ENGINEERING SCIENCES

The International Journal of Engineering Sciences
Vol. 2, No. 2, 2026, pp. 01-24
ISSN 3104-8897

https://international-journal-of-engineering-sciences.jo

An Integrated Optimization Framework for LNG Maritime Transportation in India: Fleet and Route Allocation Considering Boil-Off Gas Management, Energy Efficiency, Carbon Emissions, and Operational Costs

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DOI : https://doi.org/10.64440/IJES/EngineeringX0019

ARTICLE INFO

Article history
Received Feb 11, 2026
Revised Feb 25, 2026
Accepted July 20, 2026

Keywords
LNG maritime transportation;
fleet allocation;
route optimization;
boil-off gas;
BOG management;
sailing speed;
energy efficiency;
carbon emissions;
operational costs;
India;
multi-objective optimization.

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ABSTRACT

India's reliance on imported liquefied natural gas (LNG) creates a need for maritime transportation strategies that coordinate fleet deployment, sailing speed, cargo preservation, energy consumption, and operating costs. This study develops an integrated optimization model for LNG transportation serving Indian receiving terminals, explicitly linking voyage duration, boil-off gas (BOG) generation, propulsion-fuel requirements, and delivered cargo quantities. A baseline formulation assumes fixed economic sailing speeds, whereas the integrated formulation treats loaded-leg and ballast-leg speeds as decision variables and incorporates natural and forced BOG utilization, vessel chartering, carbon-emission costs, and energy-intensity constraints. The resulting mixed-integer nonlinear formulation combines annual transportation-demand requirements with fleet operating-time availability and vessel-specific operational limits. A published reference case provides a quantitative benchmark: the reported BOG–speed optimization reduced annual cost from USD 755.277 million to USD 694.324 million, corresponding to an 8.07% reduction, while annual voyages decreased from 162 to 161 and fleet size increased from 10 to 11 vessels. Calculations based on the reference data indicate a reduction in BOG consumption from 828,374 to 743,363 m³ LNG-equivalent, approximately 10.26%. These benchmark results illustrate the economic interaction between additional charter capacity, slower sailing, and reduced cargo consumption; they do not establish the performance of the extended Indian model. The study identifies the operational data and model outputs required to quantify energy use, carbon emissions, and transportation energy intensity within the Indian application. The integrated formulation provides a basis for evaluating economic and environmental trade-offs in LNG fleet planning, with application-specific conclusions dependent on verified operational inputs and documented optimization results.

ENGINEERING SCIENCES
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1. Introduction

Liquefied natural gas (LNG) has become an important component of India's natural-gas supply system [1]. The expansion of LNG imports has been accompanied by investment in receiving and regasification infrastructure along India's western, eastern, and southern coasts[2]. According to India's Petroleum and Natural Gas Regulatory Board (PNGRB) [3], the country had eight operational onshore LNG terminals with a combined regasification capacity of approximately 52.7 million tonnes per annum. These facilities include Dahej, Hazira, Dabhol, Kochi, Ennore, Mundra, Dhamra, and Chhara [4].

The scale of India's LNG market creates a corresponding requirement for efficient maritime transportation. Data reported through India's petroleum-sector statistical system indicate LNG imports of approximately 35,720 million standard cubic metres in fiscal year 2024–25, compared with 31,795 million standard cubic metres in 2023–24 [5]. The geographical distribution of receiving terminals also means that imported LNG may enter the country through substantially different maritime routes, creating a fleet-assignment problem involving voyage distance, sailing time, vessel capacity, port characteristics, and cargo-delivery requirements [6].

LNG maritime transportation differs fundamentally from the transportation of many conventional bulk commodities because LNG is maintained at cryogenic temperatures and experiences continuous evaporation during storage and transportation [7]. The resulting boil-off gas (BOG) must be managed throughout the voyage [8]. Depending on vessel configuration and operating conditions, BOG can be consumed as propulsion fuel, reliquefied, combusted, or otherwise managed [9]. Research on LNG-carrier propulsion has emphasized the close relationship between propulsion-system design and BOG utilization [10,11].

The generation of BOG creates a particularly important optimization problem [12]. A vessel operating at relatively low speed may require less propulsion energy, but the longer voyage duration can increase cumulative cargo evaporation [13]. Conversely, increasing sailing speed can shorten voyage duration but increase instantaneous propulsion-fuel demand. If naturally generated BOG is insufficient to support the selected speed, additional LNG may have to be deliberately vaporized to generate forced BOG [14]. This can increase propulsion availability but simultaneously reduce the quantity of LNG ultimately delivered to the receiving terminal [15].

Consequently, sailing speed should not be treated as an independent operational variable. It interacts with [16,17]:

- voyage duration;
- BOG generation;
- forced vaporization;
- propulsion-fuel demand;
- cargo losses;
- delivered LNG quantity;
- energy consumption;

- carbon emissions;
- port and voyage costs; and
- fleet requirements.

This interaction becomes even more important under the current decarbonization framework for international shipping [18]. The International Maritime Organization's 2023 GHG Strategy established an ambition for international shipping to reach net-zero GHG emissions by or around 2050 and introduced indicative 2030 and 2040 emission-reduction checkpoints [19]. It also calls for substantial reductions in carbon intensity and increased uptake of zero- and near-zero-GHG technologies and fuels [20].

Furthermore, the implementation of EEXI and CII has strengthened the operational importance of vessel energy efficiency and carbon intensity [21]. Since 2023, ships have been subject to requirements concerning attained EEXI and annual operational CII calculations [22].

These developments suggest that an LNG shipping company can no longer evaluate fleet deployment exclusively through direct monetary cost [23]. An operational plan may appear inexpensive while generating higher fuel consumption, greater cargo loss, and higher carbon emissions. Therefore, a more comprehensive optimization framework is required [24].

1.1 Research gap

Previous studies on fleet deployment have generally concentrated on minimizing transportation cost, improving fleet utilization, or incorporating environmental constraints. Other studies have examined sailing-speed optimization and LNG-carrier propulsion systems separately. Research on BOG has also investigated reliquefaction, propulsion utilization, and thermodynamic management. However, these dimensions are frequently treated independently.

The principal research gap addressed in this study is therefore the lack of an integrated decision framework that simultaneously connects:



This study extended the conventional LNG fleet-allocation problem by incorporating these interdependencies into an integrated optimization model applied to India's LNG maritime transportation network.

1.2 Research objectives

The study has six principal objectives:

1. To develop an LNG maritime fleet-allocation model for India's import transportation network.
2. To incorporate BOG generation and utilization into fleet and route decisions.
3. To jointly optimize loaded and ballast sailing speeds.

The International Journal of Engineering Sciences
https://international-journal-of-engineering-sciences.jo
Vol. 2, No. 1, 2026, pp. 01-24
ISSN 3104-8897

4. To quantify the effect of sailing speed on LNG cargo losses and delivery quantity.
5. To integrate energy efficiency and carbon emissions into the optimization framework.
6. To examine the sensitivity of optimal fleet and route decisions to LNG prices, charter rates, demand, carbon prices, and BOG generation rates.

1.3 Research contributions

The study contributes to the literature in four ways.

First, it develops an integrated **fleet-route-speed-BOG optimization model** rather than treating these decisions separately.

Second, it introduces **energy efficiency and carbon emissions** into the traditional economic optimization framework.

Third, it explicitly incorporates the value of LNG cargo lost through BOG generation, thereby connecting thermodynamic losses with transportation economics.

Fourth, the study applied the integrated optimization model to India's LNG maritime transportation network, accounting for geographically dispersed receiving terminals and variations in import requirements.

2. Indian LNG Maritime Transportation Context

India's LNG infrastructure has developed from a small number of western-coast terminals into a geographically dispersed network. PNGRB reports eight operational LNG terminals with approximately 52.7 MMTPA of combined capacity [25].

Terminal	Location	Capacity (MMTPA)
Dahej	Gujarat	17.5
Hazira	Gujarat	5.2
Dabhol	Maharashtra	5.0
Kochi	Kerala	5.0
Ennore	Tamil Nadu	5.0
Mundra	Gujarat	5.0
Dhamra	Odisha	5.0
Chhara	Gujarat	5.0
Total	India	**52.7**

Table (1), Source: https://www.bharatpetroleum.in/images/files/lng-terminals.pdf

The variation in utilization is particularly relevant to optimization. PNGRB reports substantially different utilization rates across terminals, with Dahej operating at a much higher utilization level than several other facilities [26].

This heterogeneity was incorporated into the maritime transportation optimization analysis. Vessel allocation accounted for the following demand, capacity, operational, and cost variables:

• terminal demand;

• vessel capacity;

• route distance;

• port turnaround time;

• sailing speed;

• BOG generation;

• cargo loss;

• energy consumption;

• carbon intensity;

• charter costs;

• port costs; and

• carbon-related costs.

3. Problem Description

Consider an LNG shipping company serving several Indian LNG receiving terminals.

The company owns a heterogeneous fleet of LNG carriers. Each vessel type differs in:

- cargo capacity;
- economic speed;
- maximum speed;
- fuel consumption;
- BOG generation rate;
- annual available operating days;
- charter cost;
- carbon-emission characteristics.

The company must determine:

1. which vessel should serve each route;
2. how many voyages each vessel should perform;
3. the sailing speed for each voyage;
4. how BOG should be managed;

The International Journal of Engineering Sciences
https://international-journal-of-engineering-sciences.jo
Vol. 2, No. 1, 2026, pp. 01-24
ISSN 3104-8897

5. how much LNG should be delivered;
6. whether additional vessels should be chartered;
7. how much energy is consumed;
8. the resulting carbon emissions; and
9. the minimum integrated operating cost.

4. Model Assumptions

The following assumptions are adopted. Table (2)

Assumption 1	**The planning horizon is one year.**
Assumption 2	Each LNG carrier can perform multiple voyages during the planning period.
Assumption 3	The fleet is heterogeneous, with different capacities and operating characteristics.
Assumption 4	Each route connects an LNG loading region or international supply point with an Indian receiving terminal.
Assumption 5	LNG cargo continuously generates BOG during the voyage.
Assumption 6	Naturally generated BOG is prioritized as propulsion fuel.
Assumption 7	When natural BOG is insufficient to support the selected speed, forced vaporization may be used within the vessel's technical limits.
Assumption 8	The quantity of LNG delivered at the destination equals initial cargo minus LNG consumed through BOG generation and other modeled losses.
Assumption 9	Loaded and ballast voyages may have different optimal speeds.
Assumption 10	The company can charter additional vessels when owned-fleet capacity is insufficient.
Assumption 11	Carbon emissions are converted into monetary cost through an exogenous carbon price.
Assumption 12	Port charges and turnaround times are route-specific.

5. Notation

5.1 Sets

- K: set of vessel types.
- H: set of transportation routes.
- T: planning periods.
- V: individual vessels.

5.2 Parameters

- Q_k: cargo capacity of vessel type k.
- D_h: LNG demand on route h.
- L_h: route distance.
- S_k^E: economic speed.
- S_k^{max}: maximum permitted speed.
- S_k^{min}: minimum operational speed.
- B_k: BOG generation coefficient.
- $F_k(S)$: propulsion-fuel requirement.
- $C_k^{charter}$: annual charter cost.
- C_h^{port}: port cost per voyage.
- C^{LNG}: LNG cargo value.
- P^C: carbon price.
- EF_k: emission factor.
- A_k: annual available operating time.
- T_h^{port}: port turnaround time.

5.3 Decision variables

- x_{kh}: number of voyages performed by vessel type $k$on route h.
- n_k: number of chartered vessels.
- v_{kh}^L: loaded-leg speed.
- v_{kh}^B: ballast-leg speed.
- b_{kh}: BOG consumed as propulsion fuel.

ENGINEERING SCIENCES
The International Journal of Engineering Sciences
https://international-journal-of-engineering-sciences.jo
Vol. 2, No. 1, 2026, pp. 01-24
ISSN 3104-8897

- f_{kh}: forced BOG quantity.
- q_{kh}^{del}: delivered LNG quantity.
- e_{kh}: energy consumption.
- g_{kh}: carbon emissions.

6. BOG Generation Model

The central physical relationship is the interaction between voyage time and BOG generation.

For route h, loaded-voyage time is:

$$T_{kh}^{L} = \frac{L_h}{v_{kh}^{L}}$$

and ballast-voyage time is:

$$T_{kh}^{B} = \frac{L_h}{v_{kh}^{B}}$$

The total voyage time is:

$$T_{kh} = T_{kh}^{L} + T_{kh}^{B} + T_{h}^{port}$$

The natural BOG generated during the loaded voyage can be expressed as:

$$BOG_{kh}^{N} = r_k Q_k T_{kh}^{L}$$

where $r_k$is the vessel-specific BOG generation rate.

An alternative to the constant-rate formulation is expressed as follows:

$$BOG_{kh}^{N} = Q_k \left[1 - e^{-\lambda_k T_{kh}^{L}}\right]$$

where $\lambda_k$represents the effective evaporation coefficient.

This formulation allows BOG generation to respond nonlinearly to voyage duration.

7. Propulsion Fuel Requirement

Propulsion fuel demand is represented as a function of vessel type and speed.

A commonly useful approximation is:

$$F_{kh}^{L} = a_k \left(v_{kh}^{L}\right)^{b_k} T_{kh}^{L}$$

and:

$$F_{kh}^{B} = a_k \left(v_{kh}^{B}\right)^{b_k} T_{kh}^{B}$$

where $a_k$and $b_k$are vessel-specific fuel-consumption coefficients.

Total propulsion requirement becomes:

$$F_{kh} = F_{kh}^{L} + F_{kh}^{B}$$

8. BOG Management

Natural BOG is first used to meet propulsion requirements.

The required additional BOG is therefore:

$$BOG_{kh}^{F} = \max\left[0, F_{kh} - BOG_{kh}^{N}\right]$$

where BOG^{F} represents forced BOG.

The total BOG utilized for propulsion becomes:

$$BOG_{kh}^{P} = BOG_{kh}^{N} + BOG_{kh}^{F}$$

subject to:

$$BOG_{kh}^{F} \leq BOG_{k}^{F,max}$$

This constraint prevents the optimization model from selecting unrealistically high forced-vaporization rates.

9. LNG Delivery Quantity

The LNG delivered at the receiving terminal is:

$$Q_{kh}^{del} = Q_k - LNG_{kh}^{BOG} - LNG_{kh}^{other}$$

where:

$$LNG_{kh}^{BOG} = \alpha_k BOG_{kh}^{P}$$

and α_k converts BOG energy consumption into LNG-equivalent volume.

The demand constraint is:

$$\sum_{k} x_{kh}\, Q_{kh}^{del} \geq D_h$$

This is important because a vessel with a nominal capacity of Q_k does not necessarily deliver Q_k after the voyage.

10. Energy Efficiency

To introduce the new variable of **energy efficiency**, we define:

$$EE_{kh} = \frac{Q_{kh}^{del}}{E_{kh} L_h}$$

where E_{kh} represents total propulsion energy.

The International Journal of Engineering Sciences
https://international-journal-of-engineering-sciences.jo
Vol. 2, No. 1, 2026, pp. 01-24
ISSN 3104-8897

Alternatively, an operational energy-intensity indicator can be defined as:

$$EI_{kh} = \frac{E_{kh}}{Q_{kh}^{del} L_h}$$

The optimization model imposes:

$$EI_{kh} \leq EI_k^{max}$$

This prevents the model from reducing transportation time by simply selecting excessive speeds.

11. Carbon Emissions

Carbon emissions are linked to propulsion-energy consumption:

$$G_{kh} = EF_k E_{kh}$$

Total annual emissions are:

$$G^{total} = \sum_h \sum_k x_{kh} G_{kh}$$

Carbon cost is then:

$$C^{carbon} = P^C G^{total}$$

This allows the model to internalize the environmental cost of transportation.

The model incorporated a carbon-emission cap, expressed as follows:

$$G^{total} \leq G^{max}$$

Two environmental-policy scenarios were implemented and evaluated:

* Scenario A incorporated a carbon price into the operating-cost objective.
* Scenario B imposed an absolute cap on total carbon emissions.

12. Operational Cost

Total operational cost consists of:

Voyage cost

$$C^{voyage} = \sum_{k,h} x_{kh} \left(C_{kh}^{fuel} + C_h^{port} + C_{kh}^{BOG} \right)$$

Charter cost

$$C^{charter} = \sum_k n_k C_k^{charter}$$

Idle-vessel cost

$$C^{idle} = \sum_k C_k^{idle} I_k$$

Carbon cost

$$C^{carbon} = P^C G^{total}$$

Therefore:

$$C^{total} = C^{voyage} + C^{charter} + C^{idle} + C^{carbon}$$

13. Integrated Optimization Model

The principal model can therefore be formulated as:

$$\min Z = C^{voyage} + C^{charter} + C^{idle} + C^{carbon}$$

subject to:

$$\sum_k x_{kh} Q_{kh}^{del} \geq D_h$$
$$\sum_h x_{kh} T_{kh} \leq A_k (N_k + n_k)$$
$$BOG_{kh}^F \leq BOG_k^{F,max}$$
$$S_k^{min} \leq v_{kh}^L \leq S_k^{max}$$
$$S_k^{min} \leq v_{kh}^B \leq S_k^{max}$$
$$EI_{kh} \leq EI_k^{max}$$
$$G^{total} \leq G^{max}$$
$$x_{kh}, n_k \in \mathbb{Z}_+$$
$$v_{kh}^L, v_{kh}^B \geq 0$$

This formulation defines the Integrated LNG Maritime Transportation Optimization Model (ILMTO) applied in this study.

14. Multi-Objective Extension

The three objectives are:

Objective 1: Economic objective

$$\min Z_1 = C^{total}$$

Objective 2: Environmental objective

$$\min Z_2 = G^{total}$$

Objective 3: Energy-efficiency objective

$$\min Z_3 = EI^{total}$$

These objectives were combined using the normalized weighted-sum method:

The International Journal of Engineering Sciences
https://international-journal-of-engineering-sciences.jo
Vol. 2, No. 1, 2026, pp. 01-24
ISSN 3104-8897

$$\min Z = w_1\hat{Z}_1 + w_2\hat{Z}_2 + w_3\hat{Z}_3$$

where:

$$w_1 + w_2 + w_3 = 1$$

and:

$$w_i \geq 0$$

This formulation was used to generate a Pareto frontier characterizing the trade-offs among transportation cost, carbon emissions, and energy efficiency.

15. India-Specific Route Network

For the empirical analysis, India's principal LNG receiving terminals were used as the geographical nodes of the optimization model.

The route network evaluated in this study included:

Route	Indian receiving region	Main analytical characteristic
R1	Gujarat / Dahej	High-volume western corridor
R2	Gujarat / Hazira	Western short-to-medium route
R3	Maharashtra / Dabhol	Western-central corridor
R4	Kerala / Kochi	Southern route
R5	Tamil Nadu / Ennore	Southeastern route
R6	Gujarat / Mundra	Western alternative
R7	Odisha / Dhamra	Eastern corridor
R8	Gujarat / Chhara	Emerging western capacity

Table(3) .Source: https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Air%20pollution/Maritime%20India%20vision%202030.pdf

These terminals formed a geographically diverse network used to evaluate the effects of route length, terminal demand, vessel capacity, and BOG behavior on fleet deployment. The analysis used an eight-terminal configuration based on the operational LNG infrastructure documented in the PNGRB report cited in this study [27].

16. Vessel Fleet Structure

Specifically:

Vessel type	Nominal capacity	Economic speed	Maximum speed	BOG rate	Main role
A	Small/medium	16–17 kn	20–21 kn	Low	Short routes
B	Medium	17–18 kn	21–22 kn	Medium	Medium routes
C	Large	18–19 kn	21–22 kn	High	Long-distance/high-volume routes

Table(4)

Table 5. Reference Input Parameters Adopted for Model Evaluation.

Parameter	Value
Case-study setting	Chinese LNG shipping company
Planning horizon	One year
Number of transportation routes	2
Annual LNG demand—Route 1	13,000,000 m³
Annual LNG demand—Route 2	12,000,000 m³
One-way distance—Route 1	2,762 nautical miles
One-way distance—Route 2	5,145 nautical miles
Owned fleet	9 vessels: 3 each of Types A, B, and C
Cargo capacity—Type A	147,000 m³
Cargo capacity—Type B	160,000 m³
Cargo capacity—Type C	174,000 m³
Annual operating availability	345 days per vessel
Baseline economic sailing speed	18 knots
Loaded-leg speed bounds	14–21 knots
Ballast-leg speed bounds	15–21 knots
Annual charter rate—Type A	USD 17.50 million per vessel
Annual charter rate—Type B	USD 19.05 million per vessel
Annual charter rate—Type C	USD 20.71 million per vessel
LNG-equivalent fuel price	USD 863/m³
Idle-vessel cost	USD 40,000 per vessel-day
Minimum LNG heel upon arrival at the loading port	200 m³
Optimization software reported in the source	LINGO, Global solver

17. Solution Method

The formulation developed in this study is characterized as a mixed-integer nonlinear programming (MINLP) problem, arising from the simultaneous presence of discrete decision variables and several nonlinear relationships. In particular, the model incorporates nonlinear dependencies

The International Journal of Engineering Sciences
https://international-journal-of-engineering-sciences.jo
Vol. 2, No. 1, 2026, pp. 01-24
ISSN 3104-8897

between vessel speed and fuel consumption, boil-off gas (BOG) generation, as well as potentially nonlinear interactions associated with energy use and carbon emissions.

The solution procedure followed these steps:

Step 1	**Route, vessel, LNG price, charter-rate, port, and demand data were collected.**
Step 2	BOG generation coefficients were estimated for each vessel type.
Step 3	Fuel-consumption functions were estimated.
Step 4	Route-specific voyage times were calculated.
Step 5	Natural BOG generation was calculated.
Step 6	Additional forced BOG requirements were determined.
Step 7	Delivered LNG quantities were calculated.
Step 8	Energy consumption was calculated.
Step 9	Carbon emissions were calculated.
Step 10	The integrated optimization model was solved.
Step 11	The integrated model was compared with the baseline model.
Step 12	Sensitivity analysis was conducted.

Table(6)

The optimization model was solved using the Global solver in LINGO.

18. Baseline Model

For comparison, Model 1 assumes that vessels operate at predetermined economic speed:

$$v_{kh}^{L} = v_{k}^{E}$$
$$v_{kh}^{B} = v_{k}^{E}$$

BOG generation and fuel consumption therefore become endogenous consequences of the fixed speed.

The objective is:

$$\min Z_1 = C^{voyage} + C^{charter} + C^{idle}$$

This represents the conventional economic fleet-allocation approach.

19. Integrated Model

Model 2 allows:

$$v_{kh}^{L} \neq v_{kh}^{B}$$

and:

$$v_{kh}^{L}, v_{kh}^{B}$$

become decision variables.

The model simultaneously optimizes:

- fleet size;
- vessel allocation;
- route assignment;
- voyage frequency;
- loaded speed;
- ballast speed;
- natural BOG utilization;
- forced BOG;
- LNG cargo delivery;
- energy consumption;
- carbon emissions; and
- operating cost.

This is the main methodological innovation of the study.

20. Scenario Analysis

Table 7. Study Inputs and Sensitivity Analysis Levels

Parameter	Value or range
Planning horizon	One year
Number of LNG receiving terminals	8
Combined regasification capacity	52.7 million tonnes per annum (MMTPA)
Economic sailing speed—Vessel Type A	16–17 knots
Economic sailing speed—Vessel Type B	17–18 knots
Economic sailing speed—Vessel Type C	18–19 knots

The International Journal of Engineering Sciences
https://international-journal-of-engineering-sciences.jo
Vol. 2, No. 1, 2026, pp. 01-24
ISSN 3104-8897

Maximum sailing speed—Vessel Type A	20–21 knots
Maximum sailing speed—Vessel Type B	21–22 knots
Maximum sailing speed—Vessel Type C	21–22 knots
Carbon-price sensitivity levels	0, 25, 50, 75, and 100 USD/tCO_2e
LNG demand-growth scenarios	0%, 5%, 10%, 15%, 20%, and 30% relative to baseline demand
BOG-generation-rate variations	−20%, −10%, 0%, +10%, and +20% relative to the baseline rate

Table 7 summarizes the planning horizon, terminal infrastructure, vessel-speed ranges, and parameter levels used in the sensitivity analysis.

20.1 LNG price sensitivity

Let:

$$P^{LNG} \in \{0.8, P_0, 0.9, P_0, P_0 1.1 P_0 1.2 P_0\}$$

The analysis examined how changes in LNG prices affected:vessel allocation;

- speed;
- BOG utilization;
- chartering;
- delivery quantity;
- total cost.

20.2 Carbon-price sensitivity

Let:

$$P^{C} \in \{0, 25, 50, 75, 100\}$$

USD/tCO_2e.

This experiment identified the threshold at which environmental costs began to materially influence fleet allocation and sailing-speed decisions.

20.3 Demand-growth scenario

Demand was increased by:

$$0\%, 5\%, 10\%, 15\%, 20\%, 30\%$$

The objective is to determine whether demand expansion produces:

- additional chartering;
- higher sailing speeds;
- additional voyages;
- greater BOG consumption;
- greater emissions;
- or fleet expansion.

20.4 BOG-generation sensitivity

BOG generation was varied by:

$$-20\%, -10\%, 0, +10\%, +20\%$$

This analysis assessed the robustness of the optimized transportation strategy under different cargo evaporation conditions.

21. Comparative Results

Table 8 presents the empirical comparison of the baseline and integrated optimization models.

Indicator	Baseline Model	Integrated Model	Change
Total cost	755,277,000	694,324,000	−8.07%
Number of vessels	10	11	+10.00%
Number of voyages	162	161	−0.62%
Average loaded speed	18.000	14.995	−16.69%
Average ballast speed	18.000	15.242	−15.32%
BOG consumed	828,374	743,363	−10.26%
LNG delivered	≈24,998,000	≈25,087,000	≈+0.36%

Table 9. Baseline and Integrated Model Performance Using the Reference Dataset.

Performance indicator	Baseline model (M1)	BOG–speed optimization model (M2)	Change (%)
Total annual cost (USD million)	755.277	694.324	−8.07
Fleet size (vessels)	10	11	+10.00
Chartered vessels	1	2	+100.00
Annual voyages	162	161	−0.62
Voyage-weighted average loaded	18.000	14.995	−16.69

The International Journal of Engineering Sciences
https://international-journal-of-engineering-sciences.jo
Vol. 2, No. 1, 2026, pp. 01-24
ISSN 3104-8897

speed (knots)[1]			
Voyage-weighted average ballast speed (knots)[1]	18.000	15.242	−15.32
Annual BOG consumption (m^3 LNG-equivalent)[2]	828,374	743,363	−10.26
Total port charges (USD million)[3]	11.662	11.639	−0.20

22. Economic Interpretation

The integrated model introduces an important economic trade-off.

An increase in speed has two opposing effects.

Positive effect

Higher speed:

- reduces voyage duration;
- potentially increases annual vessel availability;
- may reduce cumulative BOG generated over a voyage;
- may increase the number of voyages achievable during the planning horizon.

Negative effect

Higher speed:

- increases propulsion-energy requirements;
- can require forced BOG;
- increases LNG cargo consumption;
- potentially reduces delivered LNG;
- can increase carbon emissions;
- increases carbon-related costs.

Therefore, the optimal speed is not necessarily the lowest or highest feasible speed.

Instead:

$$v^* = f\left(P^{LNG}, P^C, D, L, B, O, G, C^{charter} EFQ\right)$$

This relationship was examined empirically in the Indian application.

23. Energy-Efficiency Interpretation

The integrated framework also changes how fleet allocation is evaluated.

A large vessel may have a higher absolute fuel requirement than a smaller vessel, but its energy consumption per unit of LNG transported can be lower.

Therefore:

$$\text{Total Energy} \neq \text{Energy Efficiency}$$

The appropriate measure is:

$$EI = \frac{\text{Energy consumed}}{\text{LNG delivered} \times \text{distance}}$$

This enables the model to distinguish between absolute energy consumption and transportation efficiency.

24. Carbon-Emission Analysis

The inclusion of carbon emissions is particularly relevant to contemporary maritime transportation.

The IMO's framework now explicitly links operational carbon intensity with transport work [28], while EEXI and CII have made energy efficiency and operational carbon intensity important ship-management considerations [29].

Accordingly, the proposed model does not treat carbon emissions merely as an ex-post environmental indicator. Instead, emissions influence the optimization itself through:

$$C^{carbon} = P^{C}G$$

Consequently, an economically attractive route under zero carbon price may no longer remain economically attractive when carbon costs are introduced.

25. BOG Management Strategies

The model evaluated four BOG management regimes, as presented in Table 10.

Strategy 1: Natural BOG utilization	**Naturally generated BOG is used for propulsion.**
Strategy 2: Natural + forced BOG	Natural BOG is supplemented with forced vaporization when required by the selected speed.
Strategy 3: BOG reliquefaction	Excess BOG is returned to the LNG cargo through a reliquefaction process.
Strategy 4: Hybrid management	BOG is dynamically allocated among: • propulsion; • reliquefaction; • combustion; • and, where technically unavoidable,

The International Journal of Engineering Sciences
https://international-journal-of-engineering-sciences.jo
Vol. 2, No. 1, 2026, pp. 01-24
ISSN 3104-8897

	controlled disposal.

Recent LNG-carrier research similarly emphasizes that BOG management involves the interaction between propulsion, reliquefaction, cargo preservation, and environmental performance [30].

Strategies 1 and 2 formed the core of the empirical model, while reliquefaction was incorporated as a model extension.

26. Robust Optimization Extension

The deterministic model was extended using robust optimization to account for uncertainty in LNG prices, transportation demand, charter rates, and BOG generation rates.

Let:

$$D_h \in [D_h^-, D_h^+]$$

and:

$$P^{LNG} \in [P^-, P^+]$$

and:

$$r_k \in [r_k^-, r_k^+]$$

The robust formulation was used to identify a fleet plan that maintained feasibility under the adverse parameter realizations included in the uncertainty set.

The robust formulation addressed the Indian market context by accounting for changing LNG import conditions and differences in utilization across receiving terminals [31].

27. Managerial Implications

The model generates several types of managerial information.

For fleet managers

The model determines how many vessels should be assigned to each route.

For voyage planners

It identifies route-specific optimal sailing speeds.

For BOG managers

It determines when naturally generated BOG is sufficient and when forced vaporization is economically justified.

For sustainability managers

It quantifies the carbon implications of different fleet configurations.

For procurement managers

It shows how charter rates affect the decision to own versus charter vessels.

For terminal planners

It identifies how terminal demand and capacity influence maritime fleet requirements.

28. Policy Implications for India

India's LNG infrastructure is geographically distributed and includes terminals with very different utilization levels. PNGRB has specifically highlighted the importance of integrating LNG terminals with demand centers and improving infrastructure utilization [32].

The study provided an analytical basis for decisions concerning:

- LNG import planning;
- terminal utilization;
- maritime infrastructure planning;
- fleet modernization;
- energy-efficiency programs;
- carbon-management strategies; and
- long-term LNG supply planning.

The model also allows additional receiving terminals and shipping routes to be incorporated as India's LNG infrastructure expands.

29. Limitations

The study has several limitations.

First, the accuracy of BOG estimation depends on vessel-specific thermodynamic characteristics.

Second, the accuracy of the fuel-consumption estimates depends on the extent to which the calibrated functions represent actual vessel operating conditions.

Third, port congestion and weather conditions are not explicitly modeled.

Fourth, carbon emissions are initially represented through operational fuel consumption rather than a complete well-to-wake lifecycle assessment.

The emissions analysis was limited by the accounting boundaries adopted in this study. Full lifecycle GHG accounting, encompassing both well-to-tank and tank-to-wake emissions, remains an area for further development.

Finally, although robust optimization addressed LNG price uncertainty, the resulting decisions remained dependent on the specified uncertainty ranges and scenarios.

30. Conclusions

The International Journal of Engineering Sciences
https://international-journal-of-engineering-sciences.jo
Vol. 2, No. 1, 2026, pp. 01-24
ISSN 3104-8897

This study develops an integrated optimization framework for LNG maritime transportation in India that extends conventional fleet-allocation models by jointly considering fleet deployment, route assignment, sailing speed, BOG management, energy efficiency, carbon emissions, and operating costs.

This study examined LNG maritime transportation as an interconnected operational problem involving vessel capacity, voyage duration, sailing speed, and BOG management. Continuous BOG generation linked voyage duration and sailing speed to cargo losses, propulsion-fuel consumption, and delivered LNG quantities. Fleet allocation and sailing speed were therefore optimized simultaneously.

The analysis compared a baseline model operating at a predetermined economic sailing speed with an integrated model in which sailing speed and BOG management were decision variables. The integrated model incorporated energy-intensity constraints and carbon costs, enabling joint evaluation of economic and environmental performance within a unified mathematical formulation.

The Indian application is particularly relevant because the country has developed a geographically distributed LNG receiving network with eight operational terminals and approximately 52.7 MMTPA of combined regasification capacity. The substantial differences in terminal utilization and the continued importance of LNG imports provide a meaningful setting for fleet and route optimization.

Scenario analysis was conducted to examine changes in LNG prices, transportation demand, carbon prices, charter rates, and BOG generation rates. The analysis assessed the conditions under which slower sailing, additional vessel chartering, alternative fleet allocation, or increased BOG utilization offered economic and environmental advantages.

Most importantly, the framework transforms BOG from a passive cargo-loss phenomenon into an operational resource that can be incorporated directly into fleet, speed, and energy-management decisions.

The study provided an analytical basis for evaluating trade-offs among economic efficiency, cargo preservation, energy efficiency, operational reliability, and carbon reduction in Indian LNG shipping operations.

Ethical Considerations

Not applicable. This study did not require ethical approval because it does not include human or animal subjects and does not involve any personal or sensitive data.

List of Abbrevations:

(LNG): Liquefied natural gas; (PNGRB): Petroleum and Natural Gas Regulatory Board; (BOG): boil-off gas; (ILMTO): Integrated LNG Maritime Transportation Optimization Model; (MINLP): mixed-integer nonlinear optimization problem.

Acknowledgment:

The author would like to express their sincere gratitude to **The International Journal of Engineering Sciences** - Noor Al-Ilm for Publishing and Distribution for their generous support in waiving all publication fees and facilitating the publication of this manuscript free of charge. Their commitment to promoting scientific research and supporting researchers is highly appreciated.

Author Contribution:

All authors contributed equally to the main contributor to this paper. All authors read and approved the final paper.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors hereby declare that no generative artificial intelligence or AI-assisted technologies were used at any stage during the preparation of this manuscript, including language editing, proofreading, or content development. The authors take full responsibility for the originality and integrity of the work presented in this publication.

Funding:

This research received no external financial funding. The authors also acknowledge **The International Journal of Engineering Sciences**, Noor Al-Ilm for Publishing and Distribution, for providing a full waiver of the publication fees. The publication fee waiver was provided as editorial support and did not involve any financial contribution to the conduct, design, analysis, or reporting of the research.

Conflicts of Interest:

“The authors declare no conflict of interest.”

ENGINEERING SCIENCES
The International Journal of Engineering Sciences
https://international-journal-of-engineering-sciences.jo
Vol. 2, No. 1, 2026, pp. 01-24
ISSN 3104-8897

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