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## Optimizing LNG efficiency by implementing reliquefaction technology to reduce boil-off gas and enhance profitability

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### Abstract

Run an analysis of this abstract, focusing on its relevance, format, flow, and coherence. Technological advancements compel companies to enhance the efficiency of their business operations, including those in the oil and gas sector. Natural gas, particularly Liquefied Natural Gas (LNG), is a vital commodity in significant demand. A primary challenge within the LNG supply chain is minimizing the losses caused by gas evaporation (boil-off gas) during distribution and reception. This study proposes the implementation of a reliquefaction plant on a 170,000 m<sup>3</sup> Floating Storage and Regasification Unit (FSRU). Through this innovative approach, this study aims to optimize the utilization of Boil-off Gas (BOG) and augment the company's revenue. The results indicate that the liquefaction plant can reduce BOG by 77 percent, significantly outperforming conventional methods. The economic feasibility analysis revealed a Net Present Value (NPV) of \$82,892,970 and an Internal Rate of Return (IRR) of 25 percent, suggesting substantial profit potential. Furthermore, the reliquefaction of 1,777.6 MMBtu BOG per day could potentially increase the company's revenue by IDR 94,078,421,500 annually, surpassing initial estimates. This study contributes significantly to the advancement of more efficient LNG management technologies, providing concrete solutions to minimize energy waste and enhance profitability within the LNG industry. These findings facilitate the implementation of similar technologies at other LNG facilities, potentially transforming industry-wide practices.

### Keywords:

Liquefied natural gas, reliquefaction plant, floating storage and regasification unit, boil-off gas, economic feasibility.

### 1 Introduction

The rapid growth of the industry today is causing more people to depend on energy, including natural gas. In facing the industry 5.0 trend, businesses are developing various business process strategies to optimize their supply chain, especially in the gas distribution sector for industrial and residential networks.

Natural gas is the third-largest natural resource reserve in the world, followed by coal and oil. However, their utilization is still limited owing to challenges in transportation and storage, which limits their widespread adoption [1]. Liquefied Natural Gas (LNG) is a viable solution because it has a small storage volume (1/600 of normal conditions) and a high calorific value of 12,000 kcal/kg [2], [3].

In LNG facilities, particularly Floating Storage and Regasification Units (FSRUs), one critical challenge is managing the Boil-off Gas (BOG). BOG occurs naturally during LNG storage and transportation and has significant economic and environmental implications [4]. The Boil-off Rate (BOR) varies depending on the vessel size and operating conditions, ranging from 0.1-0.15% per day in large carriers to 0.2-0.6% per day in smaller vessels [5] [6].

Recent studies have shown that implementing reliquefaction systems can effectively reduce the BOG by up to 82% [4], [7]. However, the application of reliquefaction technology to FSRUs presents the unique challenges of spatial constraints and economic feasibility considerations [8]. Although several studies have demonstrated the potential of reliquefaction for BOG utilization [9], [10], there is limited research addressing the specific design requirements for FSRUs and comprehensive economic feasibility analysis.

This study aims to fill this gap by focusing on two important areas: first, the design of a space-efficient reliquefaction plant adapted specifically for FSRU utilization, and second, a detailed economic assessment to ascertain the feasibility of its implementation. The main contribution of this research is the development of an optimized design for a reliquefaction system, which aligns technical constraints with economic feasibility. With this approach, this study offers a practical solution for managing BOG in floating LNG facilities.

Using a combination of technical design optimization and economic analysis, this study provides a robust framework for making decisions regarding the deployment of reliquefaction systems in FSRUs. The methodology and findings presented herein are expected to provide valuable insights for both academic investigations and practical applications in LNG facility operations. Although specific details regarding the research year and location cannot be disclosed due to the proprietary nature of the data, it does not diminish the relevance or applicability of the research findings to similar facilities and operational contexts.

### 2 Materials and Methods

Utilizing unutilized Boil-off Gas (BOG) as the research subject, this quantitative descriptive study was conducted within a natural gas distribution company. BOG was chosen due to its currently high levels and underutilization, presenting an opportunity to increase company revenue. Data for the research objectives were acquired using documentation approaches, including BOG data, send out data, temperature data, pressure data, and gas composition data. The research process, from problem formulation to decision-making, is depicted in Fig. 1, which illustrates the sequential steps involved.

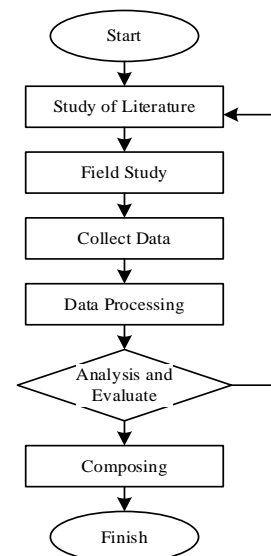


Fig. 1. Flow chart research.

The data were analyzed in several stages. The first stage involves analyzing the average Boil-off Gas (BOG) in the LNG tank. The second stage of the analysis include BOG calculations, compressor capacity, cooling capacity, pipe diameter, choice of reliquefaction plant type, and economic analysis. The equations utilised in the analysis are Eq. 1- Eq. 5 [2], [5], [11]:

$$PV = nRT \quad (1)$$

where:

$P$  = Pressure

$V$  = Volume

$n$  = Moles of gas

$R$  = Constant

$T$  = Temperature

$$dn = \frac{\sqrt{4Q}}{nxv} \quad (2)$$

where:

$n$  = Period

$dn$  = Minimum diameter

$Q$  = Flowrate (kg/h)

$v$  = Velocity (m/s)

$$r = \frac{n\sqrt{P_{out}}}{P_{in}} \quad (3)$$

where:

$r$  = Compressor ratio

$n$  = Stage

$P_{out}$  = Pressure out

$P_{in}$  = Pressure in

$$IRR = \sum_{t=0}^n \left[ \frac{A_t}{(1+r)^t} \right] = 0 \quad (4)$$

where

$n$  = Period

$r$  = Interest rate

$$Net\ Present\ Value(NPV) = \sum_{t=0}^n \frac{At}{(1+k)^t} \quad (5)$$

where:

$k$  = Discount rate

$At$  = Cash flow

### 3 Results and Discussion

This research aims to analyze data related to tank pressure induced by the development of Boil-off Gas (BOG) using a descriptive quantitative method. The analysis results are presented in numerical form with interpretations based on the findings. The analysis identifies a simple solution to overcome the BOG tank pressure, which involves burning gas in the Gas Combustion Unit (GCU). However, this solution has some drawbacks, including the loss of potential financial benefits for the company since the burned BOG cannot be reused, and the negative environmental impact caused by pollutant emissions from the combustion process. Therefore, to examine the BOG tank pressure issue, this research will investigate alternate options that are more sustainable and environmentally friendly, while also considering economic and operational aspects.

#### 3.1 Average Boil-off Gas

Based on the analysis of the assessed year on the FSRU, as indicated in Fig. 2, the BOG level in the tank still exceeds the recommended maximum limit of 0.15% [6]. This is an essential issue because unutilized or unburned BOG in the gas combustion unit generates zero revenue for the company. One solution is to

establish a reliquefaction plant [12]. This instrument was used to re-liquefy the BOG generated in the LNG tank by cooling it to -160°C with N<sub>2</sub>.

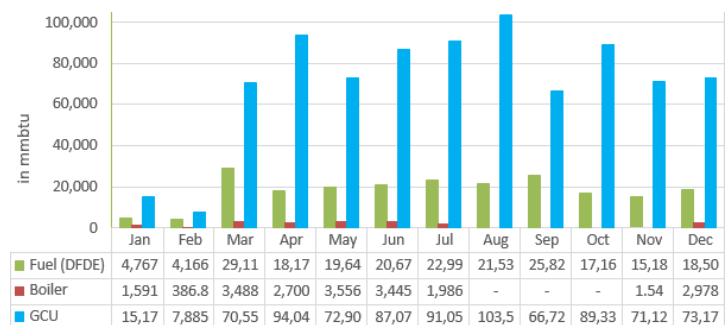


Fig. 2. Boil-off Gas (BOG) in a year.

The utilization of Boil-off Gas (BOG) at the plant studied was divided into three different allocations, as shown in Fig. 2. First, BOG is utilized as fuel for Dual-Fuel Diesel Energy (DFDE) requirements. Second, BOG was used as fuel in the boiler. Third, the unutilized BOG is piped into a Gas Combustion Unit (GCU). In this research, BOG is divided into two categories: BOG used for operational purposes and BOG that has not been utilized. The unutilized BOG was obtained by calculating the resulting BOG value and then subtracting the BOG value required for equipment operation. We then focused on the BOG route before it was piped as fuel to the gas combustion unit.

As shown in Table 1, there is significant potential for optimizing BOG utilization. According to the data, the total volume of unused BOG in one year was 842.621 MMBtu. This is equivalent to rates of 70.218 MMBtu per month, 2.308 MMBtu per day, and 96.18 MMBtu per hour.

Table 1. Average unutilized BOG

Month	Unutilized BOG (MMBtu)
January	15,175
February	7,885
March	70,557
April	94,048
May	72,906
June	87,074
July	91,053
August	103,560
September	66,725
October	89,337
November	71,123
December	73,178
Total	842,621
Average (month)	70,218
Average (day)	2,308.55
Average (hour)	96.1896

The highest BOG volume occurred in August, which coincided with the minimum LNG shipment period. This condition, known as "hotel mode," causes FSRU to experience longer periods of expansion, resulting in more BOG.

#### 3.2 Hysys

As previously stated, designing a reliquefaction facility necessitates thorough evaluation of various elements, such as the type of compressor, pipe specifications, and coolant usage. This is closely related to the composition of Boil-off Gas (BOG) produced from the LNG tank and routed to the GCU. The composition of BOG to be processed is shown in Table 2.

The next step is to select the appropriate compressor type based on the determined BOG composition. In this research, Hysys is used as a tool to select a compressor that meets the requirements of the plant that will be used.

Table 2. BOG composition

Operating mode	Composition	Send out	Hotel mode
Gas composition	Methane	96.5155 %	96.363 %
	Ethane	2.5818 %	2.788 %
	Propane	0.5271 %	0.567 %
	I-Butane	0.1034 %	0.096 %
	N-Butane	0.1280 %	0.118 %
	I-Pentane	0.0241 %	0.023 %
	N-Pentane	0.0026 %	0 %
	CO2	0.0044 %	0 %
	Nitrogen	0.1131 %	0.045 %
Inlet temperature	°C	-160	-160
Inlet pressure	Bar	1	1
Discharge pressure	Bar	76.53	76.53
Discharge temperature	°C	18.3	18.3

A proper compressor must be selected to ensure that the reliquefaction facility runs properly. This is because the compressor is responsible for providing BOG at the appropriate mass flow rate. Fig. 3 and Fig. 4 show that for BOG processing in a reliquefaction plant with a known composition, the compressors employed in the sendout mode and hotel mode must be capable of handling BOG mass flows of 6,232 kg/h and 6,731 kg/h, respectively.

Vapour	1,0000
Temperature [C]	-160,0
Pressure [kPa]	100,0
Molar Flow [kgmole/h]	370,2
Mass Flow [kg/h]	6232
LiqVol Flow [m3/h]	19,38
Molar Enthalpy [kJ/kgmole]	-7,622e+004
Molar Entropy [kJ/kgmole-C]	150,7
Heat Flow [kJ/h]	-2,822e+007

Fig. 3. Hysys sendout mode.

Vapour	1,0000
Temperature [C]	-160,0
Pressure [kPa]	100,0
Molar Flow [kgmole/h]	398,4
Mass Flow [kg/h]	6731
LiqVol Flow [m3/h]	20,82
Molar Enthalpy [kJ/kgmole]	-7,584e+004
Molar Entropy [kJ/kgmole-C]	150,6
Heat Flow [kJ/h]	-3,022e+007

Fig. 4. Hysys hotel mode.

### 3.2.1 Compressor Type Design

Based on the results of the Hysys simulation, it was discovered that the BOG masses for the sendout and hotel modes were 6,232 kg/h and 6,731 kg/h, respectively, allowing for the use of a similar compressor type. Table 3 shows the selection of compressor types based on the debit capacity for achieving BOG.

Table 3. Compressor type based on Hysys

Type	Series-3
Flowrate	7,000 kg/h
Inlet pressure	4.8 Bar
Outlet pressure	100 Bar
Suction temperature	-170°C ~ 45°C
RPM	4,000
Power	5,360 hp

Based on the existing tables and references, the Series-3 compressor was determined to be acceptable for this application, with a maximum BOG flow rate of 7,000 kg/hour. This capacity

exceeds the BOG mass flow requirements for both operating modes, ensuring safe and efficient operation of the Series-3 compressor. The selection of this compressor type is also appropriate for the proposed reliquefaction plant, as its flowrate capacity is equal to that of the Series-3 compressor, as shown in Fig. 5.



Fig. 5. Compressor Series-3.

### 3.2.2 Pipe Design

Based on the calculations from Eq. 2, the minimum pipe diameter was determined to be 16 inches (rounded from 15.99 inches). This pipe complies with the ASME B36.19M standard and is made of stainless steel [13], [14]. The selection of stainless steel is based on the fluid flowing through the pipe, which is natural gas. The pipeline specifications are listed in Table 4.

Table 4. Pipe specification

Name	Specifications
NPS	16
DN	400
Schedule No.	5S
Outside diameter (in)	16
Wall thickness (in)	0.165
Plain (mass)	27.93
Weight (kg/m)	41.56
Material	Stainless steel

### 3.2.3 Cooling Type Selection

The cooling material utilized in the reliquefaction plant requires the capability to chill the BOG to a temperature below -160°C, because this temperature threshold allows the BOG to transition back into a liquid phase. Nitrogen (N<sub>2</sub>) is an appropriate liquid for cooling the BOG to -160°C. Nitrogen has several advantages including its extraordinary cooling ability, which allows it to reach temperatures as low as -195.8°C, which makes it very effective in cooling boiling gas (BOG). Furthermore, N<sub>2</sub> is easily accessible and widely distributed, making it a viable option [15].

According to Table 5, all N<sub>2</sub> coolers that use direct surface cooling are suitable for use. Nevertheless, the design of the reliquefaction plant in this research will employ a variant with a pressure of 6 bar, as it is compatible with the previously chosen compressor with an inlet pressure of 4.8 bar.

Table 5. N<sub>2</sub> type

Direct surface cooling N <sub>2</sub> type		
Pressure (bar)	Boiling temperature (°C)	Heat of vaporization (kJ/kg)
1	-195.8	5,592.8
3	-185.1	5,157.5
6	-176.6	4,720.3
9	-170.8	4,351.5
12	-166.3	4,005.4

### 3.2.4 Selection of Reliquefaction Plant Technology

The variety of types and characteristics of reliquefaction plants, as well as different fluids, necessitate the selection of appropriate technologies. The function of this facility is to liquefy unused BOG and redirect it back to the LNG tank. Furthermore, reliquefaction is also aimed at preventing the degradation of LNG, ensuring that the composition of LNG remains consistent throughout the flow until it re-enters the tank. The required capacity for this reliquefaction plant can be determined based on the maximum BOG value of 8,278.88 MMBtu/day and the highest pressure of 6,462.43 MMBtu/day.

The proposed reliquefaction plant employed a Brayton Cooling Cycle with N<sub>2</sub> as the coolant. The Brayton Cooling Cycle is known for its minimalist, robust design that minimizes the need for additional equipment [16]. However, this reliquefaction plant requires a Gas Combustion Unit (GCU) to convert the BOG from the cargo tank back to LNG. Fortunately, the FSRU already has a GCU, eliminating the need for additional investment and redesigning the gas combustion unit.

Based on the data shown in Table 6, two types of plant reliquefaction can be considered. Both types of plants have been used in several FSRUs with a capacity of 170,000 m<sup>3</sup>, making them both suitable for consideration [17]. However, in this study, the MARK III plant type was selected for reliquefaction because of its lower energy consumption of 5500 kW, compared to the EcoRel type, which has an energy consumption of 6000 kW.

### 3.3 Reliquefaction Plant Design

The process of choosing an appropriate Piping and Instrumentation Design (P&ID) begins with identifying the type of reliquefaction facility. Prior to the planning of the reliquefaction installation, it is imperative to conduct calculations to ascertain the appropriate compressor size using Eq. 3.

It is assumed that the BOG compressor uses two stages and the N<sub>2</sub> compressor uses three stages because the reciprocating

compressor has a compression ratio of 3–4 [18]. Therefore, the BOG compressor achieves a compression ratio (r) of 4, whereas the N<sub>2</sub> compressor achieves a ratio of 3. These values remained within the acceptable range for reciprocating compressors. Further consideration must be given to the refrigerant fluids. Two refrigerants are required to cool the two gases (BOG and N<sub>2</sub>) that pass through the reliquefaction facility.

Fig. 6 illustrates the P&ID reliquefaction plant installed at the FSRU. This design uses two BOG compressors to flow the BOG into the BOG condenser. The liquefied BOG then flowed to the separator and returned to the LNG tank. The cooling process in the BOG condenser is performed using N<sub>2</sub> fluid, which has undergone a process in the heat exchanger. BOG that exceeds the capacity of the separator is directed toward the GCU to be burned.

Table 6. Reliquefaction plant type

Variable	Mark III	EcoRel
Supplier	HGS	Cryostar
Operational cycle	Brayton	Brayton
Refrigerant	N <sub>2</sub>	N <sub>2</sub>
Work pressure	58-12 bar	47-9.5 bar
Expansion temp	-166.3°C	168°C
BOG cycle	Centrifuge	Centrifuge
Compressor type	Series-3	Series-2
N compressor	4.8 bar	4.8 bar
Compressor temperature	Room temperature	-120°C
Suction	Interm refrigerations	Interm refrigerations
Observation	Sea water	N <sub>2</sub>
Pipe diameter	16 inch	16 inch
Capacity liquefactions	7000 kg/h	7000 kg/h
Power	5500 kW	6000 kW

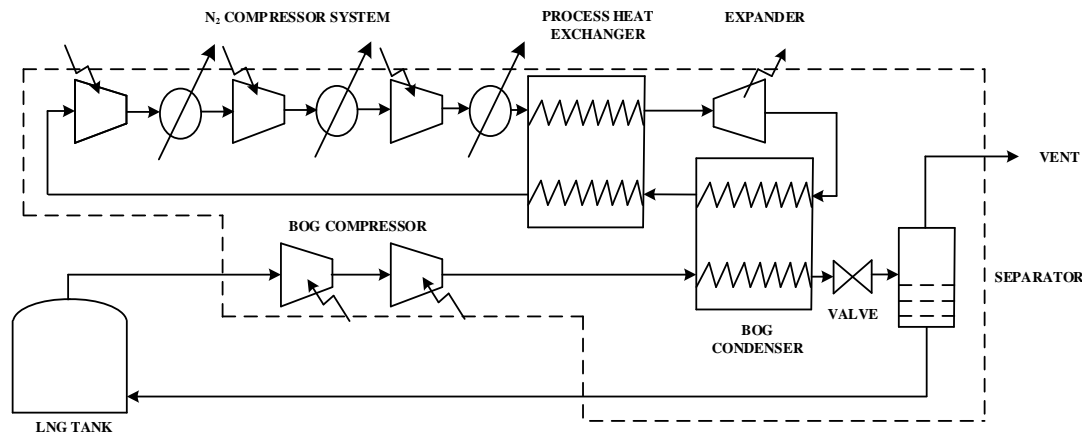


Fig. 6. Reliquefaction plant P&ID.

### 3.4 Unutilized BOG

Data regarding the varying BOG utilized were collected in various scenarios, including hotel mode (idle), low gas supply (<100 MMSCF), normal gas supply (100–200 MMSCF), and maximum gas supply (>200 MMSCF) [10]. Variations in LNG shipping conditions enable the company to ascertain the BOG volume that is feasible for liquefaction and calculate its revenue value. Utilizing a reliquefaction plant based on Aspen Hysys and referring to the existing data, the BOG efficiency can be computed.

As shown in Fig. 7, column a indicates that the unutilized BOG value was 2308.6 MMBtu/day before using the reliquefaction plant. However, after using the reliquefaction plant (column b), the unutilized BOG value is reduced to 531 MMBtu/day. Thus, it can be seen that the use of reliquefaction plants can reduce BOG by 77% from the previous value.

Heat exchanger costing				
Name	a	b	c	HT Config
Default	2308.6	531.0	0.2	Heat Exchanger

Fig. 7. Heat exchanger costing.

### 3.5 Economic Analysis

Conducting an economic analysis of the investment in a reliquefaction plant is the next step, after determining the amount of BOG that can be reused. Calculations to assess the investment and operating costs of a reliquefaction plant for recycling the BOG produced in LNG tanks will be part of the analysis. Investment calculations will also focus on NPV and IRR [8].

This preliminary economic analysis was conducted in accordance with the Standard No. 33E-14 of the Association for the Advancement of Cost Engineering (AACE International) [19]. An economic analysis was carried out with the assumption that the

USD exchange rate was IDR 14,500, gas price of US\$ 10 per MMBtu based on Indexmundi (Indonesia LNG), where this value fluctuated all the time, and the OPEX escalation determination of 2%, referring to the Minister of Finance Regulation [20] and Minister of Energy and Mineral Resources Regulation No. 58 of 2017 [21], as well as amendments to the Minister of Energy and Mineral Resources Regulation No.14 of 2019 [22]. The results of the economic analysis are considered feasible if the NPV value is greater than zero, and the IRR is higher than the 4.5% interest rate set by Bank Indonesia.

Construction costs for the reliquefaction plant totaled \$21,390,166, as shown in Table 7. Operating costs accounted for 2% of CAPEX, or \$427,803. This calculation takes into account an inflation rate of 8% and a currency exchange rate of IDR 14,500 per US dollar. Factory income is obtained from the sale of disbursed BOG. The amount of BOG sold was calculated by subtracting the amount consumed during the disbursement process. Table 8 shows that the volume of BOG that can be liquefied and sold per day is 1,777.6 MMBtu with a selling price of \$10 per MMBtu.

Table 7. CAPEX component

Component	Amount	Price	Total
Compressor	5 units	\$689,000	\$3,445,000
Cooler	2 units	\$863,000	\$1,726,000
Separator	1 units	\$749,000	\$749,000
Pipe	40 m	\$5,229	\$209,160
Elbow	6 units	\$4,759	\$28,554
Valve	4 units	\$8,863	\$35,452
Expander	1 units	\$197,000	\$197,000
Installation cost	1	\$10,000,000	\$10,000,000
Operational cost	1	\$5,000,000	\$5,000,000
Total cost			\$21,390,166

Table 8. Components of economic studies

Component	Value
CAPEX	\$21,390,166
OPEX	\$427,803
US inflation	8%
Course	IDR14,500
BOG (day)	1,777.6 MMBtu
Price	\$10

Economic analysis for the purpose of this research was carried out using Microsoft Excel and Eq. 4 and Eq. 5. The results show an NPV of \$82,892,970, IRR of 25%, and 8% discount rate.

### 3.6 Total Reliquefaction Plant Revenue

The revenue that will be obtained after the plant is running, provided that the reliquefaction plant is economically feasible. The annual revenue of the reliquefaction facility at the FSRU was estimated to be \$6,488,167, which is equivalent to IDR 94,078,421,500, as shown in Table 9. The revenue was generated through the resale of liquefied BOG at a price of \$10 per MMBtu for 365 days, with a daily volume of 1,777.6 MMBtu. The calculated monthly average plant reliquefaction was predicted to reach \$540,681, which is equivalent to the IDR. 7,839,868,458.

Table 9. Total revenue from the use of reliquefaction plant

Total BOG disbursed	Income
MMBtu	\$ /Yr
1,777.6	6,488,167
	94,078,421,500

## 4 Conclusion

The objective of this research is to optimize the utilization of Boil-off Gas (BOG), which is an important challenge in the Liquefied Natural Gas (LNG) supply chain, by integrating a reliquefaction plant in a Floating Storage and Regasification Unit

(FSRU) with a capacity of 170,000 m<sup>3</sup>. The research results show that the reliquefaction plant can reduce BOG by up to 77%, with the ability to reliquefy BOG of 1,777.6 MMBtu per day. Economic feasibility analysis shows a Net Present Value (NPV) of \$82,892,970 and an Internal Rate of Return (IRR) of 25%. This BOG disbursement can increase the company's income by \$6,488,167 per year. Thus, the use of the reliquefaction plant has proven to be effective in optimizing BOG and has a positive impact in increasing company revenue. This study makes an important contribution to the development of efficient LNG management technologies and strategies.

## References

- [1] M. Kalikatzarakis, G. Theotokatos, A. Coraddu, P. Sayan, and S. Y. Wong, "Model based analysis of the boil-off gas management and control for LNG fuelled vessels," *Energy*, vol. 251, p. 123872, 2022.
- [2] D. Kim, C. Hwang, T. Gundersen, and Y. Lim, "Process design and economic optimization of boil-off-gas reliquefaction systems for LNG carriers," *Energy*, vol. 173, pp. 1119–1129, 2019.
- [3] Y. Li, X. Chen, and M.-H. Chein, "Flexible and cost-effective optimization of BOG (boil-off gas) reconcondensation process at LNG receiving terminals," *Chemical engineering research and design*, vol. 90, no. 10, pp. 1500–1505, 2012.
- [4] S. K. Kochunni, P. Ghosh, and K. Chowdhury, "Optimization of UA of heat exchangers and BOG compressor exit pressure of LNG boil-off gas reliquefaction system using exergy analysis," presented at the IOP Conference Series: Materials Science and Engineering, IOP Publishing, 2015, p. 012090.
- [5] J. W. Moon, Y. P. Lee, Y. Jin, E. S. Hong, and H. M. Chang, "Cryogenic refrigeration cycle for re-liquefaction of LNG boil-off gas," International Cryocooler Conference, 2007.
- [6] B. M. Beladjine, A. Ouadha, and L. Adjlout, "Performance analysis of oxygen refrigerant in an LNG BOG reliquefaction plant," *Procedia Computer Science*, vol. 19, pp. 762–769, 2013.
- [7] C. K. Pil, M. Rausand, and J. Vatn, "Reliability assessment of reliquefaction systems on LNG carriers," *Reliability Engineering & System Safety*, vol. 93, no. 9, pp. 1345–1353, 2008.
- [8] K. Kim, K. Park, G. Roh, and K. Chun, "Case study on boil-off gas (BOG) minimization for lng bunkering vessel using energy storage system (ESS)," *Journal of Marine Science and Engineering*, vol. 7, no. 5, p. 130, 2019.
- [9] T. Guo *et al.*, "Optimization and control strategy of BOG reliquefaction process for LNG vessels," *International Journal of Refrigeration*, vol. 153, pp. 253–265, Sep. 2023, doi: 10.1016/j.ijrefrig.2023.05.021.
- [10] M. Al-Breiki and Y. Bicer, "Comparative cost assessment of sustainable energy carriers produced from natural gas accounting for boil-off gas and social cost of carbon," *Energy Reports*, vol. 6, pp. 1897–1909, 2020.
- [11] P. Tomasz Włodek MSc, "Prediction of boil off rate in liquefied natural gas storage processes," *International Multidisciplinary Scientific GeoConference: SGEM*, vol. 17, no. 1.5, pp. 405–413, 2017.
- [12] Y. Sohn, D. Kim, S. Choi, and Y. Yang, "Design Development of BOG Handling System In LNG-FSRU," presented at the The Twentieth International Offshore and Polar Engineering Conference, Jun. 2010, p. ISOPE-I-10-461.
- [13] G. R. Frazee, "Allowable external loading of buried smooth-wall steel piping: parametric evaluation using the latest guidance," *Journal of Pipeline Systems Engineering and Practice*, vol. 13, no. 1, p. 04021081, 2022.

- [14] M. L. Nayyar, *Piping handbook*, vol. 6. McGraw-hill New York, 1992.
- [15] O. Beteta and S. Ivanova, "Cool down with liquid nitrogen," *Chem Eng Prog*, vol. 111, no. 9, pp. 30–35, 2015.
- [16] H.-M. Chang, B. H. Kim, and B. Choi, "Hydrogen liquefaction process with Brayton refrigeration cycle to utilize the cold energy of LNG," *Cryogenics*, vol. 108, p. 103093, 2020.
- [17] J. R. Gómez, M. R. Gómez, R. F. Garcia, and A. D. M. Catoira, "On board LNG reliquefaction technology: a comparative study," *Polish Maritime Research*, vol. 21, no. 1, pp. 77–88, Jan. 2013, doi: 10.2478/pomr-2014-0011.
- [18] D. A. Wood and M. Kulitsa, "A review: Optimizing performance of Floating Storage and Regasification Units (FSRU) by applying advanced LNG tank pressure management strategies," *International Journal of Energy Research*, vol. 42, no. 4, pp. 1391–1418, 2018.
- [19] Peter R. Bredehoeft, Larry R. Dysert, John K. Hollmann, and Todd W Pickett, "87R-14: Cost Estimate Classification System – As Applied in Engineering, Procurement, and Construction for the Petroleum Exploration and Production Industries," *International Recommended Practices*, 2020.
- [20] Ministry of the Finance, *Regulation No. 32*. 2020. [Online]. Available: <https://peraturan.bpk.go.id/Download/127465/32~PMK.010~2019.pdf>
- [21] Ministry of Energy and Mineral Resources, *Regulation No. 58*. 2017. [Online]. Available: <https://peraturan.bpk.go.id/Download/133723/Permen%20ESDM%20Nomor%2058%20Tahun%202017.pdf>
- [22] Ministry of Energy and Mineral Resources, *Regulation No. 14*. 2019. [Online]. Available: <https://peraturan.bpk.go.id/Download/133721/Permen%20ESDM%20Nomor%2014%20Tahun%202019.pdf>