A Bottom-Up Comparative Assessment of LNG and Diesel Fuel Pathways for Decarbonizing Port Operations

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ABSTRACT

Maritime ports represent concentrated emissions zones due to the simultaneous operation of manoeuvring ships, auxiliary engines and diesel-driven cargo equipment. This research applies a detailed bottom-up framework to quantify emissions arising from port operations, comparing marine diesel oil (MDO) to liquefied natural gas (LNG). A 600,000 TEU container terminal was modelled with representative vessel data and operating pro-files sourced from simulation, auxiliary load modelling and equipment duty cycles. Marine diesel operation produced approximately 595,000 tonnes per year of carbon dioxide (CO_2), 6,480 tonnes per year of sulphur oxides (SO_x), 276 tonnes per year of nitrogen oxides (NO_x) and 14.2 tonnes per year of particulate matter (PM). Switching to LNG eliminated SO_x, reduced PM by more than eighty per cent and lowered NO_x by fifty-eight per cent, while cutting CO_2 emissions by approximately twenty-two per cent. Yet even under LNG, the terminal would require more than 150,000 hectares of mature temperate forest to offset its residual CO_2. The analysis highlights LNG as an effective transitional fuel that alleviates air quality burdens while ports invest in electrification and prepare for zero-carbon alternatives such as ammonia, hydrogen and renewable-derived synthetic fuels.

Keywords: Liquefied Natural Gas; Marine Diesel; Port Emissions; Decarbonisation; Bottom-Up Inventory; Maritime Energy Transition

INTRODUCTION

Maritime transport underpins global trade by facilitating the movement of approximately eighty per cent of internationally exchanged goods [1]. Despite its central role in supply chain function, shipping contributes significantly to both global greenhouse gas burdens and regional atmospheric pollution. Approximately seventy per cent of ship exhaust emissions occur within four hundred kilometres of shorelines, which positions ports and coastal cities at heightened risk of pollutant exposure [2]. Numerous epidemiological studies link proximity to port emissions with increased incidences of asthma, cardiovascular disease and premature mortality [3, 4, 5].

The environmental impact of shipping extends beyond carbon dioxide. Heavy fuel oil and marine diesel contain sulphur and complex hydrocarbons that generate sulphur oxides, nitrogen oxides and soot when combusted. Nitrogen oxides further react photochemically to form ozone, while fine particulates penetrate deep respiratory pathways and are implicated in long-term morbidity [6]. These concerns prompted unprecedented tightening of international maritime regulations, including sulphur caps under MARPOL Annex VI and the IMOs commitment to reduce sectoral greenhouse gas emissions by fifty per cent by 2050 [7, 8].

To navigate this transition, ports require granular, activity-based emissions data rather than broad fuel sales statistics. Top-down inventories are insufficient to character-ize local impacts or guide capital allocation for mitigation technologies [9]. By contrast, bottom-up models incorporate vessel manoeuvring, berthing durations, load factors and machinery profiles to estimate emissions at fine operational scales [10]. This study ap-plies such a framework to quantify port emissions and assess the environmental benefit of transitioning from marine diesel to LNG.

Liquefied natural gas is the most commercially mature transitional marine fuel offering reductions in local air pollutants and a moderate decline in CO_2. Engine tests reveal reductions of eighty to ninety per cent in PM and substantial declines in NO_x [14]. CO_2 reductions arise from the lower carbon intensity of methane relative to petroleum-based fuels. Yet LNG remains a fossil fuel and total climate benefits depend on management of methane slip, a potent greenhouse gas [15, 16]. The present analysis evaluates LNG on a tank-to-wake basis solely within port boundaries.

LITERATURE REVIEW

Studies examining maritime transport and air quality converge on the conclusion that ports bear a disproportionate share of shipping's environmental costs. The IMOs global greenhouse gas studies identified shipping as responsible for roughly 2.5 to 3.0 per cent of global CO_2 output [7, 8], a figure expected to rise with trade growth unless counteracted by improvements in fuel and vessel design. Johansson et al. showed that regional emission distributions reveal higher urban concentrations of NO_x and PM near major ports, particularly in enclosed seas such as the Baltic and the Mediterranean [11]. Similarly, Watson et al. found that in-port emissions may constitute a substantial portion of total urban inventories, particularly when ship engines remain active during berthing [12].

Bottom-up approaches emerged in response to deficiencies in aggregate bunker-based methods. Jalkanen and colleagues introduced AIS-integrated modelling that allowed emissions to be assigned to physical locations and time periods, laying the foundation for more spatially resolved planning [10]. Subsequent applications across Chinese and North American coastlines demonstrated that manoeuvring and hotelling emissions can only be accurately captured by activity-based methodologies [13, 3].

LNG has received increasing attention as a transitional marine fuel. Sharafian and Sattari demonstrated significant reductions in criteria pollutants when LNG is combusted in marine engines, including nearly complete elimination of sulphur oxides and a dra-matic decline in PM generation [14]. Balcombe et al. investigated lifecycle emissions and cautioned that without tight control of methane slip, true greenhouse gas savings may be diminished [15]. Hall and colleagues identified the scaling of LNG bunkering infrastructure as a critical step in enabling the transition [17]. Research into future fuels such as ammonia and hydrogen continues, but deployment remains limited by technol-ogy readiness levels, safety regulations, fuel energy density challenges and infrastructure constraints [18, 20].

Electrification of port equipment provides promising complementary pathways. Acciaro and McKinnon observed that electrifying yard equipment materially reduces emissions and enhances worker occupational health [19]. When combined with shore power, a large portion of hotelling emissions can be eliminated, particularly when grid electricity derives from renewable sources.

The literature therefore confirms that LNG acts as a transitional tool situated between conventional fossil fuels and future zero-carbon carriers. Its adoption provides immediate public health benefits and aligns with regulatory standards while enabling gradual infrastructure evolution toward fully decarbonised systems.

METHODOLOGY

A container terminal handling approximately six hundred thousand TEU annually was selected as the case system. The representative vessel size was set at 1,100 TEU, yielding:

$$N_{calls} = \frac{600,000}{1,100} \approx 545 \tag{1}$$

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Three primary operational states give rise to emissions: manoeuvring from the fairway entrance to the berth, auxiliary engine operation during hotelling, and diesel consumption by cargo handling equipment.

Fuel consumption during manoeuvring was derived from simulator logs recording time-resolved fuel flow for a representative port approach. Total propulsion fuel was determined by integrating mass flow over the manoeuvring period:

$$Q_{\text{man}} = \int_0^t \dot{m}_f(t)\, dt \qquad (2)$$

This calculation produced approximately 41.5 tonnes per manoeuvre, yielding 30,200 tonnes annually.

Auxiliary loads during berthing were estimated by treating auxiliary power demand as fifteen per cent of main engine capacity and applying the equation:

$$Q_{\text{hotel}} = N_{calls} \cdot t_{\text{berth}} \cdot LF \cdot P_{\text{aux}} \qquad (3)$$

This produced a berthing fuel requirement of approximately 156,000 tonnes annually. Cargo-handling energy demand was calculated using published load factors, equip-

ment counts and engine power ratings according to:

$$Q_k = 365 \cdot n_k \cdot q'_k \cdot k_N \cdot k_T \cdot P_k \qquad (4)$$

The resulting annual fuel use for equipment was approximately 240 tonnes, several orders of magnitude lower than vessel requirements.

Emissions from diesel and LNG were determined using published emission factors for CO_2, SO_x, NO_x and PM.

Scope and System Assumptions

The analysis standardizes all vessels to the representative class to isolate the impact of fuel choice rather than fleet heterogeneity. Weather, tidal variability and berth con-gestion effects are not differentiated, resulting in a deterministic rather than stochastic calculation. Although this abstraction excludes operational variability, it preserves focus on comparative emissions performance between fuel systems.

Uncertainty Considerations

Sources of uncertainty include variation in engine condition, potential overestimation of berthing duration, and differences in auxiliary power use among vessels. Methane slip was excluded to ensure consistency with tank-to-wake accounting; its inclusion would reduce LNGs overall climate advantage. Emission factors used are median values from a range of engine types.

Relevance for Port Authority Planning

The boundaries selected align with interventions available to port authorities. LNG fueling services, electrified equipment deployment and shore-power connections fall within locally manageable policy levers, while vessel routing and oceanic transits remain external.

System Boundary

The system boundary encompasses all operational states within port limits. Activities excluded from the boundary include oceanic transit emissions and upstream emissions attributable to fuel extraction, liquefaction, refinement or transport.

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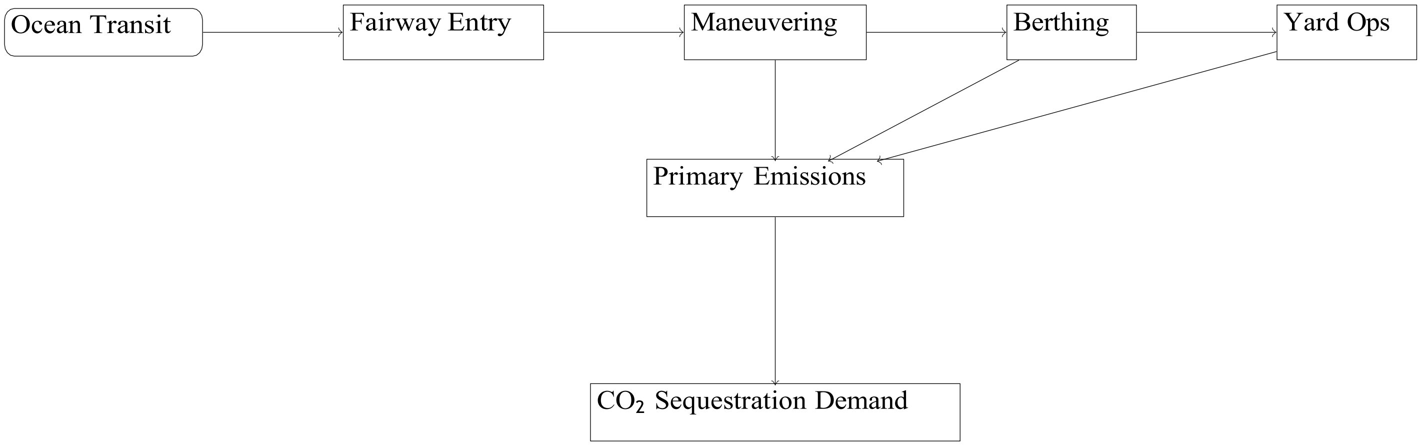

Figure 1: Boundaries and flows included in the emissions inventory.

RESULTS

Annual Fuel Consumption

The combined annual fuel consumption under marine diesel was approximately 186,440 tonnes, with berthing dominating usage due to extended time at dock. Maneuvering rep-resented a smaller but substantial fraction, while yard equipment fuel consumption remained marginal relative to vessel activity. These proportions demonstrate that emissions mitigation strategies focused on vessel operations will yield the greatest benefits.

Comparative Emissions

Annual emissions derived from marine diesel and LNG are presented in Table 1. Car-bon dioxide emissions exhibited an absolute decline from approximately 595,000 tonnes to approximately 465,000 tonnes under LNG. Sulphur oxide emissions were essentially eliminated due to the negligible sulphur content of LNG. Nitrogen oxide emissions declined by more than half, falling from 276 tonnes to approximately 116 tonnes annually. These changes align with combustion thermodynamics reflecting lower flame temperatures and reduced liquid droplet burnout pathways. Particulate matter abatement was similarly pronounced due to reduced soot and residue formation.

Table 1: Annual emissions by fuel type

Pollutant	Diesel (t/y)	LNG (t/y)
CO_2	595,000	465,000
SO_x	6,480	≈0
NO_x	276	116
PM	14.2	2.6

The following figures illustrate these relative changes.

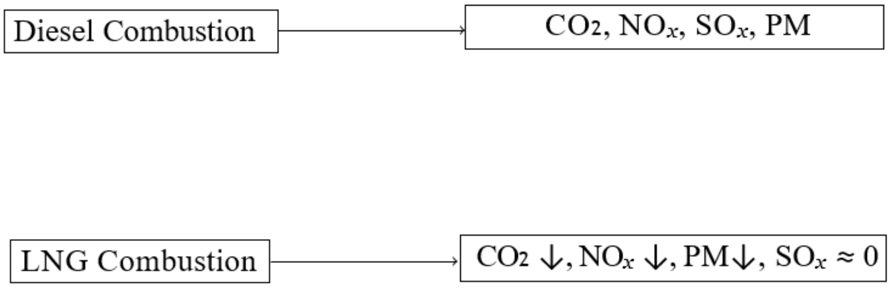

Figure 2: Comparative emission species for diesel and LNG combustion

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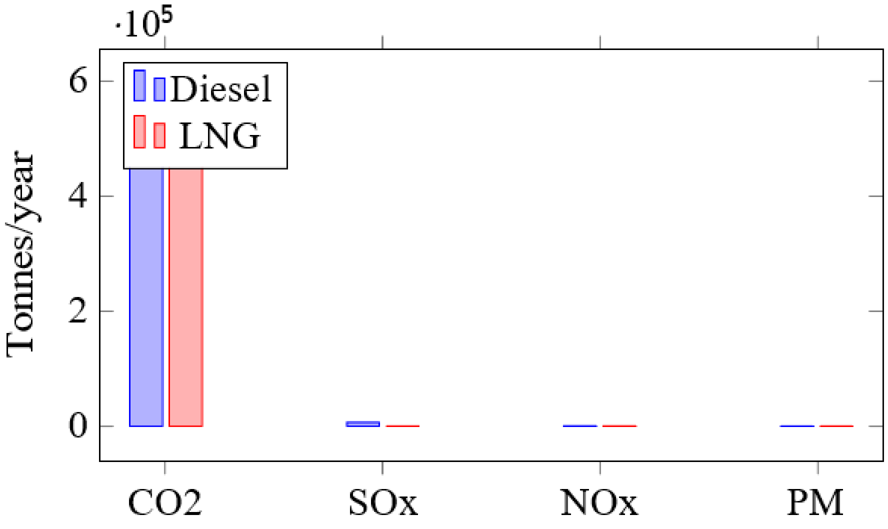

Figure 3: Emission reductions through LNG use

Ecological Offset Requirements

Forests in temperate zones absorb roughly three tonnes of CO_2 per hectare annually [21]. Meeting the annual carbon uptake requirement for diesel emissions would therefore require approximately 198,000 hectares of forest, while LNG emissions would demand approximately 155,000 hectares. These values highlight the insufficiency of incremental emission reductions relative to the scale of decarbonisation required.

DISCUSSION

The findings produced by the bottom-up model validate the widely held view that switching from marine diesel to LNG provides multiple layers of benefit within port boundaries. Most visibly, sulphur oxide emissions are eliminated entirely, owing to the absence of sulphur compounds in the fuel. This alone is sufficient to reduce acid formation and respiratory exposure pathways, both of which have been demonstrated to correlate with increased disease burdens in coastal communities.

Reductions in particulate matter and nitrogen oxides further compound these gains. LNG combustion results in fewer solid carbon particles and reduced thermal NO_x forma-tion, a direct consequence of lower combustion temperatures and the absence of complex hydrocarbons found in petroleum products. These outcomes translate into improved hu-man health at the point of exposure and considerably reduce the likelihood of regulatory non-compliance as enforcement tightens.

Despite these benefits, the analysis reveals the continued scale of carbon-related im-pact. Even under LNG usage, the magnitude of CO_2 emissions remains large enough to challenge climate mitigation objectives. Carbon sequestration requirements derived from the model demonstrate that LNG cannot satisfy even mid-century climate targets without being paired with broader systemic measures. For ports, this indicates that LNG should represent the first step in a staged pathway rather than a final destination. Shore power presents a direct opportunity to eliminate auxiliary engine emissions entirely. Electrification of cargo handling machinery, already underway in technologically leading ports, offers another pathway and requires only capital deployment rather than propulsion innovation.

Beyond electrification, the longer-term horizon is shaped by emerging alternative fuels. Hydrogen and ammonia each exhibit distinct operational advantages and liabilities, both requiring substantial infrastructure changes and adapted safety protocols. Their adoption will likely coincide with declining renewable energy costs and increasing policy support. The decision to deploy LNG today therefore reduces immediate operational emissions while establishing the technical and logistical readiness needed for future green fuels.

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Policy and Economic Extensions

A. Carbon Pricing Implications

If emissions were priced at a conservative fifty dollars per tonne of CO_2, the annual carbon cost under diesel operation would exceed twenty-nine million dollars per year. LNG adoption would lower the implied liability to approximately twenty-three million dollars. These cost signals provide ports with significant financial incentives to accelerate fuel switching in parallel with decarbonisation mandates.

B. Social Cost of Emissions

Applying a median social cost of carbon value of ninety-seven dollars per tonne yields an implied welfare burden exceeding fifty-seven million dollars annually under diesel and forty-five million dollars under LNG. These values reflect societal costs not traditionally borne by port operators but increasingly incorporated into policy analysis.

C. Methane Slip Sensitivity

If methane slip of one per cent were included, LNG's net greenhouse gas reduction would likely decline from approximately twenty-two per cent to closer to ten per cent on a carbon dioxide equivalent basis. Slip levels above three per cent could eliminate LNG's climate advantage entirely, underscoring the importance of selecting appropriate engine types and containment systems.

D. Relative Energy Intensity

On an energy basis, LNG requires approximately twenty per cent lower mass combustion than diesel to produce equivalent propulsion output. This relationship is visible in fuel consumption figures and partly explains lower CO_2 emissions. However, volumetric energy density challenges increase storage requirements relative to diesel.

E. Port Stakeholder Implications

The transition to cleaner fuels requires coordination among shipping lines, port authorities, and municipal regulators. LNG bunkering infrastructure demands capital deployment but also creates co-benefits, such as international vessel calls and competitive positioning for regional cargo flows.

F. Shore Power Scenario

If berth-side electrical supply were introduced across the full call volume and powered by renewable electricity, the annual berthing emissions could be reduced by close to one hundred per cent, lowering total port emissions by more than eighty per cent without any change in propulsion fuel.

CONCLUSION

This research confirms the efficacy of bottom-up modelling approaches in quantifying port-attributed emissions and comparing mitigation scenarios at an operational level. Marine diesel operation imposes significant burdens across greenhouse gas, particulate and sulphur oxide profiles. LNG provides substantial relief with respect to local air pollution and reduces climate emissions on a tank-to-wake basis. However, the analysis underscores that LNG alone cannot deliver compliance with long-term climate commitments. Rather, it constitutes a transitional stage enabling ports to gain experience with alternative fuels, scale new infrastructure and reduce immediate exposure risks.

A layered strategy emerges from the findings: ports should adopt LNG in the immediate term to eliminate sulphur emissions and dramatically lower NO_x and PM, invest in electrification and shore power systems to reduce remaining in-port emissions, and accelerate readiness for next-generation zero-

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carbon fuels. Only through such sequential progression can port operations credibly align with the IMOs net-zero ambitions.

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