

Article

Integrated Onboard Carbon Dioxide Capture and Liquefaction System for Dual-Fuel Marine Engines

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Abstract

Onboard carbon capture and storage (OCCS) is promising, but downstream CO₂ conditioning and liquefaction dominate energy and operability constraints. An integrated OCCS onboard for CO₂ conditioning, deep cooling, phase separation and liquid CO₂ (LCO₂) storage for a dual-fuel marine engine was introduced and investigated. In addition, the proposed system has been scrutinized under Aspen HYSYS V12.1 steady state mode and a comprehensive sensitivity sweep on deep-cooler temperature and separation pressure. Sensitivity sweeps reveal a sharp liquefaction threshold governed by the deep-cooler outlet temperature. For the engine load range from 50% to 110% and exhaust gas from 1.288 to 2.863 kg/s with CO₂ from 3.65 to 6.67%, the model is validated at 90.3% capture. Near vent-free operation for $T_{E105} < -24.58$ °C, and a P-T diagram indicates that near vent-free operation requires $P_{V105} > 190$ kPa at -24.7 °C, while -22.45 °C is unattainable within 1600–2200 kPa. Increasing compressor discharge pressure from 1500 to 2500 kPa raises compression power from 34.8 to 80.23 kW at -21 °C without improving vent/yield under throttled control. By identifying threshold-based deep-cooling setpoints, creating a separator pressure-temperature feasibility envelope for near-vent-free operation, and clearly quantifying CO₂-rich vent slip as a system-level loss term, this study offers an operability-driven design layer for onboard CO₂ liquefaction.

Keywords: onboard OCCS; CO₂ liquefaction operability; deep cooling threshold; CO₂ slip minimization; vent-flow suppression



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1. Introduction

Carbon emissions are among the most severe environmental challenges facing the world today. The International Maritime Organization (IMO) ambition is to attain a reduction in GHGs by at least 55% by 2030 and to enact net-zero carbon emissions by 2050 [1]. In the context, onboard carbon capture and storage (OCCS) is an approachable and promising solution for the sustainable marine industry due to its tremendous advantages of CO₂ emissions decline without immediate fuel switching. Despite the shipboard implementation being constrained by limited space, weight, auxiliary power and carriable engine loads [2,3]. This can be significantly altered by other system-level emissions accounting when capture, liquefaction and onboard storage are considered together [4]. High capture level at 90% CO₂ removal is considered a promising approach due to its deep decarbonization thresholds and sustainable emissions eligibility of marine vessels [5]. However, there

are substantial technological obstacles in the way of reaching such collecting rates onboard. High capture ratios greatly increase energy consumption, and exhaust heat could not be enough to maintain constant operation, raising questions about the viability and integration of the system. These limitations suggest that, in addition to capture performance, high capture ratios must be assessed considering downstream processing and storage needs. Previous studies on ship-based carbon capture have mostly focused on the capture stage, which involves solvent absorption, membrane separation, and adsorption technologies, with sophisticated process modeling tools such as Aspen HYSYS used to estimate capture efficiency and column performance [6,7]. The existing liquefaction and refrigeration cycles usually use SEC/COP, thus assuming a conditioned CO₂ feed [8,9]. Several studies compare capture technologies and recover waste heat, but often remain conceptual on conditioning specifications with water removal and CO₂ quality examination. Due to their heavy reliance on selectivity assumptions, membrane and liquefaction studies may not take solvent-loop or ship-wide operability restrictions into consideration [10]. Yi et al. (2025) reviewed more than 60 studies on onboard CCS, in which recent OCCS studies increasingly shifted toward simulation-based assessment [11]. Additionally, LNG regasification of cold energy might possibly lower refrigeration requirements for CO₂ liquefaction, making dual-fuel LNG vessels an untapped energy opportunity [11,12]. In this study, the capture-to-LCO₂ storage integration was designed and investigated based on the thermodynamic mass and energy balancing principles. The system proposes a full approach including deep chilling with cold energy reutilization supply, multi-stage compression-intercooling combination, and on-board LCO₂ storage. As a result, the overall energy consumption and practical operability imply that the process of LNG cold energy supply diminishes the refrigeration. The most visible obstacle to onboarding OCCS is energy consumption, especially at high capture objectives. Impurifying CO₂ stream conditioning can create freezing, plugging, or unstable operation during the liquefaction process, while deep refrigeration and multi-stage CO₂ compression usually account for most auxiliary power requirements. In terms of dual-fuel LNG-diesel vessels, the cold energy produced during LNG regasification offers a substantial and promising waste-heat-to-power source. LNG cold energy utilization reduces the refrigeration duty for CO₂ liquefaction or cryogenic capture approaches, as several recent studies have shown [13,14]. However, there is yet no systematic integration of LNG cold energy into a completed capture-to-liquefaction-to-storage OCCS configuration, which consists of deep dehydration, phased condensate removal, and upstream compression [15]. This configuration reflects practical shipboard CO₂ compression systems and mitigates excessive moisture carryover to downstream units, which is critical for stable cryogenic operation [16]. Thus, the feasibility and design trade-offs of onboard LCO₂ storage systems on dual-fuel LNG-diesel vessels. In this specific study, the liquid CO₂ captured and storage processes have been illustrated in Figure 1.

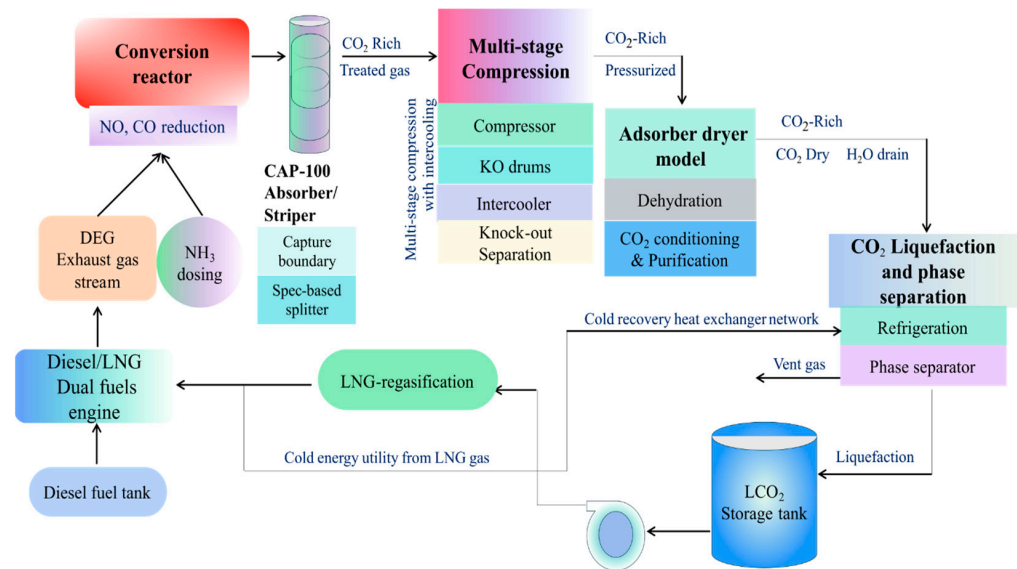


Figure 1. LCO₂ captures to storage onboard block diagram concept.

2. Process System Description

Existing onboard carbon capture systems for marine engines typically treat the capture, compression, dehydration, liquefaction and storage processes as separate subsystems, which limit overall energy optimization.

Figure 2 illustrates an integrated onboard CO₂ conditioning-liquefaction-storage subsystem coupled with a dual-fuel main engine supplied by a diesel fuel tank and LNG from the LNG tank via the heat exchanger and LNG gasifier. The CO₂-rich stream is conditioned in the conversion reactor with NH₃ dosing, cooled in cooler 1, and dewatered in separator 1. Splitter 1 is used to enforce a controlled CO₂ feed boundary to the liquefaction train. The stream then undergoes staged compression and intercooling combination of compressors 1–3 with cooler 2–5 with intermediate condensate removal in separator 2–5 withdrawals via KO3–KO5 to ensure operability prior to low-temperature processing. Splitter 2 enforces the downstream split/boundary condition before final cooling. The stream is pre-cooled in cooler 6 and further cooled in deep cooling to promote condensation, followed by phase separation in separator 6; liquid CO₂ is routed to the LCO₂ storage tank handled by the LCO₂ pump, while the overhead is treated as vent/off gas CO₂ slip. Cold recovery from LNG vaporization, in other words, LNG gasification cold energy provides a ship-specific integration pathway to reduce the refrigeration burden.

2.1. Integrated OCCS System Configuration

A marine medium-speed dual-fuel engine serves as the reference prime mover in the integrated onboard carbon capture and storage (OCCS) study. Table 1 provides the specification parameters of the baseline engine, such as bore 280 mm, stroke 320 mm, 8 cylinders, 1600 kW at 750 rpm, mean effective pressure 1.62 MPa, and compression ratio 11.42. The literature dataset utilized in this work specifies the associated exhaust boundary conditions as mass flow rate and CO₂ concentration, and model assessments are performed at actual operational loads ranging from 50 to 110%. Boundary conditions are implemented at the input of the downstream OCCS process chain to separate engine performance characterization from CO₂ conditioning and liquefaction assessment in the following sections. In addition, load-dependent exhaust boundary conditions such as mass flow rate and CO₂ mole fraction are adopted from [17] and used to parameterize the OCCS inlet.

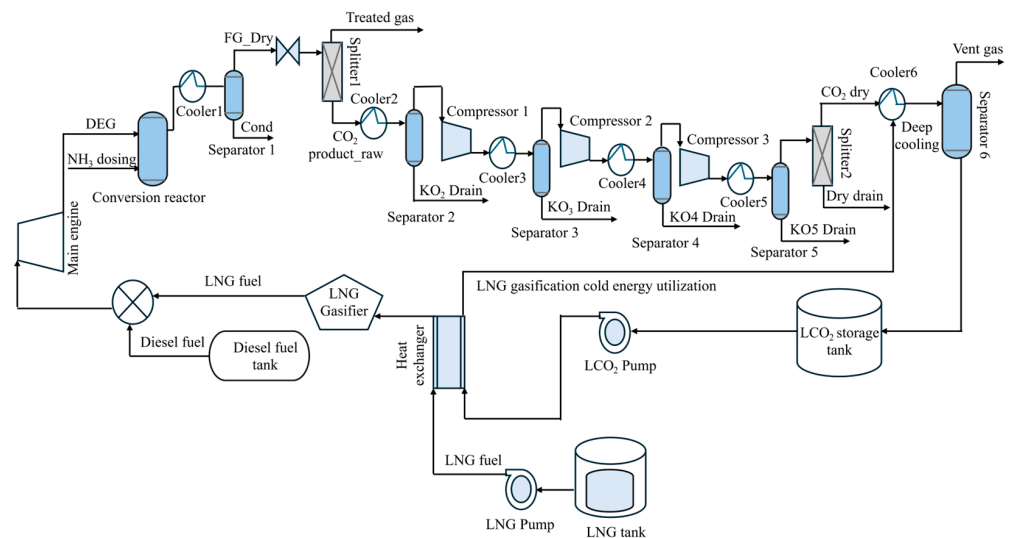


Figure 2. LCO₂ recovery, liquefied and storage onboard design.

Table 1. Main parameters of MAN L28/32DF [18].

Parameter	Specification
Bore, mm	280
Stroke, mm	320
Cylinder number	8
Rating power, kW	1600
Rating speed, RPM	750
Mean effective pressure, MPa	1.62
Compression ratio	11.42

2.2. CO₂ Conditioning, Liquefaction and LNG Cold Energy Integration

Modeling Assumptions

The integrated onboard carbon capture and storage system is modeled in Aspen HYSYS V12.1 as a steady-state process, aiming to evaluate mass and energy balances as well as the overall energy penalty associated with CO₂ capture and storage onboard a marine vessel as presented in Table 2. To ensure numerical stability and engineering relevance, the following assumptions are adopted. In addition, the exhaust gas specifications are accessible in Table 3.

Table 2. Energy losses of key components in the combined system.

Component	Exergy Destruction
Conversion reactor	$E_D^{Conv} = E_{101} + E_{NH_3} - E_{102}$
Cooler 1	$E_D^{Cooler1} = E_{102} - E_{104}$
Separator 1	$E_D^{Sep1} = E_{104} - (E_{105} + E_{106})$
Splitter 1	$E_D^{Split1} = E_{105} - (E_{107} + E_{109})$
Cooler 2	$E_D^{Cooler2} = E_{109} - E_{110}$
Separator 2	$E_D^{Sep2} = E_{110} - (E_{111} + E_{112})$
Compressor 1	$E_D^{Comp1} = W_{Comp1} + E_{111} - E_{113}$
Cooler 3 (Inter-cooler 1)	$E_D^{Cooler3} = E_{113} - E_{114}$
Separator 3	$E_D^{Sep3} = E_{114} - (E_{115} + E_{116})$
Compressor 2	$E_D^{Comp2} = W_{Comp2} + E_{115} - E_{117}$
Cooler 4 (Inter-cooler 2)	$E_D^{Cooler4} = E_{117} - E_{118}$
Separator 4	$E_D^{Sep4} = E_{118} - (E_{119} + E_{120})$

Table 2. Cont.

Component	Exergy Destruction
Compressor 3	$E_D^{Comp3} = W_{Comp3} + E_{119} - E_{121}$
Cooler 5 (Inter-cooler 3)	$E_D^{Cooler5} = E_{121} - E_{122}$
Separator 5	$E_D^{Sep5} = E_{122} - (E_{123} + E_{124})$
Splitter 2	$E_D^{Split2} = E_{123} - (E_{125} + E_{126})$
Cooler 6 (Deep cooling-LNG cold energy)	$E_D^{Cooler6} = E_{125} - E_{127}$
Separator 6 (LCO ₂ separation)	$E_D^{Sep6} = E_{127} - (E_{128} + E_{129})$
LCO ₂ pump	$E_D^{Pump} = W_{pump} + E_{129} - E_{130}$
LNG heat exchanger (Cold energy recovery)	$E_D^{HX} = (E_{21} + E_{132}) - (E_{22} + E_{131})$
LNG Gasifier	$E_D^{Gasifier} = E_{22} - E_{23}$

Table 3. Test results about engine exhaust gas.

Parameters	Specification				
Load (%)	50	75	90	100	110
Exhaust gas mass flow rate (kg/s)	1.288	1.906	2.275	2.546	2.863
Exhaust gas temperature after turbocharger (°C)	441.2	446	428.7	416	425.7
Exhaust gas temperature before the turbocharger (°C)	520.6	560.2	568.4	577.2	591.2
CO ₂ mole fraction (%)	3.66	3.67	3.66	3.66	3.65
CO ₂ mass flow rate (kg/h)	264	390	466	521	584

3. Methodology

3.1. Simulation Methodology and Key Modeling Assumptions

The integrated OCCS process is designed and investigated under a steady-state system on the Aspen HYSYS V12.1 simulator (Aspen Technology Inc., Bedford, MA, USA), demonstrating an end-to-end configuration from exhaust gas recovery to onboard liquid CO₂ storage. Additionally, two working fluid packages were defined in the simulation, in which the Peng-Robinson was applied to the main downstream OCCS train, whereas Acid Gas-Chemical Solvents were defined for the acid-gas-related environment. The capture section was simplified as a specification-based splitter rather than being modeled as an explicit absorber. Deep dehydration was simulated using a component splitter and a phase separator located after deep cooling was used to separate liquid CO₂ from the vent gas. Pressure losses were incorporated implicitly via the specified unit pressures in Aspen HYSYS. Under base-case conditions, the CO₂-rich stream was compressed in three stages with intercooling, with the temperature lowered to about 40 °C after each main cooling step.

Regarding the mass and energy balance principle, the simulation precisely characterizes key material streams, such as CO₂-rich gas, compressed CO₂, dehydrated CO₂, vent gas, and liquid drainage [19]. A specification-based splitter is used to evaluate CO₂ capture to enforce a set removal ratio of 90.3% from the treated exhaust gas. Without making assumptions, particularly about capturing technology, this boundary-based method allows for systematic assessment of downstream conditioning, compression, and liquefaction performance. After that, a multi-stage compressor train with cooler blocks for intercooling is used to compress the CO₂-rich stream. Next, knock-out (KO) drums for staged condensate removal (separator blocks) are placed downstream of each intercooler. A component splitter is responsible for processing deep dehydration as a stand-in for an adsorber dryer, resulting in a low residual water content appropriate for cryogenic processing [16,20]. In the next stage, a refrigeration-based cooling section is utilized to chill the dehydrated CO₂

stream. Heat exchangers are used to connect the cooling section with cold energy from LNG regasification [18,21–23]. In addition, a phase separator is used to extract liquid CO₂ from non-condensable vent gas after the stream has cooled. The liquid CO₂ stream is pumped into an onboard storage tank upon completion of the LCO₂ storage procedure. Regarding CCS and cryogenic CO₂ conditioning existing technologies, multi-stage CO₂ compression with intercooling is explicitly proposed as the dominant energy contributor, while dehydration is included as a necessary operability constraint to ensure cryogenic compatibility rather than as an energy-driving process [24,25]. The simulated configuration thermodynamically endorses a system-level approach in which compression is dedicated as the dominant energy source, and dehydration is treated as an operability constraint for cryogenic feasibility; thus, LNG cold energy offsets refrigeration [19,20].

3.2. Key Performance Indicators (KPI) Definition

Key performance indicators (KPIs) are used to investigate system performance, with an emphasis on energy usage, capturing efficiency, and storage needs. The CO₂ capture efficiency is defined as the ratio of captured CO₂ to CO₂ in the engine exhaust [3]. The CO₂ capture efficiency is defined as:

$$\eta_{\text{capture}} = \frac{\dot{m}_{\text{CO}_2, \text{captured}}}{\dot{m}_{\text{CO}_2, \text{exhaust}}} \quad (1)$$

In this study, the reported SEC represents the downstream OCCS subsystem SEC, because the capture unit was imposed as a boundary condition, and the solvent-regeneration duty was not included in W_{aux} . Accordingly, the downstream SEC was evaluated based on the captured CO₂ flow entering the liquefaction train. The total auxiliary power consumption is calculated as the sum of compressor and refrigeration power [8,16,26]:

$$W_{\text{aux}} = \sum W_{\text{compressor}} + W_{\text{refrigeration}} \quad (2)$$

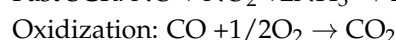
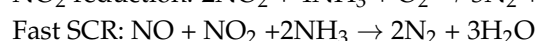
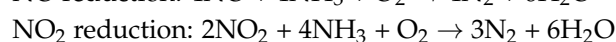
The specific energy consumption (SEC) of the OCCS system is measured:

$$SEC_{\text{downstream}} = \frac{W_{\text{aux}}}{\dot{m}_{\text{CO}_2, \text{captured}}} \quad (3)$$

The percentage of CO₂ that flashes into the vapor phase at the storage tank's saturation condition and is discharged through the vent, as determined by the liquid CO₂ mass flow rate and the corresponding phase equilibrium, is known as vent-related CO₂ loss.

3.3. Exhaust Gas Pre-Treated Process

The process starts with the exhaust gas stream from the twin engine, which predominantly comprises CO₂. The conversion reactor operates as the pre-treatment reactor for NO_x, CO reduction upstream of CO₂ conditioning, in which, with the NO and NO₂ reduction chemical reactions, toxic emissions such as NO, NO₂, and CO have been extracted [27]. The main reactions have been listed as follows:



4. Results and Discussions

4.1. Overall System Performance at 90% CO₂ Capture

The integrated OCCS system is evaluated at a target CO₂ capture ratio of 90%, corresponding to a deep decarbonization operating point relevant for future IMO compliance [1,28]. At this capture level, the system achieves stable operation across compression, dehydration, liquefaction, and storage units without freezing or phase instability, confirming the effectiveness of staged condensate removal and deep dehydration prior to cryogenic cooling. CO₂ compression and refrigeration were indicated as the major energy consumption (SEC), thus dominating the overall auxiliary power requirement [29]. Shipboard energy-system studies have shown that LNG vaporization cold energy can be integrated with main-engine exhaust heat in a cascade utilization configuration, enhancing the heat-cold integration effectiveness [19,30,31]. At the same time, LNG regasification pumps and auxiliary cooling utilities' contributions were recorded as a minor fraction. It is estimated that at high capture ratios, energy consumption continues to be an important constraint for an onboard OCCS system compared to capturing capability. While the OCCS runs at 90% capture objective, downstream liquefaction efficiency and effective storage are significantly impacted by the vent losses mitigation strategy. Safe and efficient condensation and separation processes have been assigned by the liquefied CO₂ in 2000 kPa and −25 °C conditions with zero vent gas flow. This medium-pressure liquid CO₂ storage envelope maintains operation well above the triple CO₂ point to avoid solid formation risks [32]. The absence of the CO₂ vent gas stream at this operating temperature, presenting the liquefaction stage, significantly prevented vapor carryover and solid formation. The base-case simulation's resilience is further supported by the registered drains from knockout flow. The deep-cooling domination process is demonstrated in Figure 3, where the entire cooling duty and the total compressor accounted for 77% and 7%, respectively. In which the cooler E105 is the largest contributing component with 8%; in other words, deep cooling is the main factor influencing the viability of liquefaction. Therefore, cold energy integration and E105 duty reduction should take precedence over optimization of small auxiliary systems for performance gains.

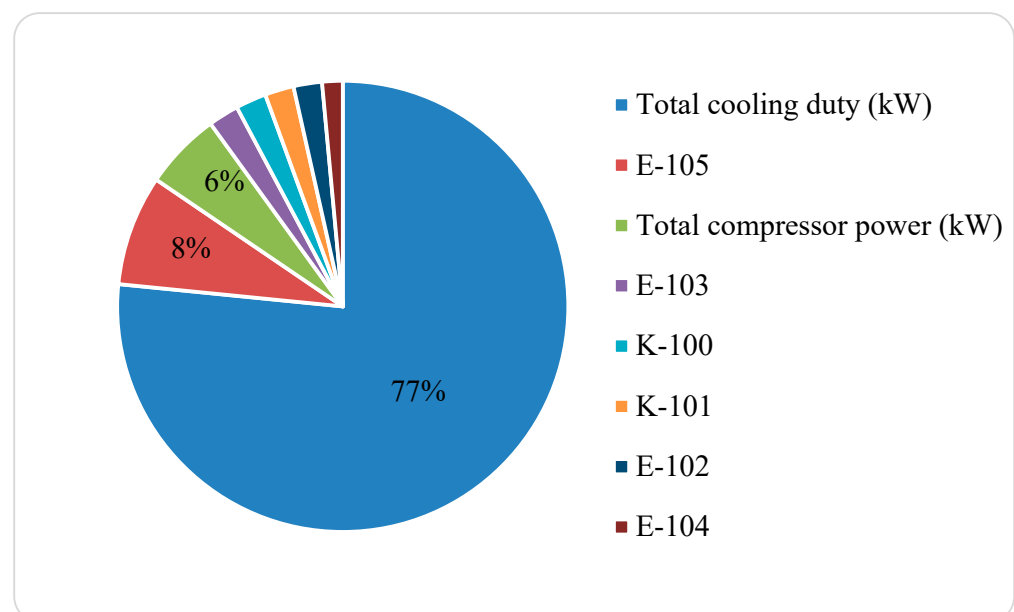


Figure 3. Thermal duty breakdown of the CO₂ conditioning train (%).

4.2. SEC Breakdown and Dominant Energy Consumers

At a high capture ratio, the electricity demand of the compression section remains substantial even when intercooling and knock-out separation are employed. Refrigeration accounts for the second-largest energy contribution under the investigated CO₂ saturation temperature range and high-pressure conditions. Severe dehydration has a significant impact on system operability but does not result in significant energy loss when simulated as an adsorber-based system. Although deep dehydration is essential for stable system operation, its direct contribution to the overall energy consumption is limited when it is modeled as an adsorber-based process. Vent-related CO₂ losses are small but not insignificant, underscoring the significance of phase separator performance in reducing capture efficiency deterioration in cryogenic circumstances. Although vent-related losses appear limited in the base case, their impact on effective SEC becomes more pronounced when the liquefaction yield is reduced near the deep-cooling threshold. Due to the high pressure required for downstream liquefaction and storage, CO₂ compression was identified with 47% as the largest energy consumer [16,21,24]. As illustrated in Figure 4, the SEC can be decomposed into contributions from three-stage compression, refrigeration duty for liquefaction, and auxiliary loads associated with dehydration and phase separation.

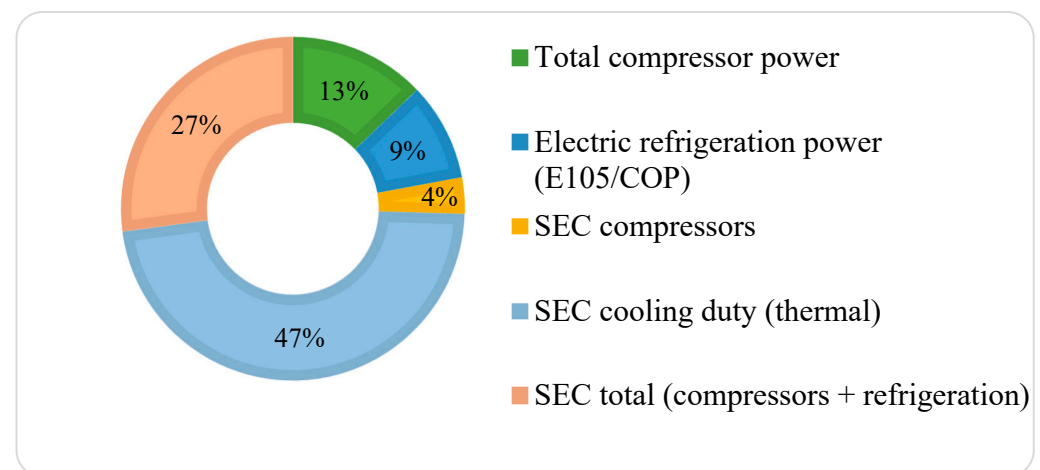


Figure 4. Electrical equivalent SEC breakdown of the CO₂ conditioning train.

Figure 5 shows that increasing compressor outlet pressure from 1500 to 2500 kPa causes a strong, near-linear increase in energy demand, dominated by the final compression stage. In particular, as the compressor outlet pressure increases, the total compression power increases monotonically, with the K-102 power rising correspondingly from 34 to 81 kW. This demonstrates that in the regime under investigation, pressure mostly serves as a cost lever. In addition, Figure 6 indicates that SEC per stored CO₂ increases nearly linearly with pressure, from approximately 183 to 198 kWh/tCO₂. The energy efficiency penalty is mostly caused by increased compression work since stored LCO₂ production largely remains constant during the pressure sweep. These results demonstrate that raising compression pressure under fixed deep-cooling conditions raises the energy penalty without enhancing liquefaction performance. This supports the notion that pressure selection should be optimized for energy efficiency rather than assumed performance gains.

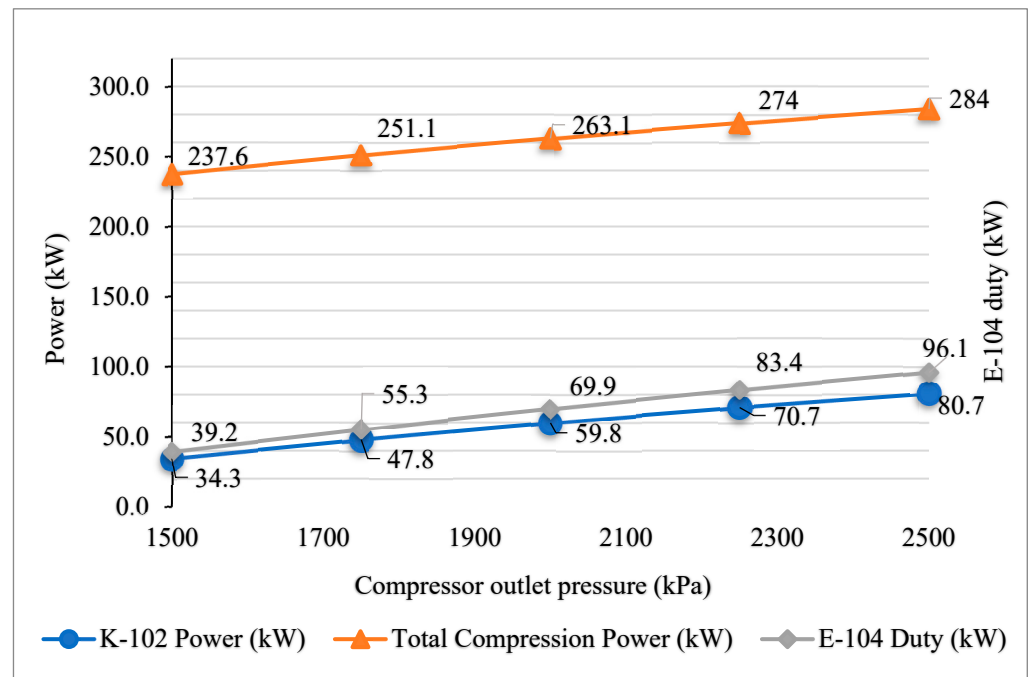


Figure 5. Pressure increases compression cost analysis.

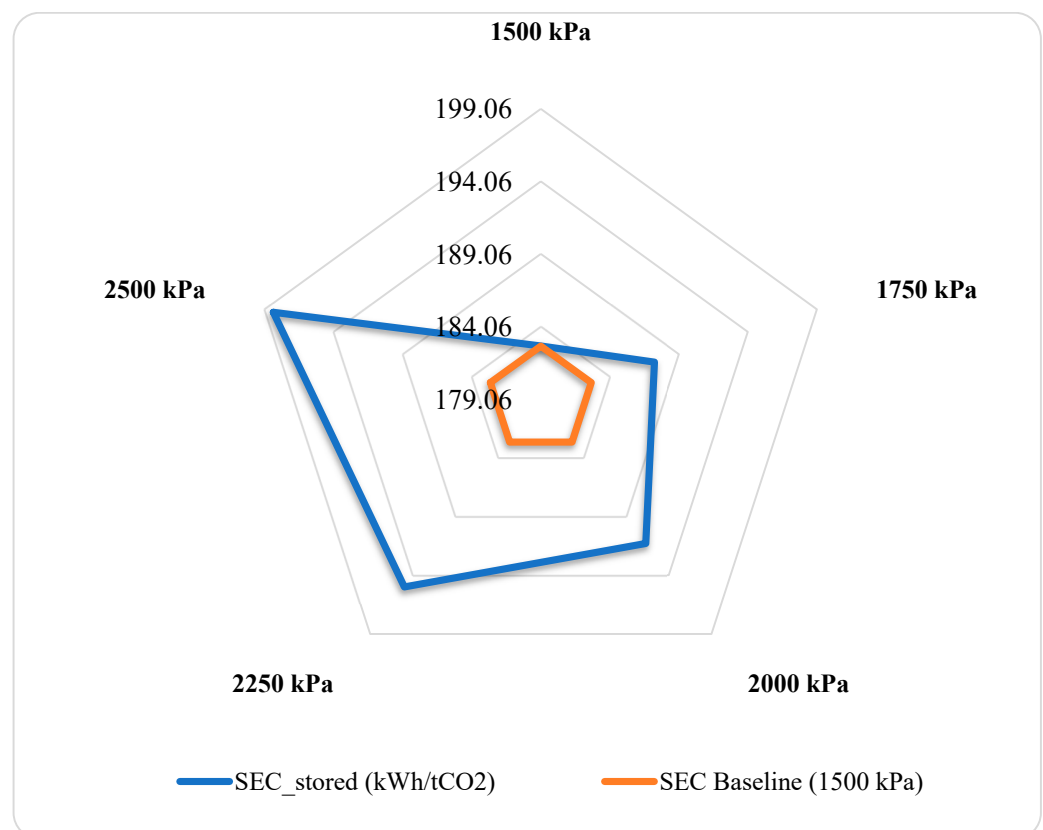


Figure 6. SEC per stored CO₂ vs. pressure analysis.

4.3. Effects of LNG Cold Energy Integration

To quantify the benefit of LNG cold energy utilization, two comparative cases are analyzed:

Base case: CO₂ liquefaction without LNG cold energy integration

Integrated case: CO₂ liquefaction assisted by LNG regasification cold energy

These two cases share identical upstream capture performance, CO₂ throughput, compressor settings, dryer specification, and storage pressure; thus, parameter changes in SEC can be attributed solely to the temperature-lift reduction achieved by the LNG-assisted pre-cooling [33]. By lowering the CO₂ inlet temperature to the refrigeration section, the integrated case decreases the refrigeration duty and associated power demand, leading to a marked reduction in refrigeration-related SEC relative to the base case. Consequently, the total system SEC is reduced, demonstrating that LNG cold energy recovery functions as an effective lever to improve onboard OCCS energy efficiency on dual-fuel LNG vessels. In the second case, the cold energy released during LNG regasification is recovered through a heat exchanger network and used to pre-cool the compressed and dehydrated CO₂ stream prior to refrigeration. This integration reduces the temperature lift required by the refrigeration system and directly lowers refrigeration power demand [34]. Results indicate a significant reduction in refrigeration-related SEC in the integrated case compared to the base case. Consequently, the total system SEC is reduced by a notable margin, demonstrating that LNG cold energy recovery is an effective strategy for improving onboard OCCS energy efficiency on dual-fuel LNG vessels. Notably, the OCCS and LNG regasification integration considers operational parameters such as increased vent losses or unstable phase behavior, confirming the compatibility of LNG cold recovery with cryogenic CO₂ liquefaction under shipboard constraints. In terms of operability examination, the deep-cooling duty under the liquefaction barrier found in the sensitivity sweep analysis makes LNG cold energy integration especially beneficial from the conventional operability standpoint.

4.4. Comparative Analysis: With and Without LNG Cold Energy

4.4.1. Comparative Analysis Storage Tank Volume Required at Different Ship Loads

The capture target and the necessary LCO₂ storage volume are connected in Figure 7. In addition to energy consumption, onboard viability is constrained by available space and operational robustness under varying engine loads [35]. This scaling provides a system-level perspective: in addition to capturing efficiency, deep capture targets should be evaluated based on the combined load of downstream auxiliary power and storage capacity. Rather than refuting the baseline case conclusions, these sensitivity results demonstrate that the practicality demonstrated at 90.3% capture depends on operating within a restricted deep-cooling temperature range.

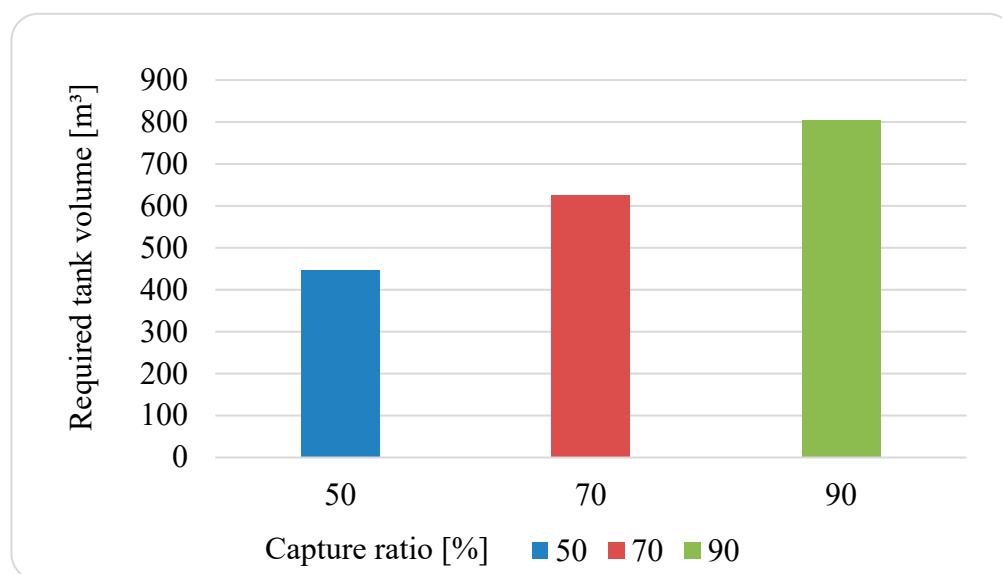


Figure 7. Storage tank volume requirement vs. capture ratio.

4.4.2. Sensitivity Analysis

The 11-case sweep provides a mechanic, boundary-resolved interpretation of ship-board CO₂ liquefaction operability. Instead of investigating isolated SEC values, the campaign identifies a condensation-governed threshold at the deep cooler and quantifies how integration leverages cold energy pre-cooling and separator pressure. This yields a design-to-operate map and a robust setpoint recommendation, which is directly feasible for onboard implementation and not available from single-point or design-point-centric assessments. The sweep analysis has been divided into three main categories with 11 case studies. Group contrasts the base configuration with the LNG cold-integrated configuration under identical assumptions to isolate how cold-energy recovery reduces the refrigeration temperature lift and power demand. The second group, named threshold and boundary identification, performs targeted sweeps of the deep-cooling outlet temperature and duty, followed by a near-boundary zoom, to reveal the condensation-governed transition. Additionally, group 3 indicates that the observed venting transition is reproducible across operating regimes. It verifies that non-dominant variables like E_{104} do not induce the transition and assesses whether separator pressure shifts, thereby confirming a mechanism-driven behavior. According to Table 4, the most highlighted output of integrating LNG regasification cold energy into an LCO₂ capture and storage system is the drastic reduction in auxiliary power consumption for CO₂ liquefaction, leading to lower energy penalty, higher net efficiency, and improved onboard feasibility.

Table 4. Comparison of LCO₂ liquefaction performance.

Parameter	With LNG Cold Energy	Without LNG Cold LNG
CO ₂ liquefaction method	LNG cold energy integration	Mechanical refrigeration
CO ₂ inlet condition	40 °C, 1 bar	30 °C, 1 bar
LCO ₂ outlet condition	−25 °C, 1980 kPa	−52 °C, 1 bar
Refrigeration of power relative	0.757	1
Auxiliary power share (%)	Significantly reduced	High
Additional refrigeration cycle	Not required/ minimized	Required
Onboard feasibility	Improved	Limited

Sensitivity results of case CS03 show a clear phase-change threshold at the deep cooler (E−105). It indicates that the outlet temperature is sufficiently low, liquid CO₂ production increases sharply and vented gas drops toward zero, while the E-105 duty rises significantly. The duty sweep in case CS09 confirms a monotonic reduction in both vapor fraction and vent flow as cooling duty increases, indicating that vent loss is governed by the residual vapor after E-105. A refined sweep near the boundary (CS10, at V-105 in 1980 kPa) pinpoints the vent-free condition at T_{E105} −24.6 °C, where vapor fraction ≈ 0 and vent gas = 0, corresponding to a duty of approximately 1.35×10^6 kJ/h. Case study 11 demonstrates that separator pressure variations in the investigated range do not induce the venting transition. Thus, the deep-cooling intensity is the primary control, while pressure provides a window-shifting effect rather than a regime trigger. Vent rises to 822.3, and LCO₂ falls to 66.53 with a little temperature relaxation to −20 °C, demonstrating highly nonlinear, condensation-governed behavior. Therefore, a lower set-point is advised for robustness, and T_{E105} below −21 °C is necessary for low-vent operation. T_{E104} , on the other hand, indicates that it is not a major lever in the investigated area by producing a flat response without a threshold.

As demonstrated in Figures 8 and 9, the sweeping results reveal a clear regime shift governed by the E_{105} deep-cooling outlet temperature. For the two case studies CS06 and CS07, a venting threshold appears at −21 °C, beyond which the vent flow rapidly

increases to 3.75 t/h while the liquefied CO₂ flow collapses from 85 kgmole/h to near zero. In contrast, case study CS08 shows nearly constant LCO₂ (66.53 kgmole/h) and venting (822 kg/h) across the swept range, indicating operation within a single (already-venting) regime without a discernible threshold. Similarly, the LCO₂-pressure sweep (CS09) remains stable with negligible venting (2.58 kg/h), suggesting that pressure variations in the tested range do not trigger the venting transition. To maintain near-vent-free operation at higher temperatures, the separator pressure must be increased; otherwise, additional deep cooling becomes unavoidable.

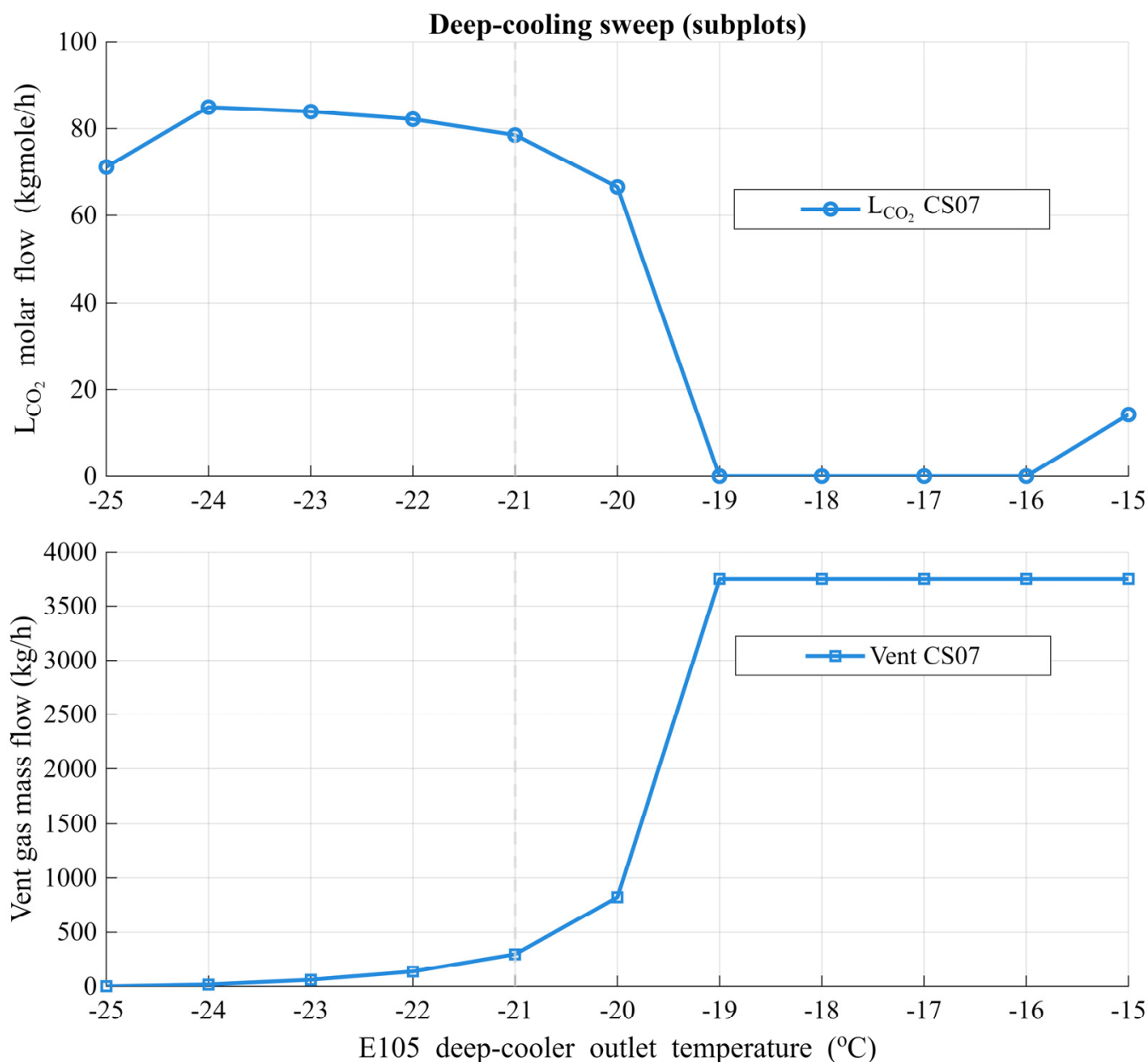


Figure 8. Deep cooling subplots sweep analysis.

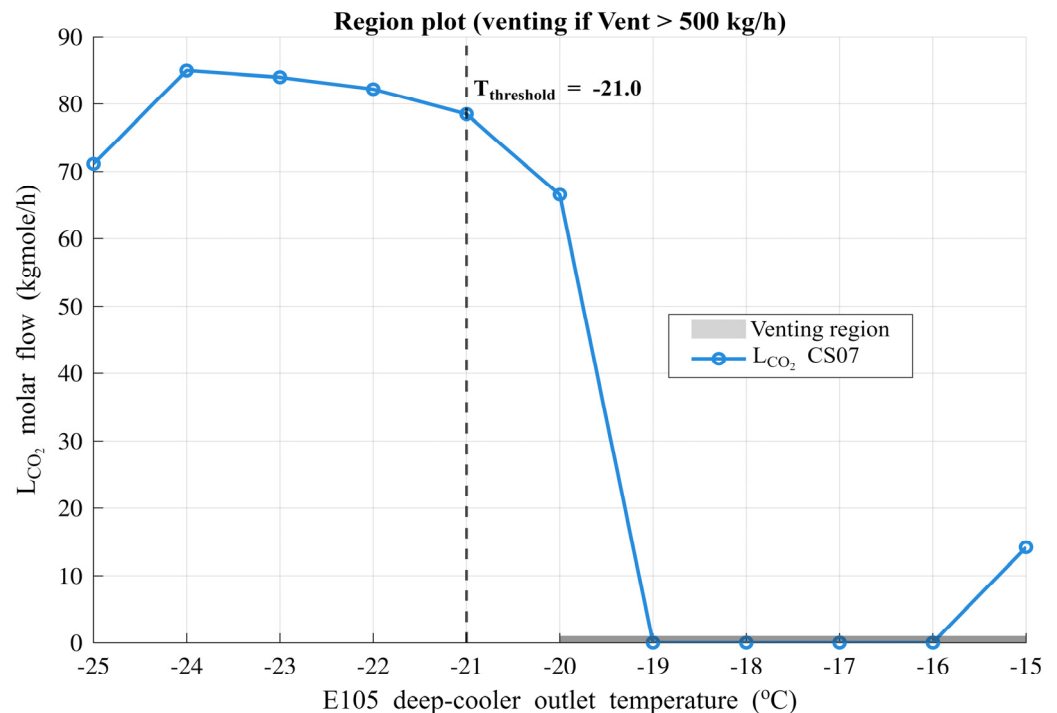


Figure 9. Deep cooling outlet temperature sweep analysis.

5. Conclusions

Onboard carbon capture and storage (OCCS) have been widely known as a promising solution to reduce carbon dioxide (CO₂) emissions from existing diesel and dual-fuel ship fleets [36]. Existing onboard carbon capture technologies are limited by high energy consumption, lack of integration with fuel systems and insufficient feasibility for liquefied CO₂ storage. This research introduced and investigated an integrated assessment of an onboard OCCS system operating at a 90% CO₂ capture ratio [37]. Stable, vent-free liquefaction is achieved when deep dehydration and staged phase separation are applied prior to cryogenic cooling, establishing a clear operability reference for high-capture onboard designs [38]. In addition, the liquefaction boundary regulates refrigeration duty, whereas compression power dominates auxiliary demand. In the study, the compressor output pressure increased from 1500 to 2500 kPa, resulting in a higher required compression energy; the final compression stage accounted for 135% power performance. However, the liquefaction performance under fixed deep-cooling conditions does not seem to be enhanced. On the other hand, pressure is less of a performance level and more of an energy level. Specific energy consumption per stored CO₂ in proportion to the downstream vent losses is used to evaluate system performance. Since the energy penalty increases from 183 to 198 kWh t⁻¹ CO₂ with pressure, while stored CO₂ remains almost constant, this indicates that the energy penalty is due to increased compression labor.

The results show that deep-cooling intensity is the key variable governing liquefaction operability and vent-loss behavior, whereas compression pressure mainly acts as an energy-penalty lever rather than a performance-improving parameter under the investigated conditions. In addition, the integration of LNG regasification cold energy improves the energy performance of the system by reducing the refrigeration burden and supporting a more practical liquefaction pathway for dual-fuel LNG vessels. Thus, a technically feasible basis for onboard CO₂ liquefaction and storage and the main trade-offs between energy demand, storage performance, and operability were investigated. These findings are key technical specifications of the preliminary design of shipboard OCCS systems, especially in identifying stable operating regions and process-control variables.

Nevertheless, the present work is limited to a process-level thermodynamic and operability assessment. Future research should therefore address detailed shipboard implementations, including equipment layout, footprint, weight, safety under marine operating conditions, automation requirements, and techno-economic as well as regulatory evaluation.

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