

Article

Techno-Economic Evaluation of Direct Low-Pressure Selective Catalytic Reduction for Boil-Off Gas Treatment Systems of NH₃-Fueled Ships

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Abstract: This study proposes a feasible solution for boil-off gas (BOG) treatment to facilitate NH₃ fuel use by ocean-going ships, which is currently considered an alternative fuel for ships. Two systems were designed and analyzed for BOG in IMO Type-A NH₃ fuel storage tanks for 14,000 TEU container ships. First, BOG lost inside the storage tank minimized economic losses through the onboard re-liquefaction system. The total energy consumed by the system to process NH₃ gas generated in the fuel tank at 232.4 kg/h was 51.9 kW, and the specific energy consumption (SEC) was 0.223 kWh/kg. Second, NH₃ was supplied to the direct Low-Pressure Selective Catalytic Reduction (LP-SCR) system to treat marine pollutants generated by combustion engines. The feasible design point was determined by calculating the NH₃ feed flow rate using three methodologies. The energy consumed by the direct LP-SCR system was 3.89 and 2.39 kW, and the SEC was 0.0144 at 0.0167 kWh/kg at 100% and 25% load, respectively. The feasibility was indicated via economic analysis. Depending on the life cycle cost, the competitiveness of the re-liquefaction system depends on the price of NH₃, where a higher price yields a more economical solution. In conclusion, the direct LP-SCR system has a low overall cost because of its low energy consumption when supplying NH₃ and its reduced amount of core equipment.

Keywords: ammonia fuel; BOG treatment; re-liquefaction; LP-SCR; specific energy consumption; life cycle cost



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1. Introduction

In 2018, greenhouse gas (GHG) emissions from shipping accounted for approximately 3% of global emissions. The International Maritime Organization (IMO) has imposed environmental regulations to control GHG emissions from the shipping industry. The 2023 IMO GHG Strategy was adopted at the 80th Marine Environment Protection Committee (MEPC) meeting in July 2023, raising the existing goal of reducing total emissions by 50% compared to 2008 levels by 2050. The committee agreed to achieve at least a 20% reduction by 2030, at least 70% by 2040, and zero net emissions by 2050 [1]. The 2023 IMO GHG Strategy includes an ambition to use at least 5% carbon-free fuels by 2030, with efforts to reach 10%.

To achieve these objectives, various methods have been proposed for reducing CO₂ emissions from ships, such as improvements in hull design, enhancements in propulsion efficiency, operational measures (like reducing speed), and the utilization of alternative energy [2]. Moreover, nitrogen oxide (NO_x) emissions are being regulated based on engine speed, as depicted in Table 1 [3]. Currently, NO_x emissions from ships meet regulations by applying the SCR system using Urea. However, merely implementing measures to improve technological and operational efficiency is not sufficient to meet the CO₂ reduction

targets for ships [4]. Furthermore, the need for long-term strategies is urgent, such as the obligatory use of zero-carbon fuels and a more rigorous approach to reducing carbon dioxide emissions. Therefore, a shift to alternative energy sources is essential [5].

Table 1. NO_x emission regulations (g/kWh) by year.

Engine Speed <i>n</i> (rpm)	Tier 1 2000	Tier 2 2011	Tier 3 2016
<130	17.0	14.4	3.4 g
130 ≤ <i>n</i> < 2000	45.0 × <i>n</i> ^{-0.2}	44.0 × <i>n</i> ^{-0.23}	9.0 × <i>n</i> ^{-0.2}
2000	9.8	7.7	2.0

Researchers are considering various alternative energies to achieve the 2050 goal of zero carbon emissions, but the two most common carbon-free energies are hydrogen (H₂) and ammonia (NH₃) [6]. Unlike heavy fuel oil (HFO), liquefied natural gas (LNG), and liquefied petroleum gas (LPG), the primary energy source for ships, the carbon reduction rates of hydrogen and ammonia are 100% [7]. Liquid hydrogen (LH₂) has a higher low heating value (LHV) than other energies but requires a very low storage temperature of −253 °C at 1 bar [7,8], which creates high facility costs for use on board ships. However, the volumetric energy density of liquid ammonia (LNH₃; 14,100 MJ/m³) is higher than that of liquid H₂ (8500 MJ/m³). Additionally, the storage temperature of LNH₃ is −33.4 °C at a vapor pressure of 1 bar [7,8]. This is similar to the boiling temperature of LPG (−42 °C at 1 bar). Because of these properties, ammonia has technological advantages in storage and handling [8].

Several organizations have published outlook reports on ammonia as a marine fuel. For instance, the International Energy Agency (IEA) [9] forecasts that ammonia’s proportion of the fuel market will increase to 8% by 2030 and 44% by 2050, and it is anticipated to secure a significant share of the shipping fuel market. The American Bureau of Shipping (ABS) noted that using ammonia is a quick way to meet GHG emission regulations [10]. Lloyd’s Register (LR) noted that ammonia regulations for ships using low-flashpoint fuel would take effect in July 2023 [11]. The company DNV-GL released a report on ammonia as a marine fuel, emphasizing its potential role in the decarbonization of maritime transport [12]. Additionally, the Korean Register (KR) published a technical report on ammonia-fueled ships and investigated their characteristics, safety, technology, and research trends with the goal of establishing future regulatory directions for ammonia-fueled ships. We also analyzed important international requirements, such as IGC and IGF CODE [8]. Based on the low-flashpoint-fuel ship rules, design guidelines describing the latest safety regulations and inspection standards for ammonia-fueled ships were published [13].

Two approaches are typically employed to use ammonia as a marine fuel: fuel cells and combustion-based systems [14]. Utilizing ammonia in a fuel cell involves converting it into high-purity hydrogen through an external reformer. This hydrogen is then supplied to a polymer electrolyte membrane (PEM) fuel cell [15], characterized by a low operating temperature, or directly to a solid oxide fuel cell (SOFC), which operates at a high temperature [16]. A fuel cell generates electricity through an electrochemical reaction, unlike the combustion reactions in internal combustion (IC) engines. This method offers the advantage of producing no nitrogen oxide (NO_x) emissions. However, it faces challenges related to its relatively low technological maturity compared to IC engines, including additional onboard facility costs and its limited capacity to respond to changes in load [17].

The second approach, combustion-based systems, has been studied for ammonia-fueled IC engines and fuel supply systems [18]. The engine maker MAN E&S expects about 27% of the fuel used by large merchant ships to be ammonia by 2050. MAN E&S is developing an ammonia engine based on LPG-fueled engines to provide a carbon-free ammonia-fueled propulsion system as a marine solution. To operate NH₃ engines, the concept of the fuel supply system is being developed for supplying liquid NH₃ to the engines. The two-stroke engine ME-LGIA is being studied with the goal of delivery

in 2025, and MAN B&W recently reported that successful ammonia combustion results were obtained for its two-stroke 4T50ME-X engine [19]. In addition, Wartsila noted that ammonia fuels are promising as carbon-free fuels in the marine industry that can satisfy IMO regulations [20]. To this end, the existing Wartsila 25 engine was developed to use ammonia fuel in a four-stroke engine [21]. However, despite these studies, solving the problem of NO_x emissions continues to be a challenge due to the combustion of ammonia [22].

Kim et al. [23] conducted a study using ammonia as a potential marine fuel, taking environmental and operational impacts into account. They proposed four propulsion systems, each suitable for a specific ship type that uses ammonia as fuel. To comprehensively evaluate the viability of these systems, they built a model ship system using five combinations of these propulsion techniques. The evaluation criteria included the economic feasibility of each union, GHG emissions, and operational efficiency. Their approach provided the potential to reduce the environmental impact of ammonia and cost-effectiveness in maritime operations. At the same time, they evaluated the economic feasibility of the system through net present value (NPV) calculations.

Lee et al. [24] conducted a techno-economic analysis of an NH₃ fuel supply and onboard re-liquefaction system for NH₃-fueled ships. Through thermodynamic and economic evaluations, including exergy destruction and Net Present Value (NPV) analysis, the research identifies conditions under which NH₃ fuel becomes economically feasible, particularly with respect to NH₃ pricing and carbon tax implications. The findings suggest that NH₃ is a promising alternative marine fuel.

Seo et al. [25] analyzed the impact of installing ammonia fuel tanks on ships and proposed two methods: cargo tanks on ammonia carriers and installing independent cylindrical tanks. Their study evaluated the economic feasibility of both methods, including an analysis of sales and life cycle costs. As a result, the practicality and economy of the installation methods were analyzed. The sensitivity analysis demonstrated that profits were significantly affected by the prices of NH₃ fuel and transportation costs.

Akturk M et al. [14] investigated the feasibility of using NH₃ fuels in medium LPG/NH₃ carriers. Their approach included a comprehensive review of the existing literature, comparing various eco-friendly fuels and focusing on their characteristics and suitability for marine use. They evaluated the potential of ammonia as a marine fuel and conducted a risk assessment of using NH₃ as a ship fuel using two methods: the What-If Technique (SWIFT) and a Hazard Identification Study (HAZID). These methodologies systematically identified and evaluated potential operational risks associated with ammonia use.

Lesmana H et al. [26] conducted an analysis on the use of ammonia as an alternative to carbon-containing fuels in the ship's combustion engines. The thermochemical properties of conventional fuels and hydrogen and ammonia alternative fuels were compared, and the basic combustion properties and properties were summarized. In addition, it provides a theoretical basis for the general fuel system and NH₃ storage and handling system for evaluating NH₃ combustion in IC engines. Additionally, the feasibility was verified through research on combustion performance through hydrogen. NH₃ has potential as a fuel but mentioned the importance of controlling NO_x, particularly related to emissions, in practical applications of combustion technology.

For the conversion of potential ship eco-friendly fuels, various aspects of ammonia fuel are continuously being studied on ships, including international regulations for the storage and transportation of ammonia, potential risks, and operational safety [27]. However, there is a lack of feasibility and economic research and analysis of BOG treatment systems, which are important solutions for NH₃-fueled ships.

Therefore, in this study, a new preliminary study was conducted on BOG generated from ships using NH₃ as a sustainable fuel for ships. This presents a solution feasible with on-board re-liquefaction systems and LP-SCR to reduce economic loss from ships. Therefore, this study proposed the LP-SCR system, a novel approach for BOG processing

that distinguishes it from existing methodologies in the literature concerning ammonia-fueled ships. This presents a new perspective on BOG processing systems for future NH₃-fueled ships. The direct LP-SCR system was quantitatively compared with the conventional LP-SCR system, considered a re-liquefaction system, from thermodynamic performance and economic perspectives. The rest of this paper is organized as follows: Section 2 explains materials and methodologies for system design, analysis, and evaluation. Section 3 introduces the results and discussion, and Section 4 presents the conclusions of this study.

2. Materials and Methods

2.1. System Design

This paper proposes two innovative systems for treating BOG in ammonia storage tanks on ocean-going ships using ammonia as fuel. The properties of ammonia used in the methodology exist in a saturated liquid state at a temperature of approximately −33 °C at atmospheric pressure, and detailed information is provided in Table 2 [7,8].

Table 2. Comparison of characteristics of ship fuel.

Property	Unit	LNH ₃
LHV	MJ/kg	18.6
Volumetric energy density	MJ/m ³	14,100
Density	kg/m ³	603 (liquid at 25 °C)
Boiling temperature at 1 bar	°C	−33.4
Condensation pressure at 25 °C	bar	9.90

In this study, the operational data of the existing 14,000 TEU ships provided by MAN E&S are used for reference [28]. The operation profile of the target ship according to the Specified Maximum Continuous Rating (SMCR) is provided in Figure 1. It is used as the base information for calculating the Urea consumption or NH₃ consumption of the two LP-SCR systems. The ship’s fuel tank is based on the energy characteristics described in detail in Table 2 [7,8]. We assume the ship is equipped with an IMO Type-A tank, the standard for liquefied gas transport of LPG and ammonia. The design pressure of NH₃ tanks for transporting large volumes of liquefied gas is close to atmospheric pressure. Therefore, the design pressure of the NH₃ tank for the ship being studied is atmospheric, and a system for BOG generated during transportation is required. Additionally, these considerations are critical because of the risk of leakage and the toxicity of ammonia. The quantity of ammonia needed for the two proposed systems was calculated using data derived from a two-stroke engine specific to internal combustion engines. In this study, we propose a re-liquefaction system using ammonia as a refrigerant and an SCR system using ammonia directly to verify the reasonable system. We employed Aspen HYSYS V14 as a thermodynamic analysis tool to determine the system’s feasibility and efficiency utilizing the equation of state (EOS) based on the Peng–Robinson equation.

2.1.1. Basis of Design

According to the literature survey for the calculation of tank size and setting of operating vessels for ammonia propulsion ships, Pacific International Lines recently ordered four 14,000 TEU LNG dual-fuel container ships, which are expected to be delivered from the second quarter of 2024 to the first half of 2025 [29]. Additionally, Hyundai Samho Heavy Industries delivered the CMA CGM Tenere, a 14,861 TEU ship operated by LNG equipped with a 12,000 m³ fuel tank [30]. DNV-GL reported that IMO Type-A tanks can store up to 50% more LNG than IMO Type-C tanks in the same space [31]. Overall, the use of Type-A tanks for ammonia in ships is anticipated to increase, and YARA Eyde, a 14,000 TEU-grade ammonia propulsion container ship, has been ordered [32]. In this way, the actual order for

ammonia propulsion ships is being made. Therefore, this study assumes the 14,000 TEU container vessel as a target ship with an existing IMO type A configuration and design information. The ammonia fuel tank was designed based on a 12,000 m³ LNG fuel tank conversion. The specifications of the ammonia tank are detailed in Table 3 [33].

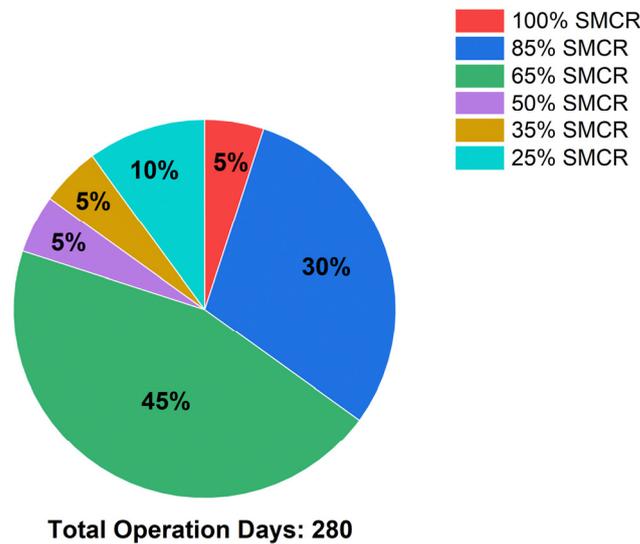


Figure 1. The 14,000 TEU operation profile of the target ship.

Table 3. Ammonia tank sizing.

Property	Unit	Value	Remark
Required energy	GJ	254,160	12000 m ³ LNG fuel tank
NH ₃ LHV	MJ/kg	18.6	
NH ₃ density	kg/m ³	673.1	Liquid saturation at 1.013 bar
Required NH ₃ volume	m ³	20,301	
NH ₃ fuel tank size	m ³	20,715	98% filling limit
BOR	%/day	0.04	
BOG	kg/h	232.4	-

The specifications of the target ship selected in this study are provided in Table 4 [28].

Table 4. Vessel particulars of a 14,000 TEU container ship.

Specification	Unit	Value
Deadweight	Dwt	150,000
Propeller diameter	m	10
Designed ship speed	Knot	23.5

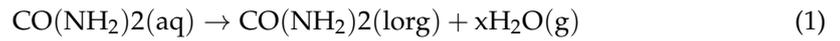
For 14,000 TEU container ships designed to reach a speed of 23.5 knots, MAN’s 12G90ME-C10.5 engine was selected. LP-SCR was applied to satisfy NO_x regulations, and detailed specifications of this engine are summarized in Table 5 [28].

Table 5. Specifications of the applied engine.

Engine	SMCR Point	NCR
12G90ME-C10.5-GI-LPSCR	64,235 kW at 78 rpm	54,600 kW

The present study implements a system based on LP-SCR for the engine under consideration. To meet the NO_x emission regulations, NO_x and reducing agents are converted

into nitrogen (N₂) and water (H₂O) through a chemical reaction in the catalytic reactor. Urea (ammonia water), a reducing agent, is used in the existing SCR to supply ammonia. Generally, urea is decomposed into ammonia and carbon dioxide through three steps, as shown in Equations (1)–(3). The first step in the decomposition is the evaporation of the water contained in the urea. In Equation (2), heat decomposes urea into ammonia and isocyanate (HNCO). In Equation (3), the HNCO produced in Equation (2) is very stable in the gaseous state, but it is readily hydrolyzed on the surfaces of metal oxides to produce ammonia and carbon dioxide. As a result, one mole of urea produces two moles of ammonia and one mole of carbon dioxide [34].



Data on urea consumption for conventional SCR were essential in the design process. Three approaches to ammonia flow were selected. The most conservative values were chosen using three methods: Resolution MEPC.291(71) from the NO_x Technical Code [35], the MAN empirical method [36], and MAN CEAS (Computerized Engine Application System) engine data [37]. Table 6 shows the information necessary to convert urea into pure ammonia.

Table 6. Estimation of required NH₃ flow rate.

Method	Strategy
Resolution MEPC.291(71) (NO _x Tech. Code)	Required NH ₃ flow rate based on NO _x Technical Code for Control of Emission of Nitrogen Oxides from Marine Diesel Engines
MAN empirical method	MAN empirical equation: Urea (L/h) = Engine power (kW) × 0.017
MAN CEAS engine data	Urea consumption from engine data NH ₃ consumption derived from the chemical equation

The calculation formula, according to the IMO NO_x Technical Code, is shown in Equation (4) [35], where u_{gas} is the ratio between the density of an exhaust component and the density of exhaust gas, and according to the NO_x technical code, it is set at 0.001586 [35]. c_{gas} is the concentration of the respective component in the raw exhaust gas, measured in ppm (parts per million). It was assumed to be 1000 ppm due to a lack of experimental data on ammonia engine exhaust and k_{hd} is the NO_x humidity correction factor, set at 0.93 [38]. q_{mgas} is the emission mass flow rate of an individual gas, calculated using Equation (4), as follows:

$$q_{mgas} = u_{gas} \cdot c_{gas} \cdot q_{mew} \cdot k_{hd} \text{ (for NO}_x\text{)} \tag{4}$$

Table 7 shows the detailed calculation results of the ammonia flow rate supplied to the system based on the MAN CEAS engine data and the MAN empirical method [36,37].

Table 7. Ammonia mass flow calculations.

Load (% SMCR)	Power (kW)	Operation Days	Exh. Gas Amount (kg/h)	Exh. Gas Temp (°C)	MAN CEAS Engine Data (kg/h)		MAN Empirical Method (kg/h)		NO _x Tech. Code (kg/h)	
					Urea	Ammonia	Urea	Ammonia	Urea	Ammonia
100	64,235	14	132.3	265	1187.7	269.2	1212.1	274.7	1145.4	259.6
85	54,600	84	116.9	258	1209.9	274.2	1030.3	233.5	1012.1	229.4
65	41,753	126	90.7	259	1132.2	256.6	787.9	178.6	785.2	178.0
50	32,118	14	72.6	270	987.9	223.9	606.1	137.4	628.5	142.5
35	22,482	14	52	295	810.3	183.7	424.2	96.2	450.2	102.0
25	16,059	28	38.4	287	632.7	143.4	303.0	68.7	332.4	75.4

2.1.2. Design of NH₃ Re-Liquefaction System

IMO Type-A tanks have a low design pressure and maintain a low temperature of about $-33\text{ }^{\circ}\text{C}$. As a result, BOG is generated because of external heat entering the tank, leading to fuel loss. Generally, BOG impacts tank pressure, whereas management reduces fuel loss and increases economic efficiency. Meanwhile, ammonia requires careful management for tank pressure regulation, a stable supply of liquid to the engine, and the prevention of external release risks due to its toxicity. The re-liquefaction system is a method for efficiently processing BOG in a confined space. This method has been continuously studied in the existing onboard re-liquefaction system [39,40]. However, in this study, the application of the SCR system was considered according to the combustion characteristics of NH₃ in the IC engine. Therefore, the applicability of this system has been verified through previous studies. A process flow diagram of the re-liquefaction system is illustrated in Figure 2.

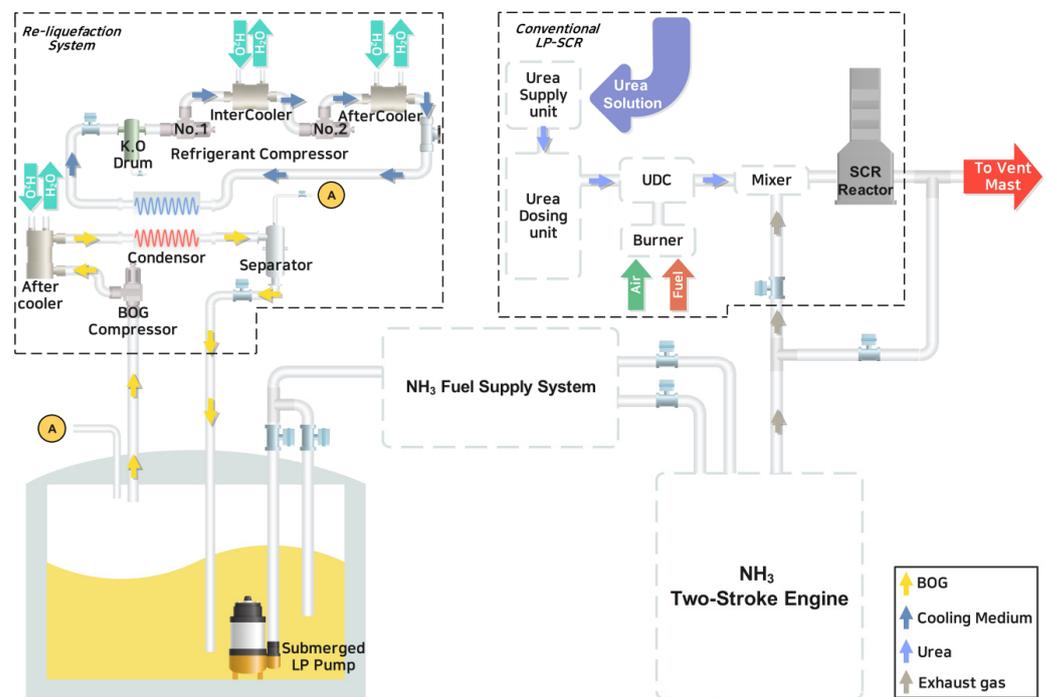


Figure 2. Ammonia re-liquefaction system process flow diagram.

The proposed re-liquefaction system employs a steam-compressed refrigeration cycle. Detailed information about the cycle is provided in Table 8. The BOG generated in the tank is assumed to be hotter than the design temperature of about $-33\text{ }^{\circ}\text{C}$. The gas is compressed to 5 bar in a compressor, cooled to $40\text{ }^{\circ}\text{C}$ in an aftercooler, and then reduced to $-15.4\text{ }^{\circ}\text{C}$ using a condenser, which moves the liquefied ammonia back to the tank through a separator. In the refrigeration cycle, the NH₃ refrigerant undergoes two compressors and heat exchangers: First, it is compressed to 15.5 bar and cooled to $40\text{ }^{\circ}\text{C}$. Then, the temperature and pressure are reduced to $-18.53\text{ }^{\circ}\text{C}$ and 2 bar, respectively, using a J-T (Joule–Thomson) valve before moving to the condenser. Some of the key assumptions applied to the refrigeration cycle design are as follows:

- (1) The minimum temperature of the condenser is $3\text{ }^{\circ}\text{C}$, and the composition of the BOG is 100% NH₃.
- (2) The adiabatic efficiency of the BOG compressor is 75%.
- (3) The NH₃ temperature at the outlet of the aftercooler following the first- and second-stage BOG compressors is maintained at $40\text{ }^{\circ}\text{C}$.
- (4) The pressure drop in the heat exchanger is negligible.

Table 8. Design of onboard re-liquefaction system.

Item	Description
Refrigeration cycle	Vapor compression
Refrigerant	Ammonia
Loop pressure (bar)	2 to 15.5
Mass flow (kg/h)	315
BOG feed temperature (°C)	−20
Suction pressure of BOG compressor (bar)	1.4
BOG composition	100% ammonia

2.1.3. Design of NH₃ Direct LP-SCR System

Existing SCR systems designed to reduce NO_x emissions require additional systems to deliver ammonia to catalysts. However, for ships utilizing ammonia as fuel, this study presents a novel approach in the form of a direct LP-SCR system. BOG generated in the fuel tank allows the removal of the urea supply system essential to the existing SCR system since BOG is supplied directly to the SCR reactor. The system is simplified, and the BOG generated from ship tanks can also be utilized efficiently. Therefore, the main equipment of the Direct LP-SCR proposed in this study is simpler than the equipment configuration of the conventional SCR. It consists of heaters for temperature rise of BOG or LNH₃, and pumps and compressors for supply. In addition, IC engines operated only with NH₃ are free from the problems caused by sulfur in SCR considered in conventional diesel engines [41]. For this reason, it minimizes the design difficulties of applying the actual Direct LP-SCR system. A process flow diagram of the direct LP-SCR system is provided in Figure 3.

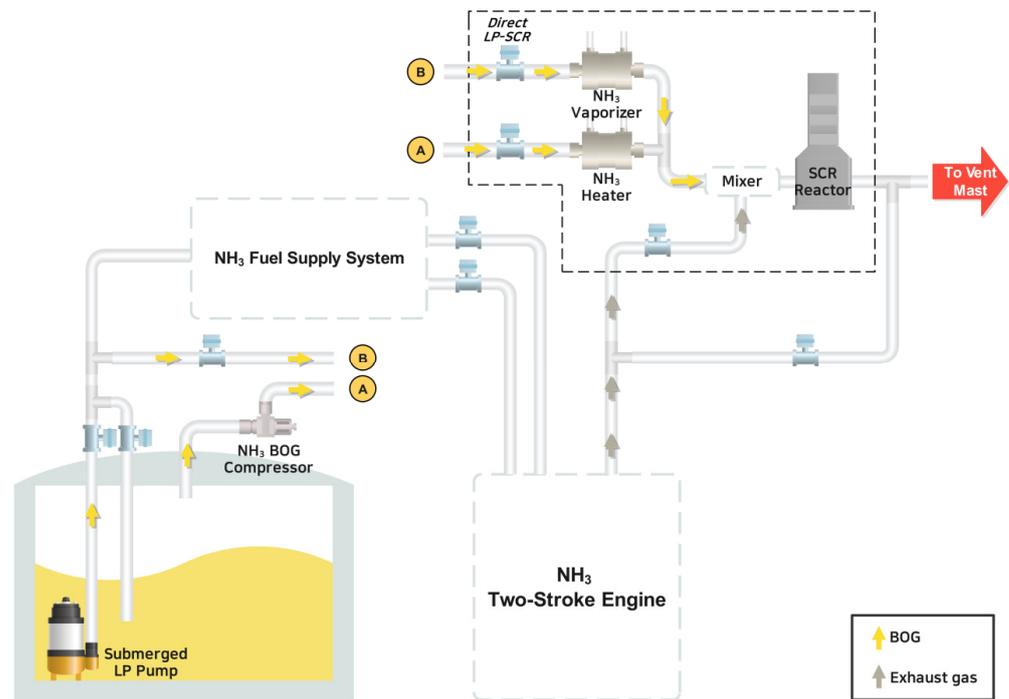


Figure 3. Direct selective catalytic reduction system process.

For the system’s design, the ammonia BOG is generated in a 20,715 m³ tank at 231.6 kg/h. However, the system’s requirement for NH₃ determines the handling of any excess gas, which is subsequently stored in the tank. The initial temperature of the feed gas is assumed to be −20 °C, which is higher than the ammonia storage temperature of approximately −33 °C in the tank. The gas is pressurized to 2 bar via a compressor and supplied to the heater at approximately 7 °C. Thereafter, it is mixed in a mixer with exhaust gas to continue the NO_x reduction process in the reactor. At this stage, the exhaust

gas discharged from the engine is supplied to the mixer at 250 °C or higher and mixed at 235 °C. However, if the amount of NH₃ gas vaporized in the tank is insufficient, NH₃ at −33 °C is supplied to the vaporizer at 2 bar using a pump and vaporized to a temperature of about 10 °C. The applied assumptions are detailed in Table 9 and below:

- (1) The composition of the BOG is 100% NH₃.
- (2) The temperature at the outlet of the NH₃ vaporizer is 10 °C.
- (3) The adiabatic efficiency of the BOG compressor is 75%.
- (4) The suction pressure for both the compressor and the pump is 1.4 bar, and the discharge pressure is 2 bar.
- (5) The pressure drop in the heat exchanger is negligible.

Table 9. Design of onboard direct LP-SCR system.

	Compressor	Pump
Efficiency (%)	75	75
Suction temp. (°C)	−20	−33
Suction pressure (bar)	1.4	1.4

2.2. System Evaluation Methodology

The methodology for comparing the two systems is described in this section. A thermodynamic analysis is conducted for the two proposed systems. It compares the energy consumed by the equipment to operate the re-liquefaction system and the Direct LP-SCR system for the BOG treatment. In addition, the feasibility of the system is compared through an economic analysis.

2.2.1. Thermodynamic Performance of NH₃ Re-Liquefaction System

The thermodynamic performance of the re-liquefaction system is evaluated using specific parameters. The energy required to re-liquefy 1 kg of BOG is determined using the specific energy consumption (SEC), which is defined in Equation (5):

$$SEC = \frac{\dot{W}_{Total}}{\dot{m}_{BOG}} \tag{5}$$

where $\dot{m}_{BOG.comp}$ is energy required for BOG Compressor and \dot{W}_{Pump} is energy required for Submerged Pump. $\dot{W}_{Ref.1}$, $\dot{W}_{Ref.2}$ is energy required for Refrigerant Compressor No. 1 and No. 2 and \dot{W}_{Total} is the energy required for re-liquefaction, calculated using Equation (6):

$$\dot{W}_{Total} = \dot{W}_{BOG.comp} + \dot{W}_{Pump} + \dot{W}_{Ref.1} + \dot{W}_{Ref.2} \tag{6}$$

2.2.2. Thermodynamic Performance of the Direct LP-SCR System

The thermodynamic properties of the direct LP-SCR system are evaluated using specific parameters, where \dot{m}_{BOG+NH_3} is the mass flow rate of the required NH₃. The SEC for calculating the energy required to supply NH₃ to the reactor is defined using Equation (7):

$$SEC = \frac{\dot{W}_{Total}}{\dot{m}_{BOG+NH_3}} \tag{7}$$

The energy required to supply NH₃ supply is calculated using Equation (8).

$$\dot{W}_{Total} = \dot{W}_{BOG.comp} + \dot{W}_{Pump} \tag{8}$$

2.2.3. Economic Evaluation

Economic evaluation is performed for the proposed systems. The cost of NH₃ due to the consumption in the system varies according to price fluctuations. Therefore, the sensitivity analysis was conducted according to the NH₃ price. The minimum price of ammonia is set at USD 250/ton and is analyzed according to USD 500/ton, USD 750/ton, USD 1000/ton, USD 1250/ton, and USD 1500/ton.

The economic evaluation in this study compares the two systems—re-liquefaction (Case 1) and the direct LP-SCR (Case 2)—based on life cycle cost (LCC) using Equation (6) [42]:

$$LCC = \sum_{t=0}^L \frac{C_t}{(1+r)^t} = \sum_{t=0}^0 \frac{CAPEX_t}{(1+r)^t} + \sum_{t=0}^L \frac{OPEX_t}{(1+r)^t} \tag{9}$$

where $CAPEX_t$ is capital expenditure at time t and $OPEX_t$ is operational expenditures at time t . r was applied at 5% as a discount rate, where L is the lifetime of the system and is set to 20 years.

CAPEX covers the initial capital costs associated with equipment installation and the system’s construction. However, because of the absence of a demonstration project for ammonia-powered ships, the initial capital costs are assumed, and the details are provided in Table 10.

Table 10. CAPEX of NH₃ direct LP-SCR and re-liquefaction plus existing LP-SCR.

Case	System	Cost (Million USD)
1	NH ₃ direct LP-SCR	1
2	Re-liquefaction + existing LP-SCR	1.5 + 1.5

OPEX includes operating costs related to energy consumption that occur when the system is in a normal operational state throughout its lifetime. This approach allows us to evaluate the total cost associated with each system from the initial setup to long-term operation. Therefore, the OPEX considerations for the two systems are presented in Table 11.

Table 11. OPEX of NH₃ direct LP-SCR and re-liquefaction plus existing LP-SCR.

Case	OPEX
1	Power cost for operation
2	Urea consumption – (BOG recovery benefit – power cost for re-liquefaction)

However, many marine projects using ammonia as fuel are currently being researched. Therefore, with the lack of empirical data related to operating costs, OPEX is calculated considering only the fuel costs. This study evaluates the cost of ammonia as fuel by calculating the LCC based on its price. Nonetheless, several assumptions have been applied to the proposed systems in the economic analysis:

- The power needed to operate both systems is generated by a 50% efficient generator using NH₃ fuel.
- The fuel consumption required to obtain thermal energy from the re-liquefaction system and direct LP-SCR is negligible.
- The BOG amount is constant at 231.6 kg/h, regardless of the engine load.
- The life expectancy of the target ship is 25 years.
- The number of driving days per year for both systems is 280.
- The price of urea was assumed to be USD 250 per ton.
- The annual discount rate is 5%.

3. Results and Discussion

3.1. Thermodynamic Performance of NH₃ Re-Liquefaction System

For the thermodynamic performance evaluation of the re-liquefaction system, the BOG generated in the tank was chosen as the design point for the facility. The BOG flow rate is 232.4 kg/h, reintroduced into the tank through the re-liquefaction process, with the BOG pressure boosted to 5 bar and the refrigerant pressure during the cycle increased to 15.5 bar. Consequently, the total power consumption required for the re-liquefaction system, including the BOG compressor, re-liquefaction compressor 1, and re-liquefaction compressor 2, is 51.9 kW, as detailed in Table 12.

Table 12. Re-liquefaction system’s power consumption.

Item	Unit	Value
BOG compressor	kW	15.41
Re-liquefaction compressor 1	kW	14.42
Re-liquefaction compressor 2	kW	22.07
Total power	kW	51.90
SEC	kWh/kg	0.223

3.2. Thermodynamic Performance of Direct LP-SCR System

The thermodynamic performance of the direct LP-SCR system is evaluated based on its design by calculating the NH₃ flow rates required for varying engine loads. The quantity of NH₃ within the system is determined through analysis utilizing CEAS engine data, the MAN empirical method, and NO_x Tech. Code. The SEC influences the power demand of the system’s compressor and pump, as the required NH₃ supply varies with the engine load. Detailed numerical information is provided in Tables 13–15.

Table 13. Direct LP-SCR power consumption using MAN CEAS data.

Load (%)	NH ₃ Mass Flow (kg/h)	MAN CEAS		
		Compressor (kW)	Pump (kW)	SEC (kWh/kg)
100	269	3.89	0.0012	0.0144
85	274	3.89	0.0051	0.0142
65	257	3.89	0.0008	0.0151
50	224	3.75	-	0.0167
35	184	3.08	-	0.0167
25	143	2.39	-	0.0167

Table 14. Direct LP-SCR power consumption using the MAN empirical method.

Load (%)	NH ₃ Mass Flow (kg/h)	MAN Empirical Method		
		Compressor (kW)	Pump (kW)	SEC (kWh/kg)
100	275	3.89	0.0014	0.0141
85	234	3.89	-	0.0166
65	179	3.89	-	0.0168
50	137	3.75	-	0.0167
35	96	3.08	-	0.0167
25	69	2.39	-	0.0168

Table 15. Direct LP-SCR power consumption using NOx Tech. Code.

Load (%)	NH ₃ Mass Flow (kg/h)	NOx Tech. Code		
		Compressor (kW)	Pump (kW)	SEC (kWh/kg)
100	256	3.89	0.0009	0.0150
85	226	3.78	0.0006	0.0165
65	175	2.93	0.0003	0.0167
50	140	2.34	-	0.0167
35	101	1.69	-	0.0168
25	74	1.24	-	0.0167

3.3. Economic Evaluation

3.3.1. NH₃ Re-Liquefaction System

To analyze the cost-effectiveness of the re-liquefaction system, a detailed cost analysis encompassing power generation, urea consumption, and the benefits of BOG recovery for BOG re-liquefaction is essential. Thus, the cost analysis was conducted based on the NH₃ price, which correlates with the thermodynamic performance evaluation. The ammonia cost savings achievable through BOG re-liquefaction were estimated to be approximately 11 times higher than the fuel costs required for system operation. Table 16 provides details on the annual NH₃ BOG cost savings enabled by the power and re-liquefaction systems necessary for operation.

Table 16. Re-liquefaction system’s operating costs.

NH ₃ Price (USD/ton)	Power Generation Cost (USD/ton)	BOG Recovery Cost (USD/ton)
250	33,750	390,415
500	67,501	780,829
750	101,251	1,171,244
1000	135,002	1,561,659
1250	168,752	1,952,074
1500	202,502	2,342,488

The results of the three calculations conducted for urea consumption are presented in Figure 4. The method resulting in the highest urea consumption was identified as MAN CEAS DATA and used to determine the most conservative design points. Furthermore, the price of urea for the conventional LP-SCR system was assumed to be USD 250 per ton, with details provided in Table 17. The total urea mass consumptions are 7291, 5417, and 5304 tons using the MAN CEAS data, MAN empirical method, and NO_x Tech. Code, respectively. According to the MAN CEAS data, the annual cost is approximately USD 1.82 million. Therefore, in the context of operating the re-liquefaction system and the conventional LP-SCR system, the higher the NH₃ price, the more economically advantageous the operation becomes.

Table 17. Conventional LP-SCR urea consumption costs.

Load (% SMCR)	Urea Consumption Cost (USD/ton)		
	MAN CEAS	MAN Empirical Method	NOx Tech. Code
100	99,767	101,818	96,212
85	609,790	519,272	510,079
65	855,943	595,637	593,637
50	82,984	50,910	52,797
35	68,065	35,636	37,816
25	106,294	50,910	55,0851
Total	1,822,842	1,354,181	1,346,392

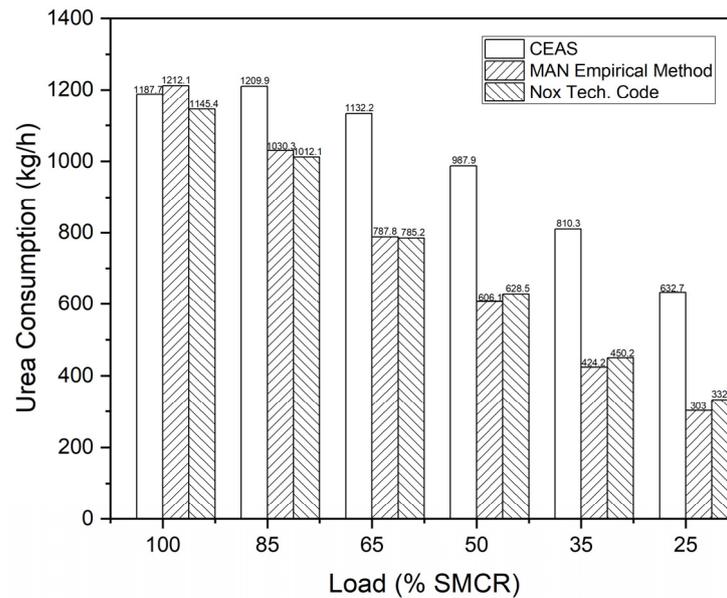


Figure 4. Urea consumption calculation results.

3.3.2. Direct LP-SCR System

Additionally, the analysis of the NH₃ consumption within the system is illustrated in Figure 5, serving as the basis for determining design points to analyze the energy and cost required by the system. As a result, the cost inputs for the direct LP-SCR system were examined. The energy consumption costs of the BOG compressor and the submerged pump in the system were calculated, as detailed in Table 18. The energy consumption cost varies depending on the amount of NH₃ used by the system. However, the analysis of the annual operating costs of the system using the three methods shows that the cost of the NH₃ used for power generation in the direct LP-SCR system is approximately 1/14 that of Case 1, presenting a significant advantage in terms of operating costs.

The consumption of NH₃, a reducing agent that reacts with NO_x in the system, is provided in detail in Table 19. The amounts of NH₃ required in the system are 1653 tons, 1228 tons, and 1202 tons. Compared with the urea price of the conventional LP-SCR system, it was determined to have economic feasibility when the NH₃ price was lower than USD 1000/ton.

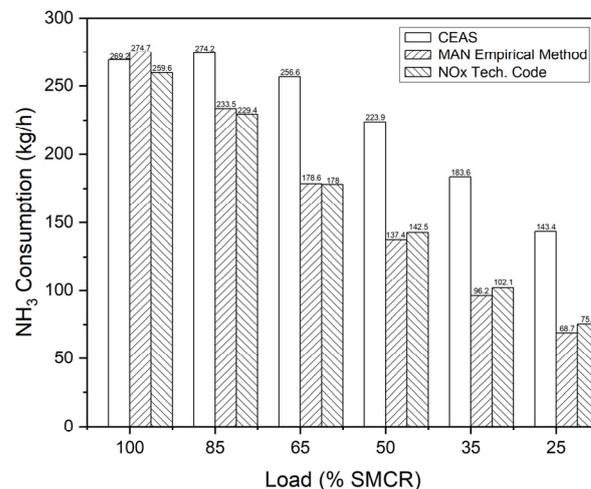


Figure 5. NH₃ consumption calculation results.

Table 18. Direct LP-SCR system’s operating costs.

NH ₃ Price (USD/ton)	Power Generation Cost (USD/ton)		
	MAN CEAS	MAN Empirical Method	NO _x Tech. Code
250	2400	1962	1931
500	4800	3924	3863
750	7200	5886	5794
1000	9600	7848	7725
1250	12,000	9810	9656
1500	14,400	11,772	11,588

Table 19. Direct LP-SCR system’s NH₃ consumption costs.

NH ₃ Price (USD/ton)	NH ₃ Consumption [USD/ton]		
	MAN CEAS	MAN Empirical Method	NO _x Tech. Code
250	413,178	306,948	305,182
500	826,355	613,896	610,364
750	1,239,533	920,843	915,547
1000	1,652,710	1,227,791	1,220,729
1250	2,065,888	1,534,739	1,525,911
1500	2,479,065	1,841,687	1,831,093

3.3.3. LCC of NH₃ Direct LP-SCR vs. Re-Liquefaction + Conventional LP-SCR

Figure 6 illustrates the comparison of the costs associated with the two systems proposed in this study. For the existing LP-SCR system combined with the re-liquefaction system, the initial facility investment cost was assumed to be USD 1.5 million for each system. Additionally, the total annual cost of the system was evaluated through an analysis of operating costs. As the price of NH₃ increases, the maintenance cost of the system decreases, ranging from USD 11.37 million to USD 1.19 million. In contrast, for the direct LP-SCR system, the initial facility investment cost was estimated to be USD 1 million, as it required less equipment than the existing LP-SCR system. The input of NH₃ fuel into the system was analyzed using MAN CEAS data, the most conservative approach. Although the LCC increases with rising costs, it remains lower than that of the existing LP-SCR system combined with the re-liquefaction system. Annually, the facility investment and operating costs range from USD 1.0137 million to USD 1.0822 million. Based on this study, the direct LP-SCR system is anticipated to be economical once the commercial use of combustion engines utilizing NH₃ as fuel in carriers and propulsion ships is established.

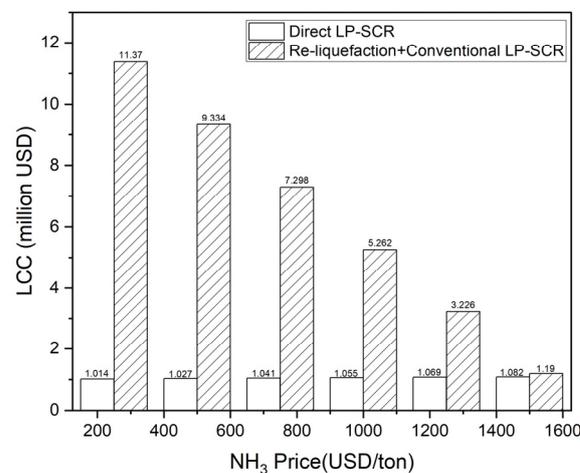


Figure 6. LCC comparison of two systems.

4. Conclusions

This study aims to address the treatment of BOG generated within the tanks of a ship utilizing NH₃ as fuel. To this end, a re-liquefaction system, an existing SCR system, and an NH₃ direct LP-SCR system were proposed and assessed for technological and economic feasibility. The re-liquefaction system operates on a steam-compression refrigeration cycle using NH₃ as the refrigerant. The SEC of this system, 0.223 kWh/kg, was determined based on the power consumption of the three compressors to assess the energy utilized within the system. In addition, we conducted an economic analysis of the existing LP-SCR system integrated with the re-liquefaction system. Furthermore, the urea flow rate needed for NO_x removal was computed using CEAS engine data, the MAN empirical method, and the NO_x Technical Code, with costs estimated at USD 250 per ton. As the price of NH₃ increases, the profitability of the re-liquefaction system also increases.

A direct LP-SCR system was proposed and analyzed for the treatment of BOG. In this system, NH₃ is directly supplied as a reducing agent for NO_x removal in the exhaust gas from the NH₃ fuel tank. This is accomplished by boosting the BOG from 1.4 bar and −20 °C to 2 bar using a compressor. Alternatively, if the amount of NH₃ is insufficient, liquid NH₃ from the tank is supplied through a pump. The flow rate, adjusted according to the engine load, and the SEC were analyzed. According to MAN CEAS data, the most conservative method, the system consumes 1653 tons of NH₃ annually. Additionally, system operation requires a compressor and a submerged pump, leading to an annual NH₃ fuel consumption of 9.6 tons. Furthermore, through thermodynamic analysis, the costs of power generation and the reducing agent required by the system were evaluated in relation to the price of NH₃. According to the LCC analysis, the direct LP-SCR system's annual cost is more cost-effective when integrated with the re-liquefaction system.

As a result, the direct LP-SCR system offers relatively stable operational costs without any significant variability due to changes in NH₃ prices for ships utilizing NH₃ as fuel. Three methodologies were used to determine the necessary ammonia flow rate for the LP-SCR system to ensure reliable analysis results. Furthermore, in the NH₃ direct LP-SCR system, since the need for core equipment is minimal, power consumption for supplying NH₃, whether as a BOG or a liquid, is comparatively low. According to the LCC analysis, the NH₃ direct LP-SCR system is more cost-effective than the combination of re-liquefaction and the existing SCR system. However, the initial capital cost for the existing LP-SCR system is higher when comparing CAPEX between the re-liquefaction system, the existing LP-SCR system, and the direct LP-SCR system. If only operating costs are considered, excluding initial capital costs, the re-liquefaction system is deemed economical when the price of NH₃ exceeds USD 1500 per ton.

NH₃ is emerging as a major energy source due to the strengthening environmental regulations. In the previous study, the study on NH₃ BOG treatment proposed a BOG re-liquefaction system integrated with the fuel supply system in an ammonia propulsion ship. According to this study, the feasible solution is proposed for solving the problems about NO_x emission and BOG treatment, which are main concerns of NH₃-fueled ships. The direct LP-SCR system is an attractive solution for using NH₃ fuel. It is applicable to the 14,000 TEU container ships considered in this study, as well as ships using internal combustion engines with NH₃ fuel. However, further research is still needed to commercialize and optimize the BOG treatment system. We hope that the results of this study will be a useful reference for supporting the research and development of ships using NH₃ as fuels.

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Abbreviations

The following abbreviations are used in this manuscript:

GHG	Greenhouse Gas
IMO	International Maritime Organization
MEPC	Marine Environment Protection Committee
CO ₂	Carbon Dioxide
NO _x	Nitrogen Oxide
H ₂	Hydrogen
NH ₃	Ammonia
HFO	Heavy Fuel Oil
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
LH ₂	Liquid Hydrogen
LHV	Lower Heating Value
IEA	International Energy Agency
ABS	American Bureau of Shipping
LR	Lloyd's Register
KR	Korean Register
IGC	International Code for Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF	International Code of Safety for Ships using Gases or other Low-flashpoint Fuels
PEMFC	Polymer Electrolyte Membrane Fuel Cell
SOFC	Solid Oxide Fuel Cell
IC	Internal Combustion
NPV	Net Present Value
SWIFT	What-If Technique
HAZID	Hazard Identification Study
LP-SCR	Direct-low Pressure Selective Catalytic Reduction
SMCR	Specified Maximum Continuous Rating
EOS	Equation of State
ppm	Parts Per Million
SEC	Specific Energy Consumption
LCC	Life Cycle Cost
CAPEX	Capital Expenditure
OPEX	Operational Expenditure

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