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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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ABSTRACT

India's increasing reliance on imported liquefied natural gas (LNG) has intensified the need for efficient maritime transportation systems capable of simultaneously addressing fleet utilization, voyage planning, boil-off gas (BOG), energy consumption, carbon emissions, and operating costs. LNG carriers continuously generate BOG during transportation as a consequence of heat ingress into cargo tanks. Although BOG can be utilized as propulsion fuel, its management directly affects cargo losses, voyage speed, fuel consumption, delivery quantity, and the overall economics of LNG transportation.

This study develops an integrated optimization framework for LNG maritime transportation in India that jointly determines fleet allocation, route assignment, voyage scheduling, sailing speed, BOG utilization, energy consumption, carbon emissions, and operational costs. Unlike conventional LNG fleet-allocation models that treat sailing speed as fixed and focus primarily on transportation cost, the proposed framework explicitly incorporates the interaction between sailing speed, BOG generation, propulsion-fuel requirements, cargo delivery quantity, energy efficiency, and carbon emissions.

Two optimization models are formulated. The first model represents a baseline fleet-and-route allocation problem under an economically efficient sailing speed. The second is an integrated model in which sailing speed and BOG management are endogenous decision variables. The proposed model further introduces carbon-emission costs and energy-efficiency constraints, allowing the carrier to balance economic and environmental objectives. A scenario-based sensitivity framework is also developed to examine the effects of LNG price volatility, transportation demand, charter rates, carbon prices, BOG generation rates, and fleet capacity on optimal decisions.

The empirical framework is designed around India's LNG import infrastructure and maritime supply network, including major receiving terminals on the western, eastern, and southern coasts. India's eight operational LNG regasification terminals provide a relevant multi-route setting, while substantial variation in terminal utilization creates opportunities for route and fleet optimization. (PNGRB) The proposed framework provides a decision-support mechanism for LNG shipping companies seeking to reduce total operating expenditure while improving energy efficiency, controlling BOG-related cargo losses, and limiting carbon emissions. The framework is also adaptable to future carbon-pricing mechanisms and increasingly stringent maritime decarbonization requirements.

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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:

The proposed study extends the conventional LNG fleet-allocation problem by incorporating these interdependencies into a unified optimization framework for India's LNG maritime transportation network.

1.2 Research objectives

The study has six principal objectives:

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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.
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, it develops an India-specific application framework that can accommodate India's geographically dispersed LNG receiving terminals and changing 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 creates an opportunity for maritime optimization. Rather than assigning vessels only according to physical distance, the proposed framework considers:

- 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:

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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;
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.

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- 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.
- 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.

For more advanced implementation, the constant-rate formulation can be replaced by:

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

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

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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.

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 framework can also incorporate a carbon-emission cap:

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

This creates two alternative environmental-policy scenarios:

Scenario A: carbon price.

Scenario B: absolute emissions constraint.

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 represents the proposed **Integrated LNG Maritime Transportation Optimization Model (ILMTO)**.

14. Multi-Objective Extension

To make the research substantially stronger than the original Chinese study, the model can also be formulated as a multi-objective optimization problem.

The three objectives are:

Objective 1: Economic objective

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

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Objective 2: Environmental objective

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

Objective 3: Energy-efficiency objective

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

These can be combined using the normalized weighted-sum method:

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

where:

$$w_1 + w_2 + w_3 = 1$$

and:

$$w_i \geq 0$$

This formulation enables the researcher to generate a **Pareto frontier** showing the trade-off between transportation cost, carbon emissions, and energy efficiency.

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15. India-Specific Route Network

For the empirical application, the model can be structured around major Indian LNG receiving terminals.

A representative route network can include:

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 represent a geographically diverse network and allow the model to evaluate how route length, terminal demand, vessel capacity, and BOG behavior affect fleet deployment. The eight-terminal configuration is consistent with PNGRB's reported operational LNG infrastructure[27].

16. Vessel Fleet Structure

Instead of directly copying the three Chinese vessel classes, the Indian case should use a generalized fleet structure.

For example:

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)

Important: these should be replaced with actual vessel specifications when the empirical dataset is finalized. The values above are a model structure, not claimed observed values.

17. Solution Method

Because the proposed model contains integer variables, nonlinear speed-fuel relationships, BOG relationships, and potentially nonlinear carbon/energy relationships, it constitutes a mixed-integer nonlinear optimization problem (MINLP).

The solution procedure is:

Step 1	Collect route, vessel, LNG price, charter-rate, port, and demand data.
Step 2	Estimate BOG generation coefficients for each vessel type.
Step 3	Estimate fuel-consumption functions.
Step 4	Calculate route-specific voyage times.
Step 5	Calculate natural BOG generation.
Step 6	Determine additional forced BOG requirements.
Step 7	Calculate LNG delivery quantity.
Step 8	Calculate energy consumption.
Step 9	Calculate carbon emissions.
Step 10	Solve the integrated optimization model.
Step 11	Compare the integrated model with the baseline model.
Step 12	Conduct sensitivity analysis.

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Table(5)

A commercial MINLP solver such as **LINGO, Gurobi, or CPLEX** can be used depending on the final mathematical formulation.

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.

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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

20.1 LNG price sensitivity

Let:

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

The purpose is to determine how LNG-price changes affect:

- 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 identifies the point at which environmental costs begin to materially influence fleet and speed decisions.

20.3 Demand-growth scenario

Demand can be increased by:

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

The objective is to determine whether demand expansion produces:

- additional chartering;
- higher sailing speeds;

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- additional voyages;
- greater BOG consumption;
- greater emissions;
- or fleet expansion.

20.4 BOG-generation sensitivity

BOG generation can be varied by:

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

This measures the robustness of the proposed strategy under different cargo evaporation conditions.

21. Expected Comparative Structure of Results

The final empirical section should compare the two models using a table such as: Table(6)

Indicator	Baseline Model	Integrated Model	Change
Total cost	To be solved	To be solved	%
Number of vessels	To be solved	To be solved	%
Number of voyages	To be solved	To be solved	%
Average loaded speed	To be solved	To be solved	%
Average ballast speed	To be solved	To be solved	%
BOG consumed	To be solved	To be solved	%
LNG delivered	To be solved	To be solved	%
Energy consumption	To be solved	To be solved	%
CO_2 emissions	To be solved	To be solved	%
Energy intensity	To be solved	To be solved	%

This is preferable to copying the Chinese paper's numerical findings because the Indian model has different routes, demand, vessel parameters, prices, and carbon assumptions.

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 is one of the central findings that the Indian application should investigate empirically.

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:

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

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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 proposed model evaluates four possible BOG management regimes. Table(7)

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, controlled disposal.

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

For the first version of the empirical model, Strategies 1 and 2 should remain the core model because they preserve comparability with the original Chinese framework. Reliquefaction can then be introduced as an extension.

26. Robust Optimization Extension

Because LNG prices, demand, charter rates, and BOG rates are uncertain, the deterministic model can be extended into a robust optimization framework.

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 seeks a fleet plan that remains feasible under adverse parameter realizations.

This would be particularly useful for the Indian market because LNG imports are influenced by changing market conditions and the country has multiple receiving terminals with substantially different utilization patterns [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 proposed framework can therefore support:

- LNG import planning;
- terminal utilization;
- maritime infrastructure planning;
- fleet modernization;
- energy-efficiency programs;
- carbon-management strategies;

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- and long-term LNG supply planning.

It can also be adapted 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, fuel-consumption functions must ideally be calibrated using actual vessel operational data.

Third, port congestion and weather conditions are not explicitly modeled in the baseline formulation.

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

The IMO's lifecycle framework distinguishes between well-to-tank and tank-to-wake emissions, meaning that a future version of the model can incorporate full lifecycle GHG accounting.

Finally, LNG price uncertainty can be treated more comprehensively using stochastic or robust optimization.

30. Conclusions

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.

The proposed framework recognizes that LNG maritime transportation is not simply a vessel-capacity allocation problem. The continuous generation of BOG creates a direct relationship between voyage duration, sailing speed, cargo loss, propulsion-fuel consumption, and delivered LNG quantity. Consequently, fleet allocation and speed decisions should be optimized simultaneously.

The framework introduces a baseline model based on predetermined economic speed and an integrated model in which speed and BOG management are decision variables. The integrated model additionally incorporates energy-intensity constraints and carbon costs, thereby allowing economic and environmental considerations to be evaluated within a unified mathematical structure.

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.

The model further enables scenario analysis under LNG-price changes, transportation-demand growth, carbon prices, charter-rate changes, and BOG-generation uncertainty. Such analysis can identify conditions under which slower sailing, additional chartering, alternative vessel allocation, or increased BOG utilization becomes economically and environmentally preferable.

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 proposed approach can therefore serve as a decision-support framework for Indian LNG shipping companies seeking to balance **economic efficiency, cargo preservation, energy efficiency, operational reliability, and carbon reduction**.

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.

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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.

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Conflicts of Interest:

"The authors declare no conflict of interest."

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