EU penalty will be imposed from 2035 onwards (Figure 1).

#### 4.2.2. EU ETS

Under the EU ETS, shipping companies are obligated to monitor, report, and verify (MRV) $CO_2$ emissions produced by their vessels on designated voyages. The emissions calculated must then be compensated through the submission of a corresponding quantity of European Union Allowances (EUAs). The equation for calculating the EU ETS is [31]:

$$ETS = (Tons\ of\ CO_2\ emmited/\ year) \times (year - rate^{(1)}) \times (Trading\ within\ or\ from/to\ Europe^{(2)}) \times (CO_2\ Price) \quad (7)$$

[1] Year-Rate: 2024: 40%, 2025: 70%, 2026:100%

[2] Within EU: 100%, From/to EU: 50%

The EU ETS calculations were based on the current $CO_2$ price [32] and future predictions [33], ranged from an initial price of USD 80/t o a conservative trajectory of USD 142/t by 2050 (Figure 1).

#### 4.2.3. MEPC83 Net Zero Framework (NZF)

A ship's annual GFI target ($GFI_T$) consists of two tiers:

1. A base target annual GFI (base target); and
2. A direct compliance target annual GFI (direct compliance target).

The $GFI_T$ is determined as follows:

$$GFI_T = \left(1 - \frac{Z_T}{100}\right) \times GFI_{(2008)} \quad (8)$$

where $GFI_{(2008)}$ is the GFI reference value equivalent to 93.3 $gCO_2eq/MJ$ (representing the average GFI of international shipping in 2008), $Z_T$ is the applicable annual reduction rate used to adjust the reference value in line with current decarbonization targets and $T$ is the calendar year to which the compliance target refers [34].

The IMO has officially announced reduction targets only for the period 2028–2035. In accordance with the regulations, the MEPC must set the $Z_T$ factors for the period from 2036 to 2040 by January 2032. The $Z_T$ value for the baseline target in 2040 is set at 65%. In this study, the targets for the period 2036–2050 were determined by extrapolating the trend of the already established targets. This is in line with the IMO NZF, which states that the GHG emissions must reach zero by 2050.

Each ship must determine its GFI compliance balance for every reporting period:

$$\begin{aligned}\text{GFI compliance balance} &= (\text{Direct compliance target annual GFI} - \text{Attained annual GFI}) \\ &\times \text{Energy}_{\text{Total}}[\text{tonnes of } CO_2eq]\end{aligned} \quad (9)$$

If the GFI compliance balance is 0 or positive, the vessel is considered to be fully compliant and can receive extra points equal to the amount of the positive balance. By contrast, if the GFI compliance balance is negative, the vessel must quantify the deficit and address it by implementing compliance measures. A vessel can have a compliance deficit in two different situations:

If Direct Compliance Target < GFI Attained $\leq$ Base Target, the Compliance Deficit is calculated from the following formula:

$$\text{Tier 1 compliance deficit} = (\text{Direct compliance target annual GFI} - \text{Attained annual GFI}) \times \text{Energy}_{\text{Total}} \quad (10)$$

If Base Target < GFI Attained, then:

$$\text{Tier 1 compliance deficit} = (\text{Direct compliance target annual GFI} - \text{Base Target Annual GFI}) \times \text{Energy}_{\text{Total}} \quad (11)$$

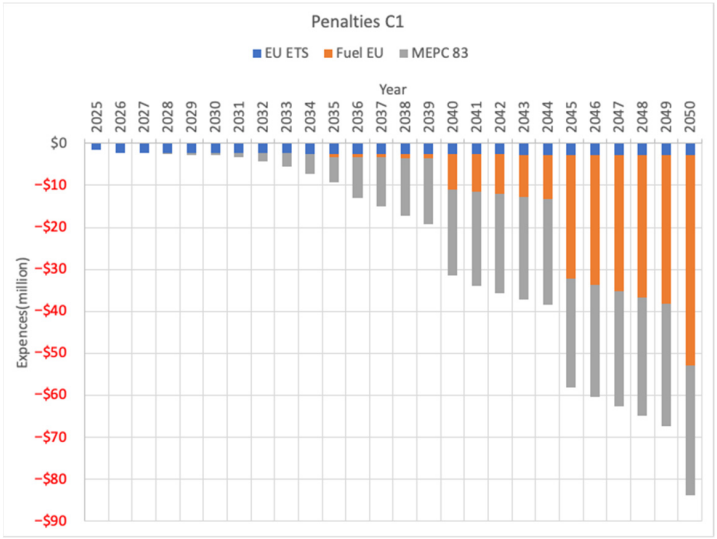
$$\text{Tier 2 compliance deficit} = (\text{Base target annual GFI} - \text{Attained annual GFI}) \times \text{Energy}_{\text{Total}} \quad (12)$$

Ships must balance their Tier 1 compliance deficit by acquiring remediation units through contributions to the IMO Net-Zero Fund for GHG emissions pricing. Ships must balance the Tier 2 compliance deficit using one or more of the following GFI compliance options:

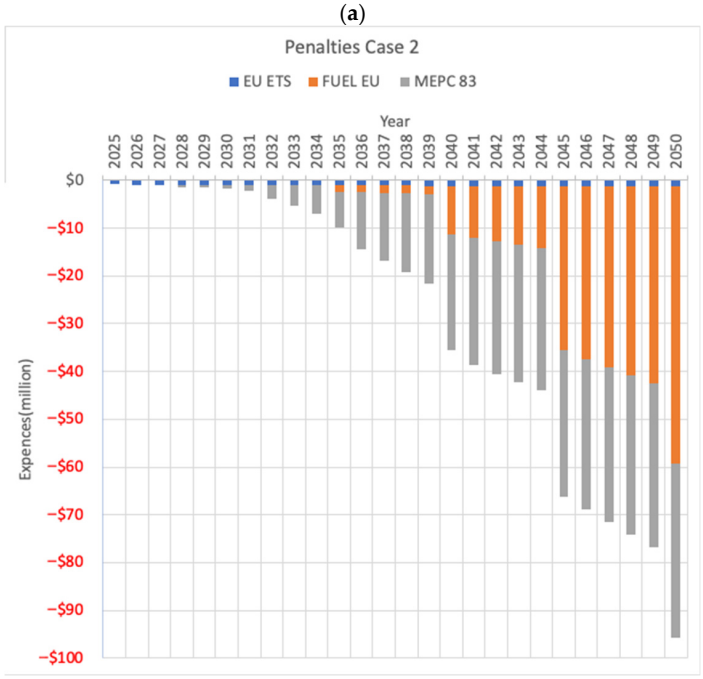
- Excess units that have been transferred from other ships.
- Units that have been put aside from previous reporting periods.
- Remedial units that were purchased through contributions for the pricing of GHG emissions in the IMO Net-Zero Fund, which are charged at Tier 2 reference rates, as defined in paragraph 9 of the regulation.

A ship that has fully dealt with its non-compliance deficiencies will be considered to comply with the annual GFI target. For the period from 2028 to 2030, the initial price of a Tier 1 remediation unit is set at USD 100/t$CO_2$eq based on the well-to-wake model, whereas for Tier 2 is set at USD 380/t$CO_2$eq. Furthermore, if a vessel has a compliance deficit for two or more consecutive reporting periods, the penalty is multiplied by an escalation factor [7].

For the calculation of the IMO's NZF penalties (Figure 2), the penalty prices have only been officially determined by the IMO for the period from 2028 to 2035. As this study examines the period from 2025 to 2050, it was necessary to estimate penalty values for the years 2036–2050. It is assumed that these penalties will increase progressively to promote decarbonization, encourage the adoption of low- and zero-emission technologies, and ensure consistency with the IMO's long-term net zero objectives. The calculations process reveals a compliance deficit for both cases from 2032 onwards.




(**a**)




(**b**)

**Figure 2.** Distribution of penalties by regulation. (**a**) 1st Case without OCCS; (**b**) 2nd Case with OCCS.

## 5. Results

The economic viability of OCCS across the vessel's lifespan is influenced by the vessel's operating characteristics, such as time at sea, engine running hours, and load profiles for both the main and auxiliary engines. Key input parameters such as LNG prices and CAPEX for OCCS equipment may vary significantly over time.

Table 3 provides a breakdown of the CAPEX from the manufacturer and shipyard, as supplied by a shipping company. The values for the loan-to-investment ratio and interest rates were selected as they are standard figures commonly used in maritime industry investments.

**Table 3.** OCCS capex.

| 2nd Case (OCCS) | Values |
|---|---|
| Equipment Costs | USD 6,000,000 |
| Shipyard Costs | USD 1,200,000 |
| Design Costs | USD 300,000 |
| Total OCCS CAPEX | USD **7,500,000** |
| Loan-to-Investment Ratio | 30% |
| Interest Rate | 4% |
| Repayment Period (2025–2050) | 25 years |
| Capital cost | 8% |

For the purposes of this case study, it is assumed that annual inflows are generated from the sale of captured $CO_2$. The equation used to calculate the total yearly inflow from captured $CO_2$ is:

$$\text{Total Yearly Inflow from } CO_2 \text{ Captured} = \text{Yearly } CO_2 \text{ Price} \times \text{Yearly } CO_2 \text{ Captured from OCCS} \quad (13)$$

For the calculations, it has been considered that the yearly GHGI of the vessel is 81.4 $gCO_2$ eq/MJ, as it has been calculated previously, without following IMOs 2024 Guidelines because as mentioned by IMO the term eoccs will need "further methodological guidance to be developed by the Organization" [5].

Operational Expenditures (OPEX) in the 2nd Case differentiate by including the MEA solvent cost, the additional fuel needed for OCCS and the offloading cost for captured $CO_2$ (Figure 3).

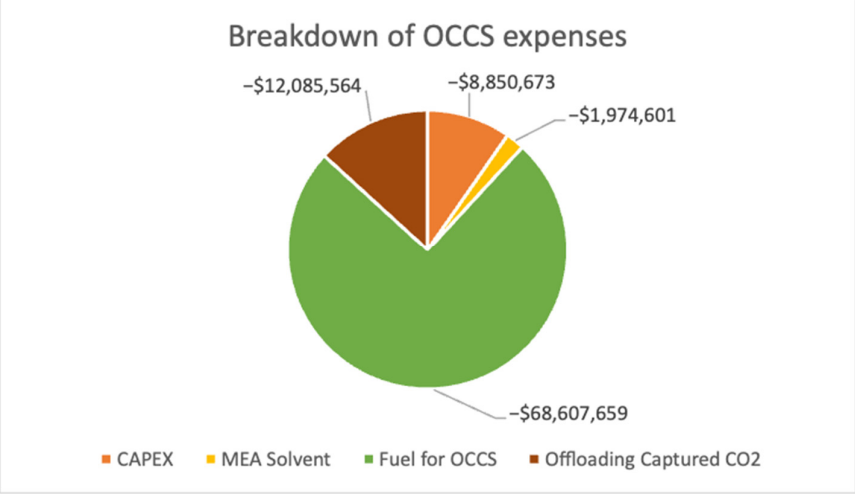



**Figure 3.** The sum of the OCCS expenses for the entire examined period (2025–2050).

For the MEA solvent yearly expenses, the following equation has been adopted:

$$\begin{aligned}\text{MEA Solvent} \quad & \text{MEA cost/year} \\ & = (\text{MEA Price [USD/ kg]} \times \text{MEA consumption [kg/ tCO}_2\text{]} \\ & \times \text{Case 2 CO}_2\text{ Emissions [t/ year]}) \\ & + (\text{Filling Amount for MEA [t]} \times \text{MEA Price [\$/ kg]} \times 100 \\ & \times \text{Number of Exchanges due to Degradation per year})\end{aligned} \tag{14}$$

For the MEA price, an average value based on North American (USD 1.3/kg) and European market (USD 1.4/kg) data for 2025 was considered [35]. The scenario of a 1% increase is applied for subsequent years, in line with the approach used for other projected price increases. For MEA consumption, the Filling Amount for MEA and Number of exchanges due to Degradation, the manufacturer's estimation is applied as follows: MEA solvent consumption: 1.5 kg/t, Filling amount for MEA solvent—Solvent mass flow (30% MEA): 68 t and two exchanges due to degradation per year. In addition, the estimated annual depreciation rate of 1% is taken into account when calculating economic feasibility.

The additional fuel needed for OCCS is calculated by the following adopted equation:

$$\begin{aligned}\text{Total fuel cost} \quad & \text{per year for OCCS} \\ & = \left(P_{\text{LNG}} \times (1 + g_{\text{LNG}})^{(Year - Year_0)} \times C_{\text{LNG}}\right) + \left(P_{\text{LSMGO}} \times (1 + g_{\text{LSMGO}})^{(Year - Year_0)} \times C_{\text{LSMGO}}\right)\end{aligned} \tag{15}$$

where P is the Bunkering price calculated as an average of the fuel prices in Houston and Rotterdam for each fuel in early 2025 (for LSMGO USD 741/t and for LNG USD 827/t) [36], g is the annual growth rate for the 1% scenario and C is the additional consumption that the vessel has due to OCCS (Table 4).

**Table 4.** OCCS values breakdown table.

| | |
|---|---|
| **Two 6L GE NG Consumption** | **2777 t/year** |
| **Two 6L GE LSMGO Consumption** | 41 t/year |
| **Total consumption for OCCS operation** | 2818 t/year |
| **Offloading Cost** | USD 13.0/t [37] |

For offloading costs, the following equation is adopted:

$$\text{Offloading cost per year} = \text{CO}_2\text{ Captured per Year [t]} \times \text{Offloading Cost [\$/ tCO}_2\text{]} \tag{16}$$

The analysis shows that most operating costs result from increased fuel consumption driven by the energy requirements of the OCCS. Costs relating to the management of captured $CO_2$, such as offloading and solvent consumption, represent a smaller percentage of total OPEX. This observation is consistent with existing literature, which emphasizes that the energy penalty is the primary cost factor for carbon capture systems, whereas $CO_2$ management costs are comparatively lower [38].

Based on the above input data and including a charter rate of USD 34,000/day [39] for the examined voyage, the Net Present Value (NPV) for the 2nd Case appears to be negative, −USD 184,251.435.

As mentioned previously, the term $e_{occs}$ plays a crucial role in determining the final results. The resolution of the MEPC.391(81) adopted on 22 March 2024, states that the Tank-to-Wake Greenhouse Gas Intensity should be calculated as follows:

$$\begin{aligned}GHGI_{TtW\ 2024\ Guidlines} \quad & = \tfrac{1}{LCV}\left(\left(1 - \tfrac{1}{100}\left(C_{slipship} + C_{fug}\right)\right)\left(C_{fCO_2} GWP_{CO_2} + C_{fCH_4} GWP_{CH_4} + C_{fN_2O} GWP_{N_2O}\right)\right. \\ & \left. + \left(\tfrac{1}{100}\left(C_{slipship} + C_{fug}\right)C_{sfx} GWP_{fuelx}\right) - S_{FC} e_c - S_{FCCU} e_{ccu} - e_{OCCS}\right) \\ & = GHGI_{TtW} - \tfrac{1}{LCV}(S_{FC} e_c + S_{FCCU} e_{ccu} + e_{OCCS})\end{aligned} \tag{17}$$

where $GHGI_{TtW}$ is the Greenhouse Gas Intensity value with the same methodology as previously, $S_{FC}$ = 0, the emissions credits haven't been generated by biomass growth and $S_{FCCU}$ = 0, the emissions credits from the used captured $CO_2$ as carbon stock will not produce synthetic fuels. In this study, the $S_{FC}$ and $S_{FCCU}$ parameters are set to zero because the system under consideration is based on the combustion of fossil LNG, and the captured $CO_2$ is not used to produce synthetic fuels or other products. These conditions mainly apply to biogenic carbon or carbon capture and utilization processes, as noted in the relevant literature on the calculation of emissions in CCS/CCU systems [40]. As a result, the formula can be written as follows:

$$GHGI_{TtW\ 2024\ Guidlines} = GHGI_{TtW} - \frac{1}{LCV} * e_{OCCS} \quad (18)$$

Up to date no official framework or standardized approach has been established for calculating the $e_{occs}$ variable. The objective of this approach (Case 3) is to demonstrate how $e_{occs}$ could contribute to reducing the well-to-wake greenhouse gas intensity (GHGI) and, consequently, the associated IMO NZF penalties (Table 5). This will provide shipowners with tangible benefits if they implement OCCS technologies on their vessels. An attempt is made to determine the coefficient $e_{occs}$ in an objective and easily calculable manner, accounting for the ratio of emissions from installing the OCCS to the corresponding fuel consumption. Table 5 illustrates how this proposal was implemented. The results of the new GHGI calculation are significantly lower than those of previous calculations, reflecting the real benefit of reducing emissions through the installation of OCCS.

**Table 5.** $GHGI_{TtW}$ according to IMO 2024 Guidelines with $e_{occs}$ estimation approach (3rd Case).

| | **LNG** | **LSMGO** |
|---|---|---|
| **Consumption [t/year]** | 19,916 | 1080 |
| **$CO_2$ emissions with slip [t/year]** | 24,233 | 1409 |
| **Emission/Consumption ratio** [$gCO_2eq/gfuel$] | 1.22 | 1.30 |
| **LCV** [MJ/gfuel] | 0.049 | 0.043 |
| **$e_{occs}$ estimation** [$gCO_2eq/MJ$] | 24.770 | 30.457 |
| **$GHGI_{TtW}$** [$gCO_2eq/MJ$] | 81.4 | |
| **New $GHGI_{TtW\ 2024\ Guidelines}$** [$gCO_2eq/MJ$] | 26.050 | |

The obtained results resonate with a corresponding study by IMO in MEPC 83-INF.9 [7] with a baseline GHG intensity of 69.9 $gCO_2eq/MJ$ for methanol and 79.3 $gCO_2eq/MJ$ for HFO. When OCCS is integrated, the study similarly reports reductions to 45.3 $gCO_2eq/MJ$ and 51.7 $gCO_2eq/MJ$. In this particular case, with $GHGI_{TtW\ 2024\ Guidelines}$ 26.05 $gCO_2eq/MJ$, the NPV is positive at USD 13,443,693, the Internal Rate of Return (IRR) is 81.73%, and the payback period is 3 years.

Sensitivity Analysis: Fuel Cost

The largest component of the OCCS operational expenditures is attributed to the additional fuel required for its operation. This sensitivity analysis examines the impact of variations in the annual fuel price growth rate on the financial indicators obtained in the 3rd Case. Although global energy market forecasts often report higher compound annual growth rates (CAGR), particularly for LNG when examined as a traded commodity, the long-term price growth of marine fuels typically evolves more gradually. This is due to sector-specific constraints, including regulated fuel specifications, supply chain inertia, competition in the bunker market, and limited short-term demand elasticity.

For LNG, the selected values of 2.5% (pessimistic scenario), 1.5% (central scenario), and 1.0% (optimistic scenario) are conservative and operationally relevant price-growth trajectories. LNG prices do not necessarily follow the CAGR of basic commodities, as they are significantly influenced by long-term contracts, infrastructure bottlenecks, regional market segmentation, and price-formation mechanisms unrelated to pure demand growth. For the LSMGO, the selected growth rates of 1.5% (pessimistic scenario), 1.0% (central scenario), and 0.5% (optimistic scenario) reflect the anticipated long-term stabilization of marine fuel prices derived from petroleum as the sector gradually transitions to low-carbon alternatives. By selecting these moderate and differentiated CAGRs, the sensitivity analysis captures a realistic range of fuel-price pathways faced by LNG carriers over multi-decade horizons. Table 6 presents the results of the sensitivity analysis, which show that they are similar to the initial calculations, except for the pessimistic scenario, where the results are negative, as expected.

**Table 6.** Results for sensitivity analysis for fuel cost (3rd Case).

| Scenarios | NPV | IRR | Payback Period |
|---|---|---|---|
| **Optimistic scenario** | USD 14,792,178 | 81.96% | 3 years |
| **Central scenario** | USD 13,443,693 | 81.73% | 3 years |
| **Pessimistic scenario** | −USD 6,198,884 | - | - |

## 6. Discussion

The aim of this research was to conduct a comparative techno-economic and regulatory compliance assessment of an LNG carrier operating with and without OCCS. A technical analysis was carried out for both cases, resulting in the calculation of fuel consumption and emissions for Case 1 (without OCCS) and Case 2 (with OCCS). Existing legislation for the EU ETS, FuelEU Maritime, and the IMO NZF framework has been reviewed, and the corresponding penalties for each case were calculated based on their respective consumption and emission profiles.

EU ETS penalties are applied based on emissions, whereas FuelEU Maritime and IMO NZF penalties are applied by placing the primary emphasis on fuel consumption and determining emissions solely through fuel $CO_2$ emission factors. Therefore, while the outcome of OCCS is desirable, the way these penalties are calculated results in disproportionate penalties for OCCS, since the system increases fuel consumption despite substantially lowering net emissions.

To assess the impact of regulatory penalties, this study introduces the concept of daily Discounted Equivalent Cash Flow (here called: DDECF). This index enables a direct comparison to be made between the cost of penalties and the Time Charter Equivalent (TCE) of the ship for the examined route. The difference between this index and the benchmark TCE value of USD 34,000, called Δ(TCE, DDEFC) here, indicates that the penalties are already financially unsustainable for the vessel in Case 1, and that they would be even more so in Case 2. Furthermore, an additional analysis was performed using the 2024 IMO guidelines (Case 3), which propose a method for adjusting the GHGI by crediting vessels equipped with OCCS with a reduction equal to $e_{occs}$/LCV. Although the guidelines do not specify how $e_{occs}$ should be calculated, this analysis considered an assumption and a methodological proposal.

The Δ(TCE, DDECF) results presented in Figure 4, reflect the substantial financial burden imposed on the operator by the penalties, which could reach up to 50% of the TCE by the year 2050. In Case 2, the Δ value worsens rather than improves, reflecting the increased penalties associated with increased consumption caused by the OCCS unit. By

contrast, Case 3 shows that if the proposed IMO guidelines are adopted as regulations, the operator would benefit from clear financial incentives to adopt OCCS.

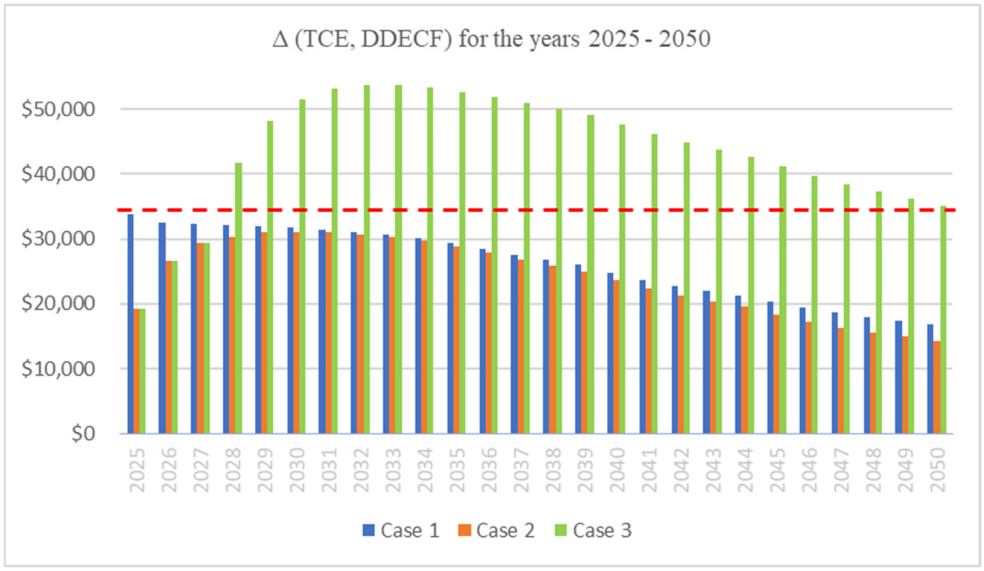



**Figure 4.** Δ(TCE, DDECF) for all cases over the entire examined period (2025–2050) compared with TCE (horizontal dashed line).

Applying OCCS to the examined LNG carrier increased total fuel consumption by 16%. However, as noted in Section 3.2, the optimized thermal integration of the OCCS with the ship's energy systems is under research, through the utilization of waste heat, for example, from the auxiliary engines, as investigated by Wohtlan et al. [21]. Furthermore, using advanced solvents or solvent mixtures, such as AMP-PZ blends instead of conventional MEA, can reduce thermal requirements and lower energy consumption in the OCCS studied by Jeong et al. [15].

These results, combined with the absence of targeted funding for the integration of carbon capture systems and other decarbonization technologies on ships, prevent operators from aligning with the IMO's NZF's interim targets for 2050. Despite their commitment to decarbonization and the global green transition, operators are unable to contribute constructively. It is important to recognize that, beyond regulatory and financial considerations, major technological transitions in the maritime sector inherently require long timeframes. Notable examples include LNG, which took approximately 40–60 years to evolve from a specialized traded commodity into a widely used marine fuel supported by established infrastructure in major global ports.

Despite the comprehensive regulatory and financial assessment, the study is subject to certain limitations. The analysis is based on specific assumptions about future fuel prices, emission allowances, and technological costs up to 2050. Furthermore, the assessment was carried out based on the operating profile of the LNG carrier, which may not fully reflect the variability of other actual operational scenarios.

## 7. Conclusions

In conclusion, although OCCS is a highly promising solution for decarbonizing the maritime industry, it is not currently economically feasible. Current EU and IMO policies tend to prioritize e-fuels, even though large volumes of these fuels are not yet available for shipping and zero-emission fuels currently represent only a very small proportion of the global marine fuel mix. The future viability of OCCS depends on clear regulatory guidelines and effective incentives that reward early adopters while offsetting investment

and operational costs. As new regulatory frameworks emerge, this study provides a baseline for evaluating future technological and legislative developments, supporting informed decision-making as the industry transitions towards net zero.

Furthermore, the potential widespread application of OCCS must overcome two more challenges. One issue is that ports are hesitant to invest in the necessary unloading infrastructure until a sufficient proportion of ships are fitted with carbon capture technology. On the contrary, shipowners are reluctant to install OCCS systems on their ships until robust and reliable unloading infrastructure has been established in ports.

The current analysis was based on the vessel's annual operational profile, derived from actual voyage data from the previous year. However, ship operations are typically characterized by dynamic changes in main engine load. These changes occur during manoeuvres, port stays, or changes in weather conditions, and will directly affect $CO_2$ capture efficiency. Investigating the dynamic operation of OCCS systems under variable conditions could be the subject of future research.

The attempt to determine the term $e_{occs}$ into the $GHGI_{TtW}$ calculation highlights a fundamental methodological issue: the incomplete recognition of carbon capture at the ship level by current emission intensity indicators. Although this study is based on the well-to-wake emissions intensity indicator in accordance with the current regulatory framework, integrating a comprehensive, process-based life cycle assessment (LCA) could provide a deeper understanding of the overall environmental impact of OCCS. In particular, an expanded LCA would allow for the assessment of emissions associated with the manufacture and replacement of equipment, the production and regeneration of solvents, and the transport and final storage or utilization of captured $CO_2$. Furthermore, comparing regulatory WtW factors with analytical LCA data could reveal discrepancies in system boundaries and emission allocation methods. Such an approach for future research will provide a coherent basis for the overall assessment of OCCS at the value chain level and will support the development of technology-neutral and environmentally consistent regulatory mechanisms.

**Author Contributions:** E.S. wrote the paper and conducted a general overview of the research; N.V. studied, implemented, and analyzed the research; G.A.L. and D.N.P. contributed to data selection and methodology development. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Data Availability Statement:** Data are contained within the article.

**Conflicts of Interest:** The authors declare no conflicts of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| OCCS | Onboard Carbon Capture and Storage |
| LNG | Liquefied Natural Gas |
| NG | Natural Gas |
| IMO | International Maritime Organization |
| GHG | Greenhouse Gas |
| EU | European Union |
| ETS | Emissions Trading System |
| NZF | Net-Zero Framework |
| NPV | Net Present Value |
| IRR | Internal Rate of Return |
| EEXI | Energy Efficiency Existing Ship Index |

| | |
|---|---|
| CII | Carbon Intensity Indicator |
| DCS | Data Collection System |
| GFS | Global Fuel Standard |
| GEM | Global Economic Measure |
| MEPC | Marine Environment Protection Committee |
| MARPOL | MARitime POLlution Convention |
| GRT | Gross Register Tonnage |
| EC | European Commission |
| MRV | Monitor, Report and Verify |
| $CO_2$ | Carbon Dioxide |
| CCS | Carbon capture and storage |
| HFO | Heavy Fuel Oil |
| TRL | Technology Readiness Level |
| MEA | Monoethanolamine |
| AMP-PZ | Amino Methyl Propanol–Piperazine |
| WtW | Well-to-Wake |
| MGO | Marine Gas Oil |
| TEU | Twenty-foot Equivalent Unit |
| SFGC | Specific Fuel Gas Consumption |
| SFOC | Specific Fuel Oil Consumption |
| SPOC | Specific Pilot Oil Consumption |
| ME | Main Engine |
| GE | Generator |
| LSMGO | Low Sulphur Marine Gas Oil |
| CAPEX | Capital Expenditure |
| OPEX | Operational Expenditure |
| VLSFO | Very Low Sulphur Fuel Oil |
| RFNBO | Renewable Fuels of Non-Biological Origin |
| CMI | Compliance Market Indicator |
| EUAs | European Union Allowances |
| GFI | Greenhouse Gas Fuel Intensity |
| GHGI | Greenhouse Gas Intensity |
| LCV | Lower Calorific Value |
| DCF | Discounted Cash Flow |
| TCE | Time Charter Equivalent |
| LCA | life cycle assessment |

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