Study on the LNG distribution to mobile power plants utilizing small-scale LNG carriers

Muhammad Arif Budiyanto a,*, Achmad Riadi a, I.G.N. Sumanta Buana b, Gita Kurnia c

a Department of Mechanical Engineering, Universitas Indonesia, Kampus Baru UI Depok, Jawa Barat 16424, Indonesia
b Department of Marine Transportation and Logistics, Institut Teknologi Sepuluh Nopember, Surabaya, Jawa Timur 60111, Indonesia
c Department of Logistics Engineering, Universitas Pertamina, Kebayoran Lama, Jakarta 12220, Indonesia

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A B S T R A C T

In recent years, the use of small-scale liquefied natural gas (LNG) has grown alongside demand from industrial users of natural gas. Small-scale LNG is an alternative to the supply of natural gas to remote areas with a cost-effectiveness challenge. To address this challenge, five mobile power plants located in remote areas with limited depth of water level in western Indonesia are used here as a case study. The objective of this paper is to optimize LNG distribution using small-scale LNG carriers and carry out an economic analysis in this region. The capacitated vehicle routing problem model was used to optimize the maritime routing of a small-scale LNG supply chain. The maximization of the volume cargo with a given LNG vessel capacity set as the objective function was therefore provided with the optimum inventory routing and economic analysis of the transport of LNG. Cluster 1 serves three power plants with a total demand of 966 m3/day and a distance is 913 Nautical Miles, while cluster 2 serves two power plants with a total demand of 690 m3/day and distance of 1,483 Nautical Miles. Economic analysis of the two clusters shows that there is a minimum difference in the margin rate needed to make it worth the investment, which is 3 USD/MMBTU for cluster 1 and 4 USD/MMBTU for cluster 2. Thus, this paper concludes that the cost of LNG transportation depends on the amount of cargo demand and shipping distances.

1. Introduction

Liquid natural gas (LNG) has become a new major clean energy source for electricity generation. Globally traded LNG volumes increased by 28.2 million tonnes in 2018 [1]. In recent years, many developing countries have increased their investment in LNG infrastructure projects to meet LNG demands [2]. The LNG supply system is in a rapid development stage in many countries, but it is not yet complete [3]. To manage the dynamic supply-demand structure of the network, an optimum supply chain for LNG remains to be determined [4]. Therefore, a minimum production schedule that addresses market demands must be developed to allow a both cost-effective and secure LNG supply network [5]. There are difficulties in optimizing the supply chain network for LNG, such as price and demand uncertainty [6], multiple gas production options [7], variable distribution modes [8], versatile navigation paths [9], yearly fluctuating demands [10], and the simultaneous need to optimize infrastructure development and inventory routing [11]. There is some difficulty in optimizing the LNG supply system due to the complexity of the LNG supply chain, so solving this problem will be challenging [12].

The LNG supply chain can be described as a network of natural gas from the gas field to the liquefaction plant to turn the gas phase into liquid that is then stored in the refinery of the LNG storage tank and delivered to gas consumers, referred to as end users [13]. LNG transportation using small-sized LNG ships is still rare, with the demand for gas from small plants between locations scattered at several points [14, 15]. Small-scale LNG carriers rely on importer-exporter market shares, it is mainly designed for inland applications in addition to large-scale LNG power generationsystems for peak demands or secondary cycles. The use of small-scale LNG will provide operational ease because its smaller vessel dimensions meet water depth requirements on shipping routes [16].

Small-scale LNG routing is a special case of the maritime inventory routing problem combined with several additional conditions, such as variable production and consumption rates and port terminal limitations [17]. The problem of vehicle routes or vehicle routing problems has been widely examined by researchers to solve maritime distribution problems [18]. Vehicle routing problems involve determining the optimal route for problems involving more than one vehicle with a certain capacity in
order to serve a certain number of customers in accordance with their requests [19]. There are several types of vehicle routing problems and several methods used to solve these problems [20]. One method of vehicle routing that has been widely used to solve capacity-based transportation cases is the branch-cut-and-price method [21], widely used to solve land transportation problems [22]. Furthermore, the development of this method is the capacitated vehicle routing problem; this method is one variant of the vehicle routing problem, with each vehicle having the same limited capacity for all vehicles that have to service requests from depots with a single type of goods from the distributor, which generates minimum distance travel [23]. Despite the many studies of capacitated vehicle routing problems, not many have applied it to the case of small-scale LNG carriers. This study aims to find the optimum capacity of LNG ships by providing variations in the results of the route with the capacitated vehicle routing problem method. This study has twofold contributions: firstly, we report the optimum route combines with the maximum capacity of mobile power plants for mobile power plants with limited depth of water level in the receiving terminal facilities. Secondly, we estimate preliminary transportation costs for small-scale LNG that combines the economic value of LNG transportation with the shipping distance and volume of the cargo. This work also will provide an overview of the optimal small-scale LNG distribution allocation for small-scale power plants and a real case study in Indonesia, which is an island nation.

2. Research methods

2.1. Capacitated vehicle routing problem

The problem of LNG distribution in this study is categorized as a capacitated vehicle routing problem (CVRP). The capacity of LNG carriers will be a limitation in LNG transportation. The difference in LNG ship capacity will provide variations in route results and transportation costs. The input parameter of the CVRP calculation using following data: the distance between location i and location j (Si,j), the demand of each receiving terminal (Di), the type of LNG vessel (k) based on loading capacity (Q), transportation costs for each route (boat rental, fuel, port fee) (Cij). The decision variable in this study is symbolized as Xijk, where ship k will transport LNG on a route (R) from location i to location j. If ship k will transport LNG from location i to location j, then Xijk is worth 1 and in other conditions will be worth 0, with i, j = {0, 1, 2, ..., n}, i, j ∈ R i ≠ j and k = {1, 2, ..., K}, k ∈ {1, ..., K}.

\[ X_{ijk} = \begin{cases} 1, & \text{if the carriers k transport LNG from i to location j} \\ 0, & \text{if others} \end{cases} \quad (1) \]

The objective function in this study is to maximize the volume cargo with a specified LNG vessel capacity so that the LNG transportation costs can be minimized. To obtain the maximum total cargo volume, an optimal route is sought by minimizing the remaining cargo transported by the LNG vessel using the following equation:

\[ \text{min} \sum_{i \in R} \sum_{j \in R} \sum_{k \in R} X_{ijk} S_j C_{ijk} \quad (2) \]

With the limiting function as follows:

\[ \sum_{i \in R} \sum_{j \in R} \sum_{k \in R} X_{ijk} \leq Q, \forall k = 1, \ldots, n \quad (3) \]

Eq. (3) sets limits to ensure that the number of receiving terminal requests served on each ship must be less than or equal to the loading capacity of the ship serving the route.

\[ \sum_{k \in R} \sum_{j \in R} X_{ijk} = 1, \forall j = \{0, 1, \ldots, n\} \quad (4) \]

The limits in Eqs. (4) and (5) aim to ensure that each receiving terminal is serviced exactly once by a ship of a certain capacity.

\[ \sum_{j \in R} X_{ijk} = 1, \forall k = 1, \{1, \ldots, n\} \quad (6) \]

The limitations contained in Eqs. (6) and (7) ensure that each route with a particular ship starts from the LNG source and then, after serving the LNG distribution, returns to LNG source h.

\[ \sum_{i \in R} \sum_{k \in R} X_{ijk} = 0, \forall h = 1, \forall k = 1, \{1, \ldots, n\} \quad (8) \]

The limit in Eq. (8) ensures the continuation of the route of the LNG distribution, meaning that every ship that has finished servicing a receiving terminal will leave the receiving terminal to continue distributing LNG or return to the LNG source.

\[ X_{ijk} \in \{0, 1\}, \forall i, j = \{0, 1, 2, \ldots, n\}, i, j \in R, i \neq j, k \in \{1, \ldots, n\} \quad (9) \]

The limit in Eq. (9) ensures that the decision variable only uses integers 0 or 1.

2.2. Case study: LNG distribution in Sumatera, Indonesia

The CVRP model was used in this case study to optimize the maritime routing of a small-scale LNG supply chain in western Indonesia. There are currently many mini-LNG terminal projects in this region to satisfy the needs of mobile power plant (MPP) gas suppliers for remote areas [24, 25]. Today, power generation in western Indonesia is mainly based on oil and coal. Renewable sources have recently been introduced, and focus has also been given to natural gas. During this transition between fossil energy sources and renewables, natural gas appears to be the natural bridge, with its economic, safer, more efficient, and more environmentally friendly features. We selected the existing floating storage and regasification unit (FSRU) as a potential LNG supply terminal by a state-owned gas company, PGN, in Lampung, Sumatera. PGN’s FSRU is capable of storing up to 170,000 cubic meters of LNG and regasifying 240 million standard cubic feet (MMSCFD) per day [26]. Considering LNG demand, there are five mobile power plants with mini receiving terminals located on different islands. Two are existing mobile power plants located in the Pontianak 4 × 25 Megawatt (MW) and Tarahan 4 × 25 MW. The other three are currently under construction and are scheduled for commissioning in the near future [27, 28, 29]. The demands used for the power plant are estimations based on the megawatt-hours conversion into cubic feet of natural gas. For power plants, it is assumed that every 1 MW of power output will require an average of 0.12 MMCFD; thus, 1 MMSCFD is equivalent to 46 m³ of LNG. Table 1 displays the demands used for daily consumption for each power plant. For the sake of brevity, the following location abbreviations for the mobile power plants are used: FSRU Lampung (A0), MPP Belitung (A1), MPP Bangka (A2), MPP Pontianak (A3), MPP Lampung (A4), and MPP Nias (A5).

Two sizes of small-scale LNG (SSLNG) carriers were taken into consideration: Kakurei Maru (2500 m³) and Akebono Maru (3500 m³). These vessels were selected since they have a draft of below 5 m and currently operate on the Japan LNG supply chain [30, 31]. These vessels also have a propulsion system with dual-fuel engine, which is can use in diesel or gas fuel-mode [32], this engine is considered to be more environmentally friendly and has greater efficiency [33]. Particular dimensions and capacities of SSLNG carriers were obtained from the classifications under which they are registered; the data are shown in...
Table 1. LNG demands of mobile power plants in western Indonesia.

| Mark | Location       | Capacity (MW) | LNG Demands (m³/day) | Coordinates (Latitude, Longitude) | Data Source |
|------|----------------|---------------|----------------------|----------------------------------|-------------|
| A0   | FSRU Lampung*  | -             | -                    | (-5.61, 105.94)                  | Ref. [26]   |
| A1   | MPP Belitung   | 1 × 25        | 138                  | (-2.89, 107.56)                  | Refs. [24, 25] |
| A2   | MPP Bangka     | 2 × 25        | 276                  | (-2.08, 106.14)                  | Refs. [24, 25] |
| A3   | MPP Pontianak  | 4 × 25        | 552                  | (0.02, 109.26)                   | Refs. [24, 25] |
| A4   | MPP Lampung    | 4 × 25        | 552                  | (-5.52, 105.34)                  | Refs. [24, 25] |
| A5   | MPP Nias       | 1 × 25        | 138                  | (1.21, 97.67)                    | Refs. [24, 25] |

* LNG Source.

Table 2. The particular dimensions of small-scale LNG carriers.

| Type of Ship | Name of Ship | Unit | SS LNG-X | SS LNG-Y |
|--------------|--------------|------|----------|----------|
| Capacity     | m³           |      | 2536     | 3587     |
| Overall Length | m        |      | 86.290   | 99.37    |
| Breadth          | m         |      | 15.1     | 17.2     |
| Draft           | m         |      | 4.31     | 4.6      |
| Maximum Speed   | knot      |      | 14.6     | 15.8     |
| Average Speed   | knot      |      | 13.2     | 14.1     |

Table 3. Distance matrix (nautical miles).

|        | A0 | A1 | A2 | A3 | A4 | A5 |
|--------|----|----|----|----|----|----|
| A0     | 0  | 188| 248| 381| 93 | 725|
| A1     | 188| 0  | 118| 213| 260| 893|
| A2     | 248| 118| 0  | 226| 327| 960|
| A3     | 381| 213| 226| 0  | 460| 1097|
| A4     | 93 | 260| 327| 460| 0  | 665|
| A5     | 725| 893| 960| 1097| 665| 0  |

Table 4. Two optimum routes based on distance and delivery time.

| Optimum route | Sea Distance (NM) | Round Trip (Days) | Total Demand/Trip (m³) | Boil-off gas (m³) |
|---------------|-------------------|-------------------|------------------------|------------------|
| Cluster 1 (Green) | A0 - A1 - A2 - A3 - A0 | 913                           | 3.3                     | 3,191.7             | 25.5               |
| Cluster 2 (Yellow) | A0 - A4 - A5 - A0 | 1,483                          | 5.0                     | 3,433.8             | 27.5               |

3. Results and discussion

The results of the case study for route optimization and economic analysis, which includes financial parameters associated with transportation costs of small-scale LNG distribution, are analyzed in this section.

3.1. Route optimization

The results of calculations with the capacitated vehicle routing problem method there are 93 possible shipping routes. From 93 possible routes, two optimum routes were selected, based on criteria, distance and delivery time. The optimum value was the smallest difference between freight loads and LNG specifications for every voyage. Two optimal routes are shown in Table 4, and the route map is shown in Figure 1. The term boil-off gas in Table 4 is an LNG cargo in the form of liquid which changes phase to gas due to environmental influences. LNG tank

In addition, the route optimization differs according to sizes of LNG carriers in the delivery path and the solution is determined using the Greedy algorithm, which takes into consideration the load, service speed, supply point reach, transportation costs, and demand variables. Many assumptions were used to reduce the sophistication of the optimization phase, and load-unloading time was constant at 6 h for all forms of carriers. To address uncertain shipping conditions, each delivery will receive an additional 3 h of buffer time from one terminal point to another [15].
insulation is designed in such a way as to keep LNG cargo at the temperature of around -160 °C Celsius at atmospheric pressure, but due to the heat from the environment, the penetration into the tank causes the temperature of the charge to rise, and change the phase to gas [37]. This gas from phase change then used as fuel from the LNG Tanker. Boil-off gas on LNG Tanker ships generally ranges from 0.1% of the total shipload per day [38]. The use of boil-off gas as fuel will value added to the operational economic value of the ship.

3.2. Economic analysis

The financial feasibility parameters for costs incurred by distribution activities of the LNG ships, including investment in new building ships of SSLNG, have been included in the economic analysis conducted in this study. Economic analyzes are carried out by using the revenue derived from the payment of LNG services to power plants based on the financial feasibility parameters. This payment for the transport service is often called the price margin for the LNG selling. Practically, this selling price margin can be analogous to the costs that gas buyers must pay to LNG supplier companies that buy LNG from LNG producers and then send it to gas buyers. Two variables, capital expenditure (CAPEX) and operational expenditure (OPEX), are considered in the economic calculation. The internal rate of return (IRR) and net present value (NPV) are parameters or criteria for financial feasibility used in the economic analysis.

CAPEX is all initial costs of investment in the new SSLNG vessel construction. In this paper, a simple model for estimating new building costs for LNG tankers proposed by Mulligan was used, as shown in Eq (10) [39].

\[
C_{LNG} = -253.012 + 2.6PPI + 1.8053DWT - 0.01009 DWT^2 \\
+ 0.0000189DWT^3
\]  

(10)

where PPI is the producer price index and DWT is the deadweight volume for each ship. The suggested PPI index is 163.1. Based on the optimization results of route selection with minimum investment cost, it has been estimated that the total investment cost for new ship construction is 177,394,660 USD.

OPEX is all costs incurred to support the operational distribution of LNG, including the operational costs of the receiving terminal and the transportation costs for transporting LNG from the refinery to the receiving terminal. The operational costs of the receiving terminal consist of ship rental fees, ship fuel costs, port costs, operational costs of the receiving terminal, electricity costs and fuel costs of the receiving terminal, maintenance costs, and payments to receiving terminal workers. The total operational costs are estimated to be USD 6,062,931.64 for cluster 1 per annum based on optimization results of route selection with the minimum investment cost.; thus, total operational costs for cluster 2 are 6,443,731.55 USD annually. Details of operational costs from LNG ship transportation are shown in Table 5.

From the total CAPEX and OPEX, the amount of revenue obtained from LNG transportation and regasification services up to the mouth of the engine in the power plant can be calculated. The benefit derives from the difference between the buying price for LNG and the selling price for LNG, or the sales margin for LNG. In order to detect the LNG market margin sensitivity, at the end of the 20-year period, a difference in LNG sales prices was observed in the LNG sales unit (MMBTU), i.e. in USD/MMBTU, or in this research. In this study, six margin variations are used, from a margin of 3.0–7 USD per MMBTU with an increase of 1 USD. The sales margin was subsequently multiplied by the LNG sell in one year to earn sales margin revenue. For variations in LNG sales margins, the total calculation for revenue can be found in Table 6.

After the income is known, the next step is to calculate the investment eligibility criteria in the form of IRR and NPV. This value is calculated to make LNG investment from financial parameters feasible. Figures 2 and 3.
display the result of the economic analysis on the LNG investment estimate for Western Indonesia with differing revenue margins. The graph shows that the greater the LNG sales margin, the faster the return on investment, the greater the investment return, and the greater the NPV value. To see a profit, the NPV value must be positive in the 20th year, where the IRR value must be greater than the discount rate value. If the government’s discount rate is set at 10%, then the economic analysis in cluster 1 will be worth investing when the margin rate is above 3 USD; in cluster 2, it will be worth investing when the margin rate is above 4 USD. The margin rate in this calculation is interpreted as the minimum value of LNG transportation costs. According to some references, the transportation cost of LNG with large-scale LNG vessels varies greatly, from 0.65 USD/MMBTU to 2 USD/MMBTU, depending on the distance [44, 45]. If the cost of transporting LNG is compared with the results of the calculation of this study, there will be a slight difference, which makes it interesting to discuss. The results of this study indicate that the economic feasibility of LNG distribution with SSLNG vessels is different from large-scale LNG vessels. In LNG distribution using SSLNG vessels, it is possible that the transportation costs are greater than the LNG price itself, where the current spot LNG price dropped into the range of 4 USD/MMBTU [46]. When that occurs, attention should be given to a robust LNG supply chain so that the economic measure is beneficial relative to other energy use. Investment calculations need to be made not only in terms of sea transportation but also in terms of infrastructure readiness and advances in LNG technology, such as high-efficiency mini power plants, mini regasification terminals, and low-draft LNG vessels.

| Item                          | Cost (USD)                  | Reference                                      |
|-------------------------------|-----------------------------|------------------------------------------------|
| Fuel and lubricating oil      | Cluster 1 4,883,371.64      | Calculated based on fuel cost 26 USD/km ≈ 48.2 USD/NM [14] |
|                               | Cluster 2 5,264,171.55      |                                                |
| Ship’s crew                   | 426,000.00                  | Estimated based on Marine Labor Convention [40] |
| Fresh water                   | 1,569.00                    | Estimated based on fresh water cost on local port data 5 USD/ton [41] |
| Port local agent expenses     | 480,000.00                  | Assumption based on local port data [42]      |
| Ship repair costs             | 4,000.00                    | Assumption based on literature study [43]    |
| Ship docking cost             | 188,000.00                  | Assumption based on literature study [43]    |
| Survey and maintenance costs  | 40,000.00                   | Assumption based on literature study [43]    |
| Overhead cost                 | 40,000.00                   | Assumption based on literature study [43]    |
| Total Operational Expenditure | Cluster 1: 6,062,931.64     |                                                |
|                               | Cluster 2: 6,443,731.55     |                                                |

Table 6. Variation of margin rate.

| Cargo demands (MMBTU) | Cluster 1 | Cluster 2 |
|-----------------------|-----------|-----------|
| 3 USD/MMBTU           | 16,929,836.02 | 10,010,516.43 |
| 4 USD/MMBTU           | 24,563,440.18 | 15,463,090.83 |
| 5 USD/MMBTU           | 32,197,044.34 | 20,915,665.23 |
| 6 USD/MMBTU           | 39,830,648.50 | 26,368,239.63 |
| 7 USD/MMBTU           | 47,464,252.66 | 31,820,814.03 |

Figure 2. Discount rate and net present value for economic analysis of cluster 1.
Another thing that needs to be considered based on the results of this calculation is margin line differences between clusters 1 and 2. It shows that the economic value of LNG transportation depends on the distance and volume of the cargo. This can be considered by the government to implement a standard system of minimum costs for each cluster.

The results obtained from this study may be different from the results conducted by other researchers. This is because the optimization problems in real life are very complex, there are many factors that need to be addressed. Specifically, in this case, the distribution of small-scale LNG in Indonesia has several challenges, namely maritime access to receiving terminals that could trigger major investment, arbitration of the distribution of shipping costs among customers, and lack of consistency in policy and regulations [47].

4. Conclusion

In this paper, a capacitated vehicle routing problem for the optimal design of a supply chain has been presented for LNG distribution using SSLNG carriers in western Indonesia. This case study was deliberately chosen because it has a unique case of receiving facilities in a remote area with limited depth of water level. The maximized volume cargo with a specified LNG vessel capacity was set as the objective function; thus, the optimal inventory routing and economic analysis of transporting LNG were presented as the result. From various possible routes, two optimal routes were determined, cluster 1 and cluster 2, where each cluster uses SSLNG vessels with a capacity of 3,587 m$^3$. Determined routes have different characteristics; cluster 1 serves three MPPs with a total demand of 966 m$^3$/day and a cruise distance of 913 NM for a round trip, while cluster 2 serves two MPPs with a total demand of 690 m$^3$/day with a shipping distance of 1,483 NM for a round trip. From the two cluster cases, an economic analysis was then performed, including the investment eligibility criteria in the form of IRR and NPV. The results show that the two clusters have different economies of scale: cluster 1 is feasible for investment if the margin rate is above 3 USD/MMBTU, while cluster 2 is feasible for investment if the margin rate is above 4 USD/MMBTU. This amount is still relatively high compared to the current transportation costs, each of which is considered reasonable because the LNG transportation business model is currently being carried out for huge cargo volumes with very long shipping distances between countries. The results of the calculation show that the cost of LNG transportation depends on the amount of cargo demand and shipping distance, so a stakeholder policy is needed so that the SSLNG transportation business is attractive to investors. The policy implications are aimed at the government and shipping operators. From the government’s perspective, the minimum transportation cost policy for each cluster can be implemented, as can the provision of incentives for clusters that have small cargo demands with long shipping distances. In terms of shipping operators, the policy of using boil-off gas as secondary fuel can be implemented in order to save on fuel costs.

Declarations

Author contribution statement

Muhammad Arif Budiyanto: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Achmad Riadi: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

I. G. N. Sumanta Buana & Gita Kurnia: Analyzed and interpreted the data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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