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Optimization of the risk-based small-scale LNG supply chain in the Indonesian archipelago

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ABSTRACT

The electricity supply in Indonesia is considered inefficient, as indicated by the increase in the Cost of Generation Provision (CGP) in the 2016–2021 period. Indications of high supply chain risks are not commensurate with the low demand for LNG. Nevertheless, every power plant on small islands must be served by minimizing costs. This study aims to develop a risk-based small-scale supply chain model to distribute LNG in archipelagic areas by minimizing infrastructure costs, including investment and operations. This paper formulates a risk-based small-scale LNG (SS-LNG) model with milk runs, which are rarely applied in LNG supply chains, thus impacting cost efficiency and the sustainability of LNG supply in Indonesia. The simulation was carried out using the vehicle routing problem with milk run (VRPMR) method. The optimization results show that the 2-vessel scheme is an optimal and efficient risk-based SS-LNG supply chain model. However, it appears that changing the scheme from 1 to 2 vessels generally increases the infrastructure tariff by 3%, or USD 0.11 per MMBTU. This risk-based supply chain model is able to ensure a fuel cost efficiency of 27% for power plants.

1. Introduction

The government of Indonesia through the Ministry of Energy and Mineral Resources encourages the State Electricity Company to increase the efficiency of electricity supply by optimizing the Cost of Generation Provision (CGP) and introducing electricity subsidies. This is necessary because the cost of providing electricity or generating power has the highest contribution to CGP with 72% while the network cost is only 11% and other operating costs are 17% [1]. It was discovered that the CGP increased from 1,025 IDR/KWh to 1,

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334 IDR/KWh in the 2016–2021 period and this indicates an increase in the inefficiency of the electricity generation system which further leads to the high cost of electricity in Indonesia.

Fig. 1 shows that almost all CGP per power plant locations are above the national average, especially in the central and eastern parts of the Indonesian archipelago. It is important to note that a high value indicates inefficiency. Moreover, the data for 2016–2025 showed 30 existing Gas Power Plant (GPP) and Gas Engine Power Plant (GEPP) using engines with dual fuel designs including gas or oil while other 22 GPP and GEPPs are already in the construction phase to be operated in 2022–2023 with a total Generating Capacity of 1,697 MW (MW) which is equivalent to 167 billion bristh thermal unit per day (BBTUD) Gas. Natural gas is required to fulfill the increasingly high demand for electricity in the Maluku, Papua, and Nusa Tenggara regions with an average growth of 12.9% per year followed by the regions of Sulawesi, Kalimantan, and Sumatra with 11%, 10.7%, and 9.4%, respectively.

The use of fuel oil, which continues to increase, causes a high dependence on imported petroleum [1] and a high CGP [2], especially in the area of small islands. There has been an increase in the burden of state electricity subsidies from IDR 45.74 trillion in 2017 to IDR 53.59 trillion in 2021 [1]. The impact is that electricity rates for households are increasingly expensive, from 93 USD/BOE in 2013 to 129 USD/BOE in 2019 [1]. This condition causes the government to require that the 30 GPPs and GEPPs currently operating using fuel oil switch to using LNG, which is cheaper.

However, the LNG supply chain system in Indonesia is not optimal; there are many risks in the LNG supply chain process, including the long distance between the source of LNG supply and the generator, the relatively small demand for LNG in each location with an average of 2.28 BBTUD [1], and shipping lanes classified as dangerous [3–5]. Shipping environmental conditions in Indonesia are very risky, with wave heights of 4–5 m [6]. The high ship accident rate of 23% is related to force majeure or environmental factors [7]. Other risks include very shallow sea depths in ports [8], a lack of necessary infrastructure to distribute LNG to GPP/GEPP sites [1], the absence of an economical multi-destination LNG supply chain model [8,9], and load uncertainty that affects transportation costs [10–12].

The many risks in the small-scale LNG (SS-LNG) supply chain in Indonesia cause the cost of LNG distribution to small islands to be more expensive. This has an impact on the high cost of LNG production, so the cost of electricity reaching the community is higher. Therefore, it is necessary to optimize the SS-LNG supply chain by minimizing risks and costs amidst uncertain fluctuations in demand. The novelty of this study is to include risk factors in the cost value. The variation in the value of each risk factor is different depending on how likely it is to occur. The percentage of risk influence on SS-LNG supply chain activities can be seen in section 3.3.

2. Literature review

2.1. The SS-LNG supply chain elements

SS-LNG supply chain is part of the conventional LNG supply chain which consists of liquefaction or regasification facilities that typically serve a larger number of end users compared to the conventional method as indicated in Fig. 2. It has 2 elements according to Zhang et al. [13] and these include the transportation lines and loading facilities such as those in the form of LNG reserve tank facilities or storage as listed in Table 1.

Fig. 2 shows that SS-LNG is part of the LNG supply chain. The blue lines show the distribution of conventional LNG while the other colors represent small-scale variances. Moreover, the red line indicates SS-LNG at disbursement and the yellow line represents SSLNG

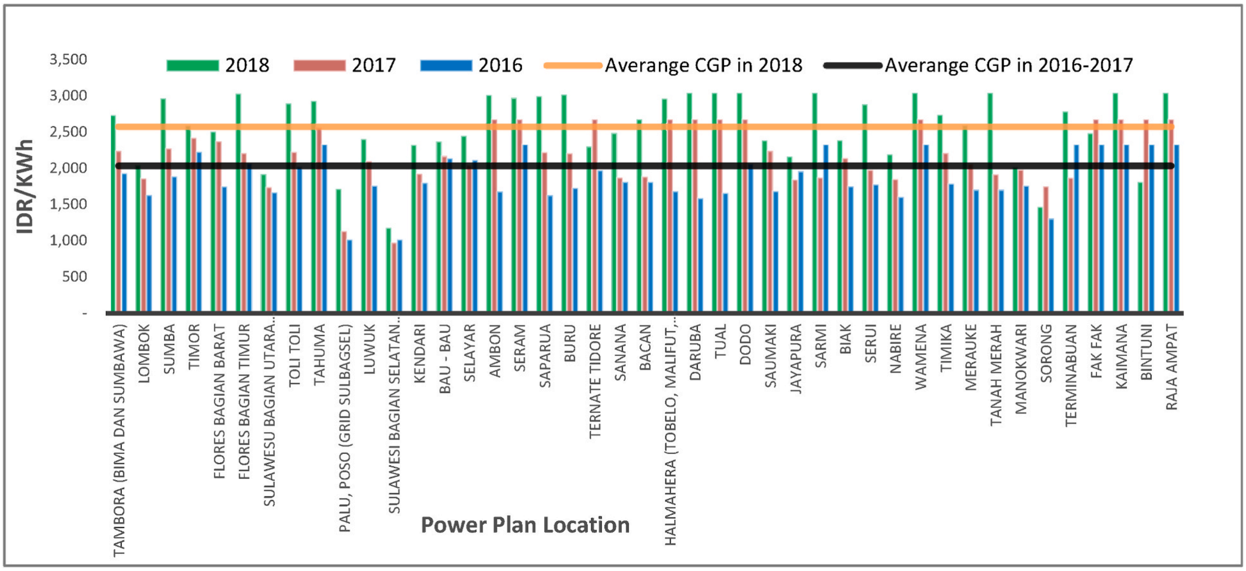


Fig. 1. Comparison of Indonesian CGP per location [1].

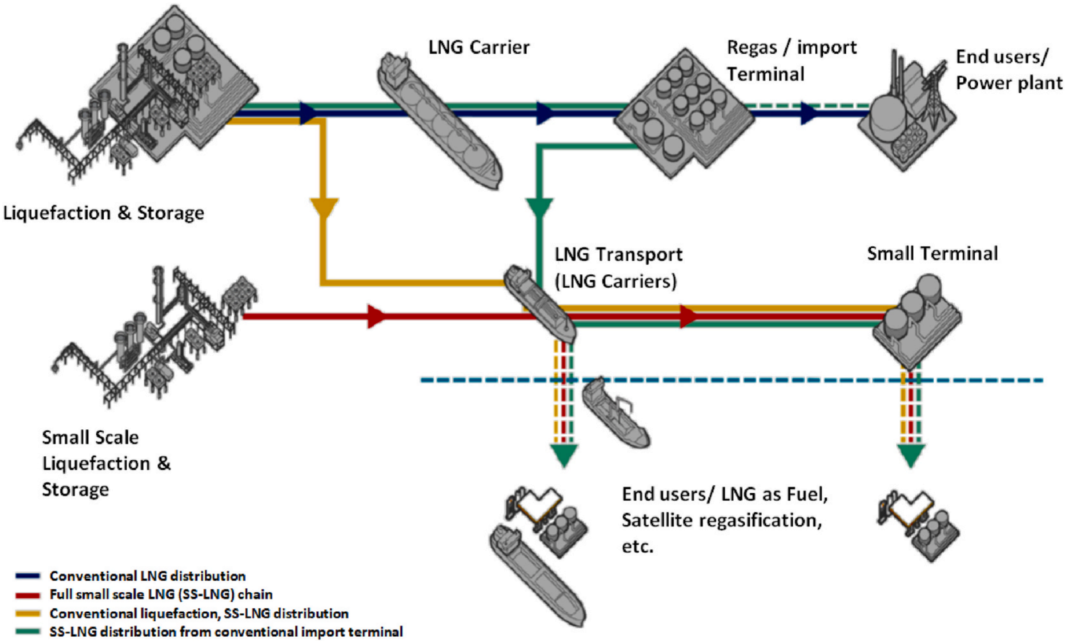


Fig. 2. The SS-LNG supply chain as part of the LNG supply chain [14].

Table 1
Elements of the LNG supply chain.

Element	Conventional LNG*	SSLNG*	SSLNG**
Supply	LNG Plant	LNG Plant, Regas & SS LNG Plant	LNG supply system
Storage	Tanks at LNG Plant	Tanks at LNG Plant & Regas Terminal	LNG reserve storage
Transport Line	Jetty	Jetty, Truck loading unit	–
Loading Facility	Berth	Berth, jetty, vessel-to-vessel, or truck loading dock	–
Transport	LNGc	SSLNGc, LNG trucks, containers, train	LNG delivery vehicle
Demand	Customers at Regasification Terminal	Customers at the small terminal	LNG receiving terminal

Description: * [14]; ** [13].

from conventional liquefaction which is broken up and sent in small packets to small-scale terminals. The green dotted line shows the small area from the regasification terminal and import to local or remote power plants not connected to the gas grid. It is important to note that there is usually no regasification when the LNG request originates only from the SSLNG terminal and the facility that receives the LNG is called an import terminal which is the green line.

International Gas Union [14] indicated two parameters normally applied as a differentiator between small-scale and large-scale LNG and these include using an LNGc capacity of fewer than 30000 m^3 and a receiving tank in the range of 500–30000 m^3. Bittante et, al [15] also stated that SSLNG uses LNGc of 1000–40000 m^3 and receiving tank which is less than 50000 m^3. It is also important to note that distances are shorter in small-scale LNG supply chains compared to conventional systems because there are optimal coverage areas for certain production and distribution scales. Moreover, vessel endurance depends on fuel storage and consumption per day or per nautical mile, the number of reserves needed at any time, as well as the consideration for unpumpable LNG in the tanks [14].

The application of a small LNG vessel can increase transportation costs compared to a larger vessel at the same distance but it is more flexible in terms of depth requirements, lower rental costs, and compatibility with the small demand for LNG supplies in the archipelago areas of Indonesia. The total costs in the LNG supply chain are divided into 2 main components which include capital expenditure (CAPEX) and operational expenditure (OPEX). According to Pratiwi et al. [8], the investment cost for the construction of the SSLNGc, jetty, LNG tank, regasification unit, and gas distribution system to the power plant is included in the CAPEX while the operating and maintenance costs of the receiving terminal and LCT are categorized as the OPEX.

This means CAPEX covers all initial investment costs incurred for the construction of existing facilities at the receiving terminal such as those related to the jetty, LNG offloading, cryogenic pipes, LNG storage tanks, LNG pumps, vaporizers, BOG compressors, generators, supporting buildings, and component installations [16]. According to Mokhatab et al. [17], the most expensive facility at the LNG receiving terminal is the storage tank which is approximately 45% of the total cost of the facility. Moreover, a typical small-scale LNG plant with a capacity of 0.05–1 mtpa is estimated to cost from 350 USD/ton per year.

OPEX is in the form of costs incurred to support LNG distribution operations such as the operating costs accrued at the receiving terminals and for transporting LNG from the refinery to the receiving terminal. It is important to note that the operating costs consist of vessel rental fees, vessel fuel costs, port fees, electricity and fuel costs for the terminal, maintenance costs, and payments to workers [8, 16,18,19].

2.2. SS-LNG supply chain risks

SS-LNG supply chain risks start from gas production to processing and separation, transportation to the LNG plant, liquefaction plant, and import terminal [17]. The most common risks include the shortage of vessels for a certain route at a particular time, natural hazards at sea such as wave height, or an imbalance in the supply or demand of vessels [20]. Furthermore, Wan [21], Machfudiyanto and Syahreza [22], and Machfudiyanto et al. [1] also divided risk categories into five which include the community, nature, management, infrastructure/technology, and operations. These are similar to the division by risk factor components as proposed by Gurning [20] but human resources and work environment categories were included with the risk factors recorded to be lack of skilled manpower, lack of motivation, seafarers' mental health, human error, unreasonable welfare, linguistic and cultural diversity, poor safety culture, and low levels of safety leadership. The risk to the environment was also studied by Al-Haidous S [2]. In this paper, the risk indicators used are output papers in the research of Machfudiyanto et al. [1].

2.3. SS-LNG supply chain modeling

Several studies have been conducted on the development of the SS-LNG Supply Scheme Model with scattered locations. Prause, F., and Prause, G [23] developed an LNG supply chain model to fulfill maritimely (vessel) fuel for ports in Germany using the Inventory Routing Problem (IRP) method. Zhang et al. [13] also proposed LNG supply system infrastructure and inventory routes using the

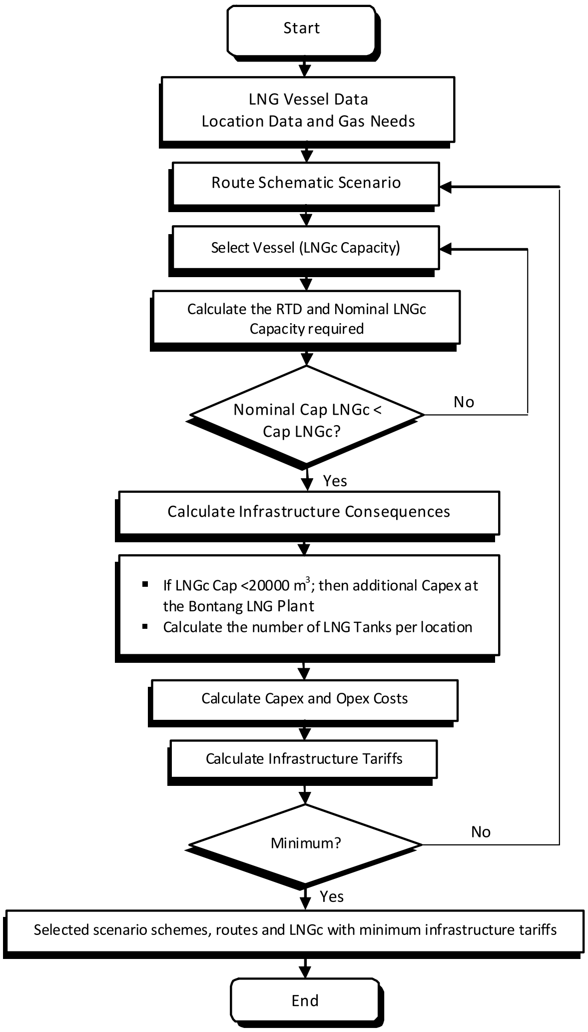


Fig. 3. The development flow of the SS-LNG supply chain, based on risk and cost.

hybrid computing method (ACO-MILP) and the model was successfully applied to the LNG supply chain along the Yangtze River in China. Related studies were also found in Indonesia as indicated by the model proposed by Wijharnasir et al. [9] to determine the optimal vessel route to transport LNG from the production terminal to the thirteen regasification terminals by considering the transportation and storage costs in Papua using the greedy analysis method. Budiyanto et al. [16] also optimized the distribution system using SS-LNG vessels and conducted economic analysis in remote areas with limited water table depth in western Indonesia through the capacitated vehicle routing problem (CVRP) method. In addition, Chen Z [24] uses a Block-matrix-based approach, and Malhotra [25] uses Using Exact and Heuristic. Werner A [26]. also did the same thing with the stochastic mixed-integer programming method so that network integration occurs. The next development model was carried out by Sangaiah AK [27], using robust optimization and mixed-integer linear programming.

The variables used in modeling the LNG supply chain vary widely and include the distance between the receiving terminals [9,13,16,18], Hub Location [13], Inventory/storage size [13], vessel capacity [9,16,18,28,29], generating capacity [9,18,29], vessel speed [18,29], transportation costs [15,18,23,30,31], route [16,28], term and length of stay [15], Capex [5,15], and Opex [15,23]. Meanwhile, the objective function often used is the minimal cost [9,15,18,23,29,32], maximum revenue [6,33], and optimal cargo volume [16]. Research on the SS-LNG optimization model is still limited to point-to-point distribution systems with definite demand, so it often does not reflect real conditions in the field. Therefore, this paper ensures that the demand used is in accordance with LNG requirements in every power plan that has demand uncertainty.

3. Methods

3.1. Problem definition and assumptions

The application of the optimization model basically has limitations; the model developed in this paper is in line with the paper developed by Humang [6] and Uygun [34] using the milk run system, but with several differences, namely Humang [6] with a bi-level approach and Uygun [34] with an ant colony system. The SS-LNG supply chain model was developed using the Vehicle Routing Problem with Milk Run (VRPMR) which was developed from the Traveling Salesman Problem model. Optimization of the shortest route is carried out based on the minimum investment and operational costs with a genetic algorithm (GA) using Python 3.7 software. The objective function of this study is to develop a supply chain model with the lowest infrastructure tariffs such as the investment (CAPEX) and operating costs (OPEX) based on the risk probability.

The development flow of the SS-LNG supply chain model in this study is described in the following Fig. 3.

The limitations of the modeling applied to achieve the objective function are assumed to be as follows:

a) Each route by LNGc vessel starts from the LNG Plant to the receiving terminal and back to the Plant.
b) Every LNGc vessel that has finished serving a receiving terminal continues the distribution or returns to the plant.
c) Each receiving terminal is served exactly once by one LNGc vessel with a certain capacity.
d) The capacity of the vessel used is less than 30000 m^3.
e) The nominal LNGc capacity calculated should be less than the capacity selected in the initial assumption.
f) The selection of LNGc with less than 20000 m^3 capacity leads to additional investment costs of $3642971 (including VAT) at the LNG Plant to modify the loading facility. Meanwhile, the selection of the scheme with 2 vessels leads to the division of the additional investment costs into two with each vessel bearing a total sum of $1821485 [18].
g) The number of LNG storage tanks at the receiving terminal is a multiple of 500 m^3 [23] and the investment costs for each is $1030000 (including VAT) [18].

3.2. Proposed model development

- Objective function

$$Minimum\ Infrastructure\ Tariff\left(\frac{USD}{MMBTU}\right)=\frac{\sum Investment\ Cost}{\sum LNG\ distribution}+\frac{\sum Operating\ Costs}{\sum LNG\ distribution}$$

$$min\sum_{r\in R_k^V}\left(C_{Capex\ r}^{k,v}+C_{Opex\ r}^{k,v}\right)x_r^{k,v}$$

- Subject to:

$$\sum_{r\in R_k^V}\left(A_{ir}^{k,v}\,x_{ir}^{k,v}\right)=1$$

$A_{ir}^{k,v}$ = 1 if i is served by route r, = 0 if not served, $\forall i\in N_k^v$

$x_r^{k,v}$ = 1 if route r is selected, = 0 if not selected, $\forall r\in R_k^v$.

- Decision variables:

$C^{k,v}_{Opexr}$ = Operating costs (OPEX) in USD per MMBTU. The total operating costs per year were divided by LNG distribution in a year and they consist of cost for the LNGc vessel rent and fuel, port service, and operations of the LNG Plants and receiving terminals

$C^{k,v}_{Capexr}$ = Investment Costs (CAPEX) in USD per MMBTU. The total investment costs were divided by LNG distribution over the design life of the terminal and they consist of the investment costs at the LNG receiving terminal and plant served by vessel k on route r

R^{v}_{k} = A collection of route r for all vessel k capacity and speed v resulting from the first step (single route) and the second step (multiple routes).

$x^{k,v}_{r}$ = A binary variable which is one (1) when route r is selected in the optimal solution and zero (0) when it is not selected in the optimization

N^{v}_{k} = A collection of terminals i served by vessel k operating at speed v

$A^{k,v}_{ir}$ = The constant is one (1) when the receiving/generating terminal i is served by route r and zero (0) if otherwise.

3.3. Determination of risk in the model

The risks that arise in the SS-LNG supply chain are converted into costs that will be included in the mathematical model, both CAPEX and OPEX costs. Determination of the risk index at the SS-LNG stage through a series of analyses, namely Delphi analysis and risk assessment. The Delphi method is to identify risks that may occur, while the risk assessment is to assess the risk index for each risk, which is determined based on risk probability and risk impact [1]. The results of the risk assessment that are classified as high risk will be converted into percent to see how much influence they have on the SS-LNG stage as a mathematical model builder. The type of risk has been described in Machfudiyanto's [1] papers, including bad weather, ship accidents, equipment damage, human error, inaccurate demand forecasts, poor safety culture, a lack of transport ships, uncertain bunkering costs, a low level of safety leadership, and others.

The risks often experienced in the SS-LNG supply chain were identified and assessed qualitatively. Each risk was calculated based on the % likelihood of occurrence and the estimated impact which was converted into monetary value. It is important to note that not all the risks were used in the model because only some were prioritized and considered high-risk with a large impact on the increase in costs based on the risk ranks as a qualitative assessment result. Furthermore, the relationship between risk and LNG supply chain modeling indicators for 8 activities as well as the magnitude of the impact is presented in Fig. 4. It was discovered that only "Vessel Speed" has a negative relationship out of all the modeling indicators. The risk was observed to have caused the vessel to experience a decrease in speed by 4% from its normal speed in docking and undocking activities during the LNG loading and unloading.

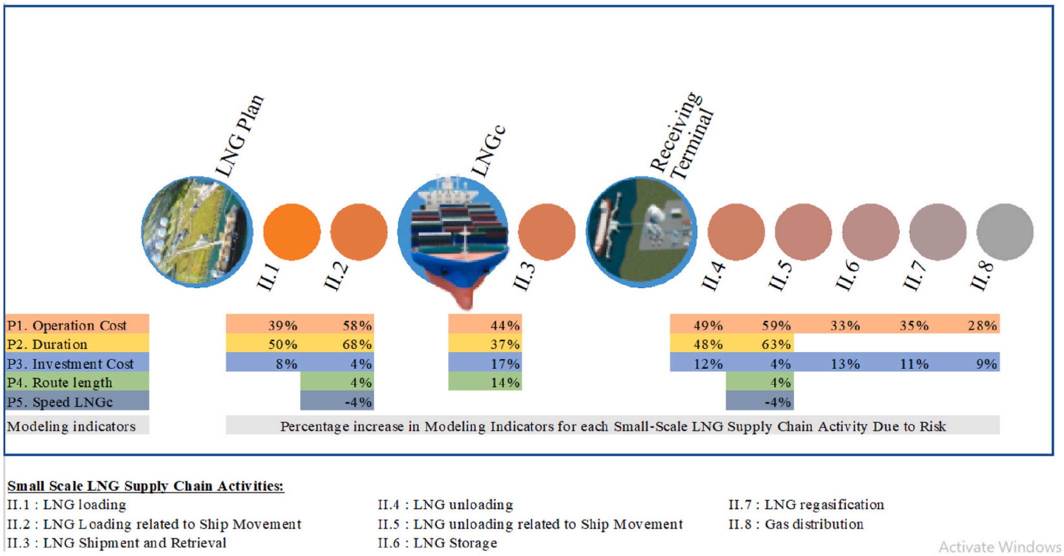


Fig. 4. Relationship between risk and supply chain modeling indicators.

3.4. Case study

3.4.1. Location of LNG receiving terminals and gas demand

There are 4 natural gas production areas in Indonesia that have facilities to liquefy natural gas and then store it in storage tanks commonly called LNG refineries, namely the Badak Refinery (Bontang, East Kalimantan), the Arun Refinery (Nanggroe Aceh Darussalam), the Tangguh Refinery (Papua), and the Donggi Senoro Factory (Central Sulawesi). In this paper, a case study was carried out at the Badak LNG Refinery, which has a total installed capacity of 21.64 million metric tons per year, consists of 8 production lines, and has produced 8.5 million m^3 per year in 2018.

Meanwhile, the location of the power plant and the average gas demand are based on the Decree of the Minister of Energy and Mineral Resources No. 13K, which shows a total gas requirement of 25 BBTUD spread over the islands of East Nusa Tenggara and West Nusa Tenggara, as shown in Table 2..

The distance between the Badak LNG Plant and the receiving terminal was calculated by considering the shipping routes using the Netpas Distance application and the results are compiled into a distance matrix in Table 3.

3.4.2. LNGc vessel data

International Gas Union [14] classified SS-LNG supply chains based on their LNGc capacity which is normally lower than 30000 m^3 and receiving tanks in the 500–30000 m^3 range. Therefore, this study used a selection of LNGc vessels with capacities in the 2500–30000 m^3 range as shown in Table 4.

3.4.3. Capex and Opex costs

Investment costs (Capex) in the SS-LNG supply chain are adjusted for eight supply chain activities, consisting of investment costs at the Bontang LNG plant to support LNG loading activities and investment costs at LNG receiving terminals at each power plant location to support LNG unloading activities, LNG storage, LNG regasification, and gas distribution. The CAPEX calculation shown in Appendix 1 refers to the research of Antara [18] and Setyorini [35].

Operating costs (Opex) consist of two main components, namely transportation costs (LNG boat rental fees, fuel costs, and service fees at the port) and terminal operating costs (terminals at the LNG Plant and LNG receiving terminal). The annual boat rental fee using rental data refers to the rental value (USD/day) in Table 4, while the Opex cost refers to Antara's paper [18], which is shown in Appendix 2.

4. Results and discussion

As an example of a case, the schemes used are 1 and 2 vessels with 1 origin and 8 destination locations as well as the application or non-application of risk factors with the index code as presented in Table 2. The determination of the operating and investment costs was followed by the formation of the infrastructure tariffs for each route scheme in USD/MMBTU as all costs incurred by the provider to conduct activities with the exclusion of the reasonable profits from the investments. This study used a distribution period of 20 years which is common for SS-LNG studies [18]. Moreover, the average maximum price at the location of the power plant sourced from LNG transported from the LNG Plant is USD 11.6 per MMBTU for a projection of 20 years. This value represents the maximum permitted infrastructure tariffs for a small-scale LNG supply chain model in the Indonesian archipelago for an end user of the power plant.

4.1. The 1 vessel scheme

The best risk-based route scheme selected in the 1-vessel simulation is 8, 4, 2, 5, 6, 1, 7, 0, 3, 8 with total infrastructure tariffs of USD 3.95 per MMBTU. The LNGc vessel departs from Bontang by carrying 18969 m^3 of LNG to GEPP Bima, continues to GEPP Rangko, Maumere, Alor, Kupang, Waingapu, Lombok, and Sumbawa sequentially to unload the LNG cargo, and returns to the Badak (Bontang) Plant to repeat the process. The selected route has a total length of 2286 NM with a round trip day (RTD) duration of 16 days, a vessel speed of 15 knots, and an LNGc utilization capacity rate of 95%.

Meanwhile, the without risk-based simulation results for 1 vessel showed that the selected route is 8, 3, 0, 4, 2, 5, 6, 1, 7, 8 with a

Table 2
Location of receiving terminals and gas demand [35].

Index no	Power Plant	Coordinate		Capacity (MW)	Demand (BBTUD)
		Latitude	Longitude		
0	MPP Jeranjang	8°35′18″S	116° 4′27″E	50	3.60
1	GEPP Kupang	10°21′13″S	123°27′30″E	40	2.90
2	GEPP Rangko (Flores)	8°27′36″S	119°56′40″E	23	1.65
3	GEPP Sumbawa	8°26′51″S	117°20′8″E	50	6.13
4	GEPP Bima	8°24′32″S	118°41′58″E	50	6.13
5	GEPP Maumere	8°37′13″S	122°20′21″E	40	2.90
6	GEPP Alor	8°14′37″S	124°31′47″E	10	1.29
7	GEPP Waingapu	9°28′36″S	120° 9′15″E	10	1.30
8	Badak NGL (Bontang)	LNG refineries			

Table 3
Distance matrix (nautical miles).

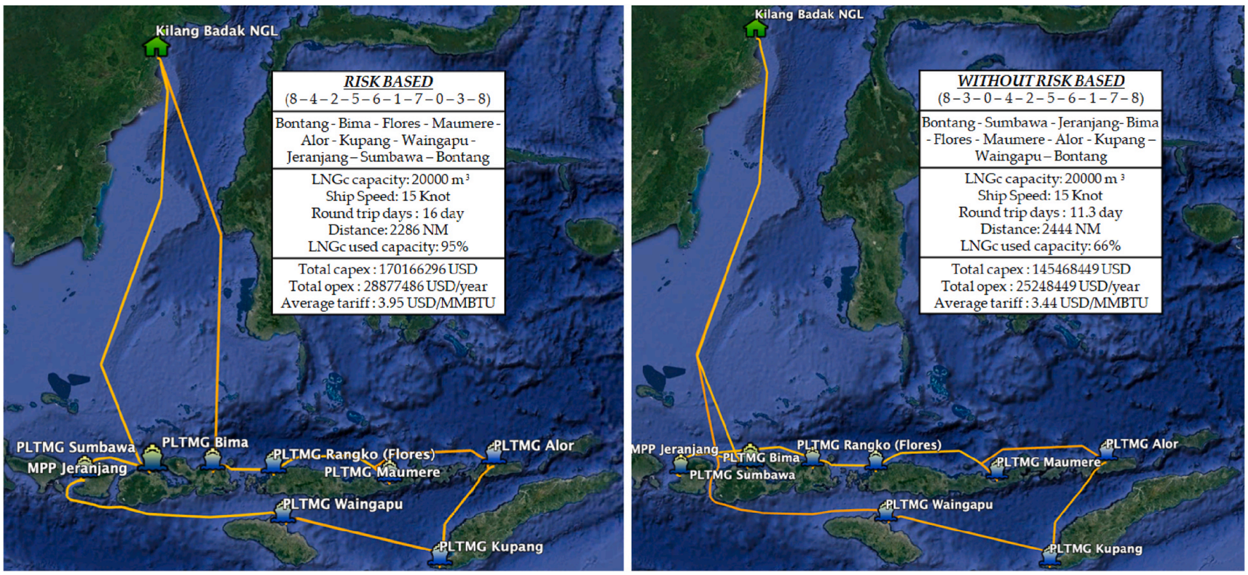
Power Plant	MPP Jeranjang	GEPP Kupang	GEPP Rangko	GEPP Sumbawa	GEPP Bima	GEPP Maumere	GEPP Alor	GEPP Waingapu	Badak NGL
MPP Jeranjang	#REF!	514	269	122	202	414	545	302	542
GEPP Kupang	514	#REF!	537	522	590	400	150	219	942
GEPP Rangko	269	537	#REF!	177	86	183	313	461	542
GEPP Sumbawa	122	522	177	#REF!	110	322	453	309	526
GEPP Bima	202	590	86	110	#REF!	236	367	394	522
GEPP Maumere	414	400	183	322	236	#REF!	176	534	619
GEPP Alor	545	150	313	453	367	176	#REF!	274	729
GEPP Waingapu	302	219	461	309	394	534	274	#REF!	780
Badak NGL	542	942	542	526	522	619	729	780	

Table 4
LNGc vessel data.

LNGc	Capacity (m^3)	DWT	GT	Speed (Knot)	Capex (USD)	Rent (USD/day)	Fuel (Ton/Day)
Shinju Maru	2500	1150	2930	13	33139078	11679	7.7
WSD59 3K	3000	2000	3900	12	36163636	12730	10.4
WSD59 5K	5000	3000	5382	14	48261870	16933	16.5
WSD59 6.5K	6500	4200	6796	13	57335545	20085	13.6
Coral Methane	7500	3450	7833	14	63384661	22187	20.5
Norgas	10000	4600	9691	14	78507453	27441	26.6
WSD55 12K	12000	9900	12300	14	90476463	31643	18.7
Coral Energy	15600	7176	14139	15	112020680	39207	43.4
WSD50 20K	20000	12500	17270	15	138440246	42538	25.1
Surya Satsuma	23000	10580	20017	15	156306015	44808	62.8
WSD50 30K	30000	15000	23483	16	198197549	69464	34.8

total length of 2444 NM, an RTD duration of 11.3 days at a vessel speed of 15 knots and an LNGc utilization capacity rate of 66%. The comparison of the best risk and without risk-based routes is shown in the following Fig. 5.

The difference between risk and without risk-based route schemes is that the total distance decreases by 6.5% (158 NM) and RTD increases by 42% (4.7 days) due to the risk in loading activities. The addition of RTD can also increase the amount of LNG inventory



(a) (b)

Fig. 5. The best scheme route using 1 vessel: risk-based (a), without risk-based (b).

and this means larger onshore LNG tanks are needed. It was discovered that the inclusion of 11 onshore tanks with a size of 500 m^3 led to a 12% increase in the tank reserve capacity due to the influence of the existing risk indicators. This subsequently increased the investment costs (CAPEX) of the LNG receiving terminal.

The infrastructure tariffs for the 1-vessel scheme provide efficiency for the existing fuel as indicated by the lower value of USD 1.65 per MMBTU or 29% from the maximum USD 5.6 per MMBTU permitted for the gas distribution duration of 20 years. The comparison of costs for the 1-vessel scheme for the risk-based and without risk-based models is fully presented in the following Fig. 6.

4.2. The 2 vessel scheme

The simulation conducted using 2 vessels with a risk-based model shows that the first vessel route is (8, 2, 3, 0, 7, 8) and the second is (8, 4, 5, 6, 1, 8). Moreover, the first LNGc vessel with a capacity of 7500 m^3 to fulfill LNG demand at 4 power plants has a route length of 1923 NM with an RTD duration of 11.9 days at a vessel speed of 14 knots and an LNGc utilization capacity rate of 92%. The second with a capacity of 7500 m^3 to fulfill LNG demand at 4 power plants has a length of 2026 NM with an RTD duration of 12.3 days at a vessel speed of 14 knots and an LNGc utilization capacity rate of 99%.

Meanwhile, the simulation model without risks showed that the first vessel route (8, 0, 4, 2, 5, 8) has a length of 1,632 NM with an RTD duration of 7.4 days, a vessel speed of 14 Knots, and an LNGc utilization capacity rate of 95%. The second route (8, 3, 7, 1, 6, 8) has a length of 1933 NM with an RTD duration of 8.3 days, a vessel speed of 14 knots, and an LNGc utilization capacity rate of 87%. The costs for the with and without risk-based route models are compared in the following Fig. 7.

It was discovered that the route of vessel movement is different and this caused an increase in total distance by 11% or 384 NM and the RTD by 55% or 8.6 days due to the risk of LNG loading, unloading, shipping, and retrieving activities.

The addition of RTD was also observed to have increased the amount of LNG inventory as indicated by the inclusion of 10 onshore tanks with a size of 500 m^3 to 32 tanks for a risk-based LNG supply chain scheme. The RTD addition further affected the nominal LNGc capacity required such that route 1 increased by 45% or 2119 m^3 from 4744 m^3 to 6863 m^3 and route 2 by 71% or 3076 m^3 from 4336 m^3 to 7412 m^3. This caused the selected LNGc vessel to experience a 50% increase in capacity from 5000 m^3 to 7500 m^3. Moreover, the costs for the routes with and without risk-based models are compared in the following Fig. 8.

The addition of 8.6 days in the RTD also influenced the modeling indicators of investment and operating costs. This is indicated by an increase in the investment costs by 17% or USD 23.97 million from USD 140.91 million to USD 164.87 million due to the number of LNG tanks added at the receiving terminal. The CAPEX cost was observed to have -increased by 16% from USD 0.25 per MMBTU to USD 1.75 per MMBTU.

The infrastructure tariffs were discovered to be dominated by operating costs which were 79% at USD 3.20 per MMBTU and investment costs at 21% at USD 0.87 per MMBTU. These tariffs for the 2 vessels scheme provide efficiency for the existing fuel because they are USD 2.5 per MMBTU higher than the maximum USD 5.6 per MMBTU permitted for the gas distribution duration of 20 years. They also ensure efficiency for the existing fuel because they produce a lower figure of USD 1.53 per MMBTU which is 27% lower than the maximum USD 5.6 per MMBTU permitted.

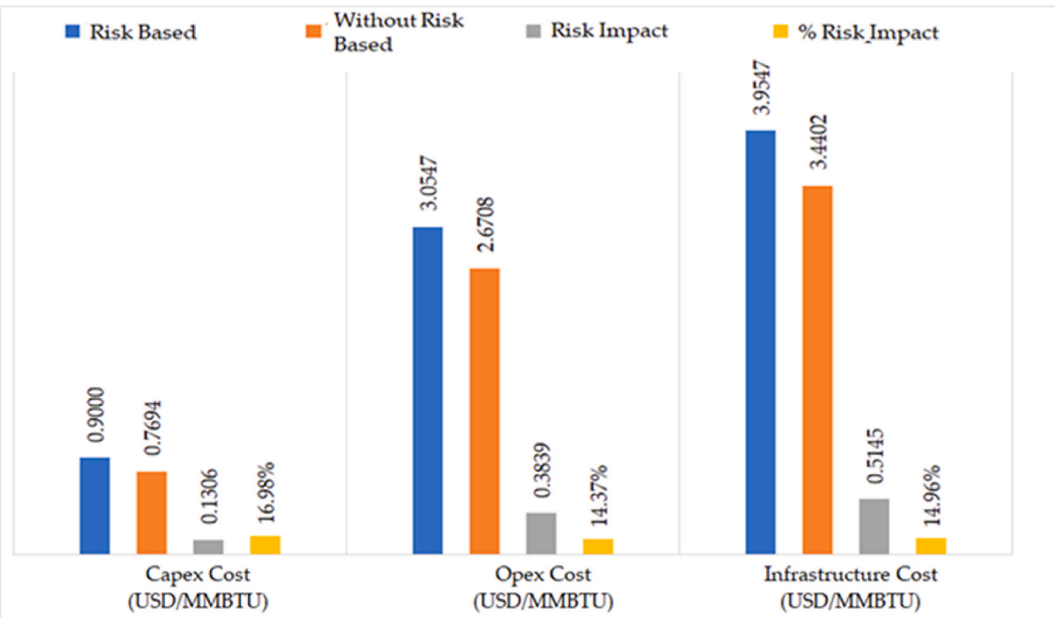


Fig. 6. Comparison of Costs for a 1 Vessel Scheme for Risk-Based and Without Risk-Based models.

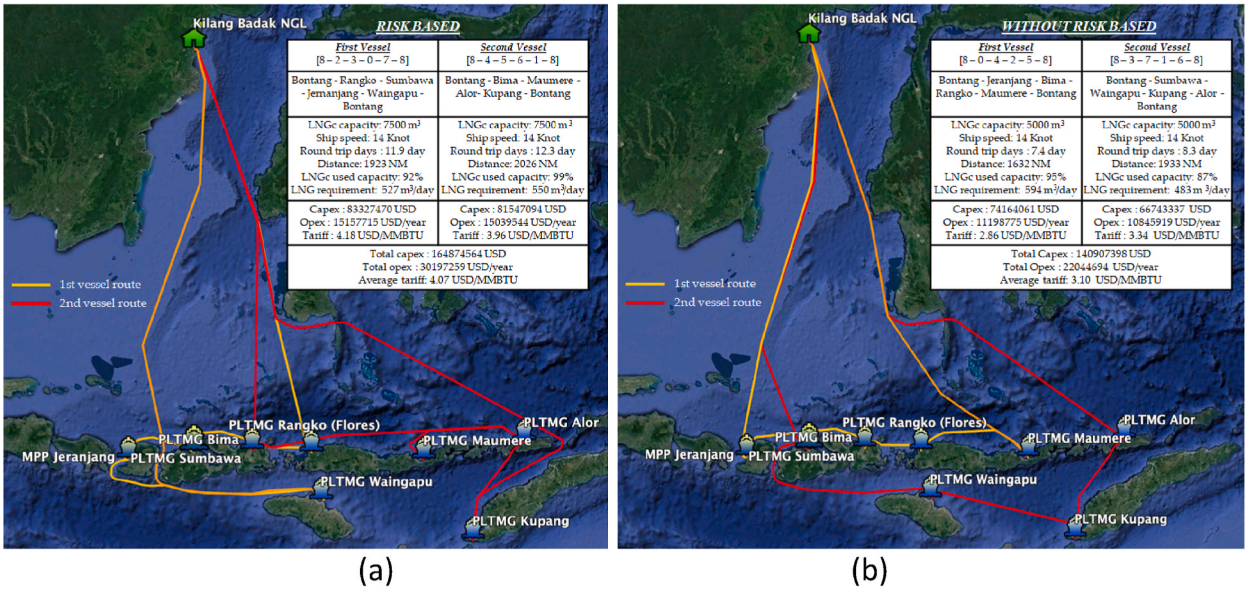


Fig. 7. The best scheme route using 2 vessels: (a) risk-based and (b) without risk-based.

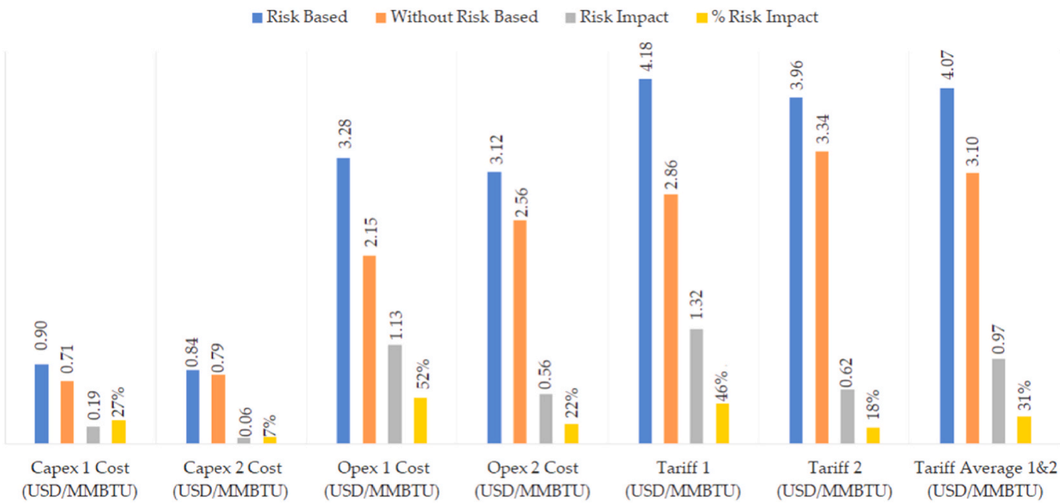


Fig. 8. Comparison of Costs for the 2 Vessels Scheme with and without Risk-Based model.

4.3. Comparison of 1 and 2 vessels schemes

The infrastructure tariffs for Scheme 1 were observed to be lower than Scheme 2 by 3% or USD 0.11 per MMBTU. This is due to an increase in operating costs by 5% or USD 0.14 per MMBTU and a decrease in investment costs by 3% or USD 0.03 per MMBTU. The increase in operating costs was due to an increment in vessel rental costs by 4% or USD 670162 per year. The changes in schemes also led to a 73% increase in route length, thereby, causing a significant increment in the LNGc vessel fuel costs by 83% or USD 1.2 million per year. Moreover, the smaller vessel capacities also had lower port service rates and this led to a decrease in port costs by USD 218386 per year. Therefore, the costs associated with the changes in vessel schemes are compared in the following Fig. 9.

The comparison of the infrastructure tariffs for the models with and without risk for the 2 route schemes showed that the risk-based models are more expensive by 15–31%. It was discovered in the 1 vessel scheme that the tariff increased due to the smallest risk of 15%. However, the risk-based model is beneficial because the needs of every LNG need for the LNG receiving terminal and power plants spread across the regions in Indonesia can be fulfilled.

The changes in vessel routes as well as the increased shipping time (RTD), operating costs, and investment costs due to risk factors are with the findings of Gurning [20] that risk is closely related to the supply chain. For example, bad weather conditions such as extreme wave height can lead to the rise of seawater to the vessel's deck, decreased vessel speed, and changes in the safer shipping

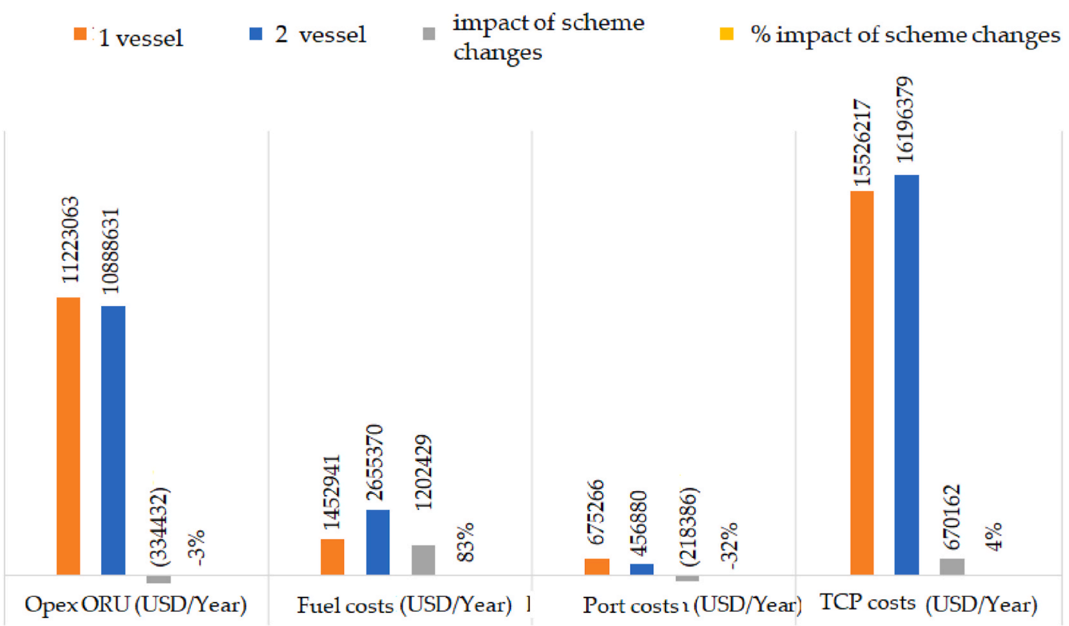


Fig. 9. Effect of changes in vessel schemes on operating costs.

lanes, thereby, causing shipping delays. The changes caused by the risk are also in line with the observation of Humang [6] that the delivery time tends to increase as the vessel route changes when the wave variable is considered in the model. The consequence of considering this wave uncertainty variable is that the delivery time becomes longer, costs increase, and gross profit decreases by 11.8%. However, the advantage is that there is a guarantee that all cargo will be distributed and this can be used to overcome the problem of scarcity in remote, outermost, and border areas of Indonesia.

The decrease in investment costs and increase in operating costs in the 2 vessels scheme is by Koza et al. [36] that the use of this model has the ability to reduce the infrastructure tariffs of the LNG receiving terminal and increase the annual operating cost, especially the LNGc vessel rental and fuel costs. This is further in line with the findings of Humang [33] that the use of clusters is better but there is a chance for inefficiency when there are too many clusters. This is also in line with the findings of Bittante, A. [37], who is able to optimize LNG distribution routes to terminal locations, ship capacity, and the amount of LNG to be supplied to demand locations. Nevertheless, of course, this research still has limitations, including the limited number of ships used in the model, limitations in demand information at each terminal (assuming demand is not real-time), and does not consider environmental factors such as high wave conditions at certain times. In addition, the application of the internal model was only carried out on two routes, whereas in real conditions there were more routes, although it was basically believed that the results of this study could be used in real conditions. In the future, this research will be continued by analyzing what mitigation can be done to reduce the risks that arise in each SS-LNG activity, as was done in Berle's paper [38].

5. Conclusions

Risk factors are often overlooked in the SS-LNG supply chain process, even though, in real-world conditions, many risks may occur and hinder the distribution process. This paper develops the VRPMR model is able to reduce risks in SS-LNG, which can be applied to operational planning. Consideration of risk indicators in the SS-LNG supply chain model has been observed to increase infrastructure tariffs by 15–31% and shipping times by 41–55%. However, it can guarantee the supply needed at each LNG receiving terminal and power plant spread across the Indonesian islands. The change from 1 to 2 vessel schemes was also found to have reduced investment costs by 3–5% due to lower capital costs to build tanks at the LNG terminal and increased operating costs by 4–5% due to increased vessel charter and fuel costs.

In general, it is observed that the change in the scheme leads to an increase in the infrastructure tariff of 3%. The optimal risk-based SS-LNG supply chain model with 2-vessel scheme ensures a fuel cost efficiency of 27%. The first LNGc vessel has a capacity of 7500 m^3 on the Bontang – Rangko – Sumbawa – Lombok – Waingapu – Bontang route with a total route length of 1923 NM, a round trip day (RTD) duration of 11.9 days, and a vessel speed of 14 knots, while the second also has a capacity of 7500 m^3 on the Bontang - Bima - Maumere - Alor - Kupang - Bontang route with a length of 2026 NM, a RTD duration of 12.3 days, and a vessel speed of 14 knots.

This paper provides new insights from previous studies by quantifying risk in CAPEX and OPEX costs which are termed infrastructure tariff. The mathematical model with the VRPMR approach is suitable as a risk-based decision-making tool. This paper has not considered the rapidly fluctuating demand conditions, and the routes obtained are still static routes. Further research is needed that takes into account the real-time system when making decisions about the routes to be traversed by vessels, the addition of wave variables, and demand uncertainty.

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Author contribution statement

Rossy Armyn Machfudiyanto: Windra Priatna Humang: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Fadhilah Muslim: Conceived and designed the experiments; Contributed reagents, materials, analysis tools or data.

Nurul Wahjuningsih: Performed the experiments.

Insannul Kamil: Performed the experiments; Analyzed and interpreted the data.

Mohammad Ichsan: Analyzed and interpreted the data; Wrote the paper.

Yanuar Yudha Adi Putra: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

Data availability statement

Data will be made available on request.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Rossy Armyn Machfudiyanto reports financial support was provided by University of Indonesia. Windra Priatna Humang reports a relationship with National Research and Innovation Agency Republic of Indonesia that includes: board membership. The authors consist of several agencies including the University of Indonesia, National Research and Innovation Agency, Bandung Institute of Technology, University of Andalas, Bina Nusantara University, and Hasanuddin University.

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Appendix 1. CAPEX Cost (USD)

No	System Name	Equipment	MPP Jeranjang	PLTMG Kupang	PLTMG Rangko	PLTMG Sumbawa	PLTMG Bima	PLTMG Maumere	PLTMG Alor	PLTMG Waingapu	Badak NGL
1	LNG distribution system	- LNG pump package	1008186	1008186	1008186	1008186	1008186	1008186	1008186	1008186	1008186
		- Cryogenic line pipe	345024	396777	552038	379525	448530	465782	293270	465782	
		- Piping, valves, insulation etc	252907	252907	252907	252907	252907	252907	252907	252907	252907
2	LNG storage system	- LNG storage tank (ISO Tank)									
		- LNG Pump (RU Feeder)	89617	89617	89617	89617	89617	89617	89617	89617	
		- Cryogenic line pipe	43180	43180	43180	43180	43180	43180	43180	43180	
		- Piping, valves, insulation etc	23180	23180	23180	23180	23180	23180	23180	23180	23180
3	Regasification System	- Heat exchanger (ambient air type)	134425	134425	134425	134425	134425	134425	134425	134425	
		- Gas heater (steam)	78114	78114	78114	78114	78114	78114	78114	78114	
4	BOG management system	- BOG compressor	784145	784145	784145	784145	784145	784145	784145	784145	
		- Piping, valves, insulation etc	196036	196036	196036	196036	196036	196036	196036	196036	196036
5	Gas Delivery System	- Line pipe gas alam	20164	20164	20164	20164	20164	20164	20164	20164	
		- Metering unit gas alam	1680	1680	1680	1680	1680	1680	1680	1680	
		- Piping, valves, insulation etc	22012	22012	22012	22012	22012	22012	22012	22012	

(*continued on next page*)

(*continued*)

No	System Name	Equipment	MPP Jeranjang	PLTMG Kupang	PLTMG Rangko	PLTMG Sumbawa	PLTMG Bima	PLTMG Maumere	PLTMG Alor	PLTMG Waingapu	Badak NGL
6	Power plants	- Self driven electric generator (diesel) skid	1344248	1344248	1344248	1344248	1344248	1344248	1344248	1344248	
7	Buildings and offices	- Control room	22404	22404	22404	22404	22404	22404	22404	22404	
		- Office building	56010	56010	56010	56010	56010	56010	56010	56010	
		- Parking lot, muster station, utility area	11202	11202	11202	11202	11202	11202	11202	11202	
8	Fire protection system	- Hydrant pillar	2801	2801	2801	2801	2801	2801	2801	2801	2801
		- Fire alarm, gas detector	5601	5601	5601	5601	5601	5601	5601	5601	5601
		- Portable fire distinguisher	504	504	504	504	504	504	504	504	504
		- Hydrant pump	2801	2801	2801	2801	2801	2801	2801	2801	2801
9	Purging System	- Nitrogen storage tank	22404	22404	22404	22404	22404	22404	22404	22404	22404
		- Piping, valves, insulation etc	2240	2240	2240	2240	2240	2240	2240	2240	2240
10	Control and monitoring system	- Process control system (PCS), DCS (hardware and software)	896165	896165	896165	896165	896165	896165	896165	896165	896165
11	Electricity system	- Electrical power system	2800	2800	2800	2800	2800	2800	2800	2800	2800
12	ESD System	- Emergency safety device (ESD) system	896165	896165	896165	896165	896165	896165	896165	896165	896165
13	Marine facilities	- Jetty and equipment	5896769	6494212	8286543	6295064	7091656	7290804	3974494	7290804	
Sub total			12161034	12810230	14757822	12593831	13459428	13633561	10144740	13633561	3311792
PPN (10%)			1216103	1281023	1475782	1259383	1345942	1363356	1014474	1363356	331179
Total Fixed Cost of Investment			13377137	14091253	16233604	13853214	14805370	14996917	11159214	14996917	3642971

Appendix 2. OPEX Cost (USD)

Activity	Cost (USD)	Vessel capacity	(GT)	2930	3900	5382	6796	7833	9691	12300	14139	17270	20017	23483
			(m^3)	2500	3000	5000	6500	7500	10000	12000	15600	20000	23000	30000
Harbor services	0.007	Per GT		19.3	25.7	35.5	44.8	51.1	63.9	81.1	93.2	113.9	132.0	154.9
Mooring services	0.007	Per GT		21.0	28.0	38.6	48.7	56.2	69.5	88.2	101.4	123.9	143.6	168.4
Ship guide services														
- Fixed	5.197	vessel/movement		10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4	10.4
- Variable	0.002	GT/vessel/movement		9.3	12.4	17.2	21.7	25.0	30.9	39.2	45.1	55.1	63.8	74.9
LTP port fee per call				60	77	102	126	143	175	219	250	303	350	49
Ship delay service														
a. 2001–3500 GT														
- Fixed	42.202	vessel/hour		506.4										
- Variable	0.001	GT/vessel/hour		27.2										
b. 3501–8000 GT														
- Fixed	59.599	vessel/hour			715.2	715.2	715.2	715.2						
- Variable	0.001	GT/vessel/hour			36.2	49.9	63.0	72.6						
c. 8001–14000 GT														
- Fixed	100.363	vessel/hour							1204.4	1024.4				
- Variable	0.001	GT/vessel/hour							89.8	114.0				
d. 14001–23000 GT														
- Fixed	220.951	vessel/hour									2651.4	2651.4	2651.4	2651.4
- Variable	0.001	GT/vessel/hour									131.1	160.1	185.6	217.7
Delay fee per location per call				534	751	765	778	788	1294	1318	2782	2812	2837	2869
Port fee per location per call				594	828	867	904	931	1469	1537	3033	3115	3187	3278

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