Fuel Analysis for Large Commercial Vessels in Port Areas

Assessment of Acceptable and Less-Preferred Fuel Options for Port Air Quality and Climate Implications

Revised report with comparative emission graphics | August 2026

Scope note: In this report, “acceptable” refers to fuel or propulsion pathways that are preferable or reasonable transitional choices from a port-area air-quality perspective while eliminating scrubber washwater. “Less-preferred” or “nonacceptable” refers to pathways that perform materially worse in this port-air framework. These labels are analytical categories and are not substitutes for vessel-specific legal compliance, fuel certification, or permitting.

Executive Summary

The local-air-quality analysis supports five fuel or propulsion pathways as acceptable or transitional options for large commercial vessels operating in port areas: battery-electric propulsion, green hydrogen fuel cells, green methanol, LNG/biomethane, and marine gas oil (MGO). These options are favored because they reduce direct vessel emissions of particulate matter, sulfur oxides, black carbon, and related port-community exposures relative to heavier petroleum fuels while eliminating scrubber discharge. Their climate implications, however, differ materially and depend on upstream energy pathways. Battery-electric and green hydrogen offer the lowest direct vessel emissions, but their lifecycle climate outcomes depend on power generation and hydrogen production. Green methanol and LNG/biomethane can reduce local pollutant emissions substantially, though LNG and biomethane require careful treatment of methane slip and upstream methane emissions. MGO remains a practical near-term transitional option but is still a fossil fuel and does not provide a deep decarbonization pathway. [1-8]

This revised report also discusses the less-preferred fuel pathways—marine diesel oil (MDO), very-low-sulfur fuel oil (VLSFO), and high-sulfur heavy fuel oil (HFO). These fuels generally perform worse in ports because of higher PM mass, greater sulfur-related emission potential, elevated black carbon, or a combination of these factors. HFO is the least favorable option in this framework. VLSFO improves on HFO with respect to sulfur content, but it remains a residual fuel with substantial PM, ultrafine-particle, and black-carbon concerns. MDO can serve as a lower-sulfur distillate option under some conditions, yet it is less favorable than MGO in this framework because PM mass is generally higher and the fuel offers no meaningful climate advantage over MGO. [1-3,6]

1. Analytical Framework

The analysis distinguishes between two distinct objectives: (1) improving local air quality in and near port areas, and (2) reducing lifecycle greenhouse-gas emissions. Furthermore, all acceptable options must contain sulfur content low enough directly meeting emission standards without the need for an exhaust gas scrubber, thus eliminating scrubber discharge. The metrics emphasized for local air quality are PM2.5 mass, ultrafine particle number (represented here as PM0.1-scale exhaust particle counts), black carbon, SOx, and NOx. The climate assessment uses a well-to-wake perspective because upstream electricity generation, hydrogen production, methane leakage, fuel synthesis, liquefaction, and transport can materially alter comparative GHG outcomes. [5-8]

A key technical point is that particulate mass and ultrafine particle number are not interchangeable. Marine studies show that lower-sulfur or cleaner-looking fuels can reduce PM mass without proportionally reducing particle number. For this reason, the report treats PM2.5 and PM0.1-related indicators separately. [1-3]

2. Discussion of Acceptable Fuels

Battery-electric propulsion. Battery-electric systems eliminate direct vessel combustion emissions while operating on battery power. This provides the strongest local air-quality benefit in ports, but the climate result depends on electricity generation and battery production. Under low-carbon grid conditions, battery-electric operation can also provide substantial lifecycle GHG reductions. [8]

Green hydrogen fuel cells. Hydrogen fuel cells can reduce direct vessel emissions of PM, SOx, black carbon, and combustion NOx to near-zero levels. Their climate benefit depends primarily on the hydrogen production pathway; renewable-electricity-based hydrogen can be low-carbon, whereas fossil-derived hydrogen can have much higher lifecycle GHG emissions. [7]

Green methanol. Methanol eliminates fuel sulfur and generally reduces PM mass and soot markedly relative to conventional marine fuel oils. Measurements from a methanol-fueled ferry showed low PM emissions, though ultrafine particles were still present in the exhaust. Methanol's climate performance depends on whether it is renewable methanol or fossil methanol. [4]

LNG and biomethane. LNG and biomethane can substantially reduce PM mass, black carbon, and SOx relative to marine oil fuels. Their principal climate qualification is methane: engine methane slip and upstream leakage can materially weaken the GHG benefit. Biomethane can improve lifecycle performance significantly when sourced from low-carbon waste or residue pathways, but methane management remains necessary. [5,6]

Marine gas oil (MGO). MGO is a practical distillate fuel that reduces sulfur-related emissions and PM mass relative to residual marine fuels. Nevertheless, marine studies indicate that ultrafine particle number can remain significant, and MGO retains the lifecycle GHG profile of a fossil petroleum fuel. Its best role is as a near-term transitional fuel while lower-emission systems scale. [1-3]

3. Discussion of Less-Preferred or Nonacceptable Fuels

Marine diesel oil (MDO). MDO is a distillate fuel and is therefore materially cleaner than residual fuels such as VLSFO or HFO, but it is generally less favorable than MGO. Published comparisons indicate that PM mass from MDO is typically higher than from MGO on the same engine, while ultrafine particle number may remain in a similar order of magnitude. MDO also offers no major climate advantage over MGO because both are fossil petroleum fuels. For these reasons, MDO is best viewed as a less-preferred distillate option in a port-air-quality framework. [1-3]

Very-low-sulfur fuel oil (VLSFO). VLSFO improves on HFO in sulfur content and therefore reduces SOx and sulfur-associated particulate matter relative to traditional high-sulfur residual fuels. However, it remains a residual fuel and can still generate substantial PM2.5, ultrafine particles, and black carbon. The lower sulfur content should not be confused with low climate impact; VLSFO is still a fossil fuel with high lifecycle GHG emissions. It is therefore less favorable than distillate and zero- or low-emission alternatives for use in ports. [1-3,6]

High-sulfur heavy fuel oil (HFO). HFO is the least favorable option in this framework. It is associated with the highest PM mass, the highest SOx emission potential, elevated black carbon, fuel-derived metals, and the greatest concern for community exposure in port areas. While HFO has historically been used widely because of cost and availability, its local pollutant profile is substantially worse than that of all of the acceptable fuels discussed above. HFO also has high lifecycle GHG emissions and adds climate concern through black-carbon forcing. [1-3,6]

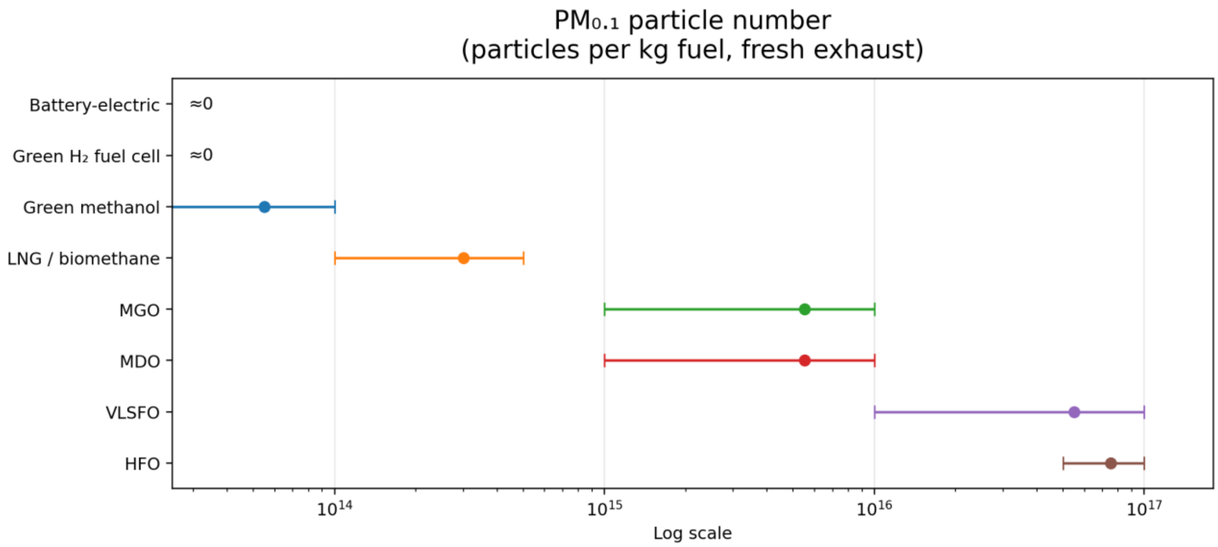
4. Comparative Summary Table

Fuel / propulsion	Port-area local air quality	Lifecycle climate	Port-air-quality category	Principal qualification
Battery-electric	Best	Potentially excellent with low-carbon electricity	Acceptable / preferred	Upstream electricity and battery production matter
Green H_2 fuel cell	Best	Potentially excellent if renewable H_2	Acceptable / preferred	Hydrogen production and infrastructure matter
Green methanol	Very good	Potentially good if renewable	Acceptable	Still combustion-based; climate depends on pathway
LNG / biomethane	Very good	Variable; methane-sensitive	Acceptable	Methane slip and feedstock strongly affect climate result
MGO	Good	High fossil GHG	Acceptable transitional	UFP can remain high; not a long-term climate solution
MDO	Moderate	High fossil GHG	Less-preferred	Higher PM mass than MGO
VLSFO	Poor	High fossil GHG	Less-preferred	Residual-fuel PM, UFP, and BC remain significant
HFO	Worst	High fossil GHG	Nonacceptable	Highest PM, SOx, BC, and metals

5. Comparative Emission Graphics

Figures 1 through 5 compare representative emission ranges across the fuel and propulsion pathways discussed in this report. The graphics are intended to support relative comparison rather than provide universal emission factors for every engine and operating condition. The ranges are derived from the literature-informed values used in this report and should be interpreted in that context.

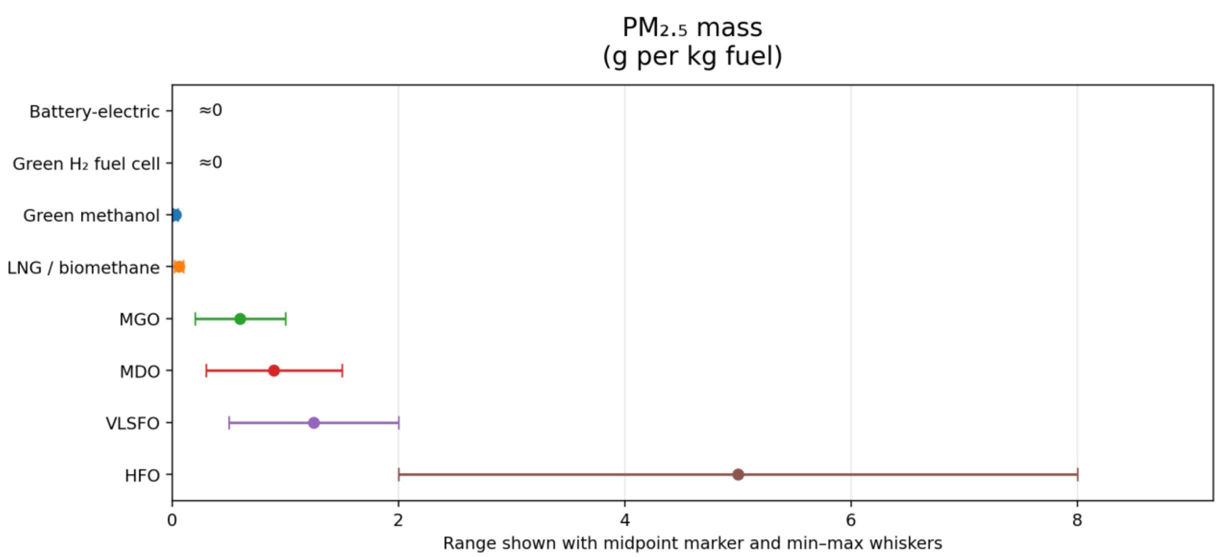
Figure 1. $PM_{0.1}$ particle number (particles per kg fuel, fresh exhaust)



Representative order-of-magnitude ranges based on literature-informed values used in the report.

Figure 1. Comparative range graphic for $PM_{0.1}$ particle number (particles per kg fuel, fresh exhaust). Each graphic shows a midpoint marker with minimum–maximum whiskers; zero-emission vessel pathways are labeled separately.

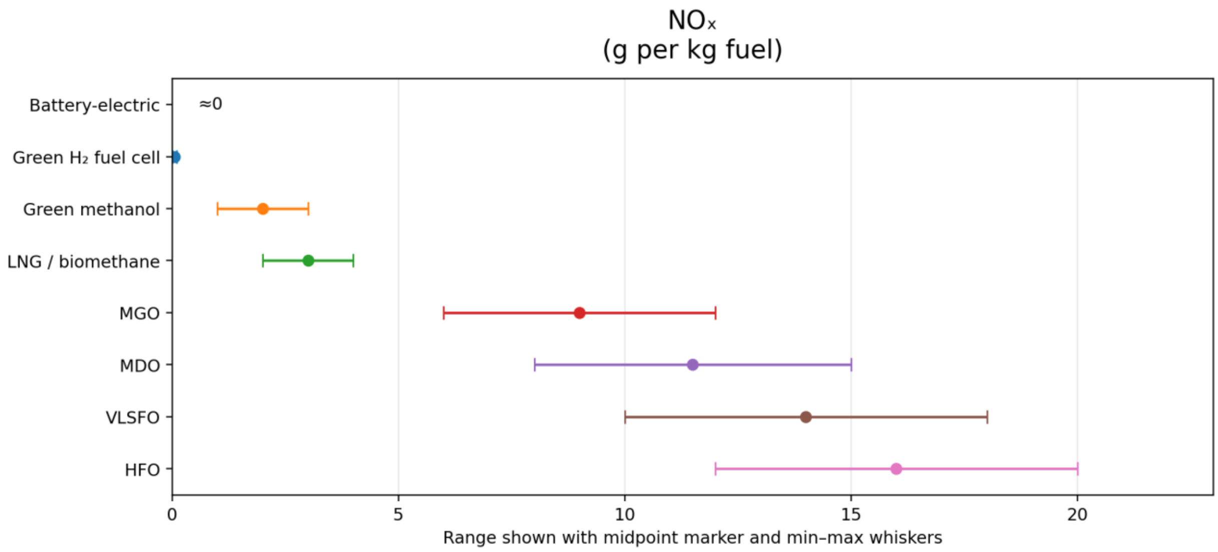
Figure 2. $PM_{2.5}$ mass (g per kg fuel)



Representative comparative ranges; values vary with engine, load, and sampling method.

Figure 2. Comparative range graphic for $PM_{2.5}$ mass (g per kg fuel). Each graphic shows a midpoint marker with minimum–maximum whiskers; zero-emission vessel pathways are labeled separately.

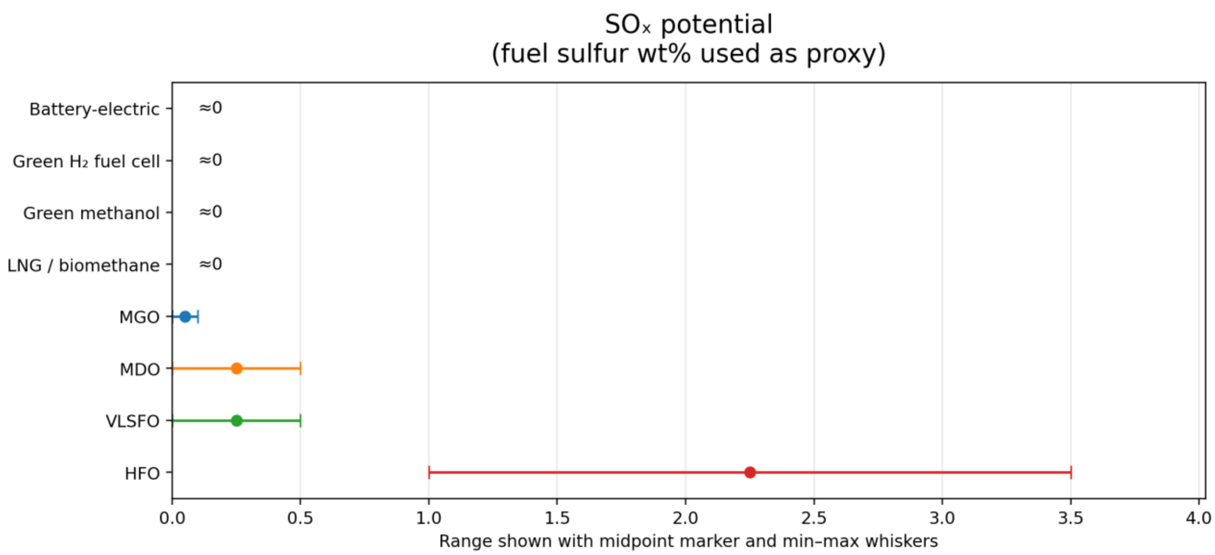
Figure 3. NO_x (g per kg fuel)



Illustrative ranges reflecting relative differences among the fuel pathways.

Figure 3. Comparative range graphic for NO_x (g per kg fuel). Each graphic shows a midpoint marker with minimum–maximum whiskers; zero-emission vessel pathways are labeled separately.

Figure 4. SO_x potential (fuel sulfur wt% used as proxy)



Fuel sulfur content is used here as a proxy for SO_x emission potential.

Figure 4. Comparative range graphic for SO_x potential (fuel sulfur wt% used as proxy). Each graphic shows a midpoint marker with minimum–maximum whiskers; zero-emission vessel pathways are labeled separately.

Figure 5. Black carbon (g per kg fuel)

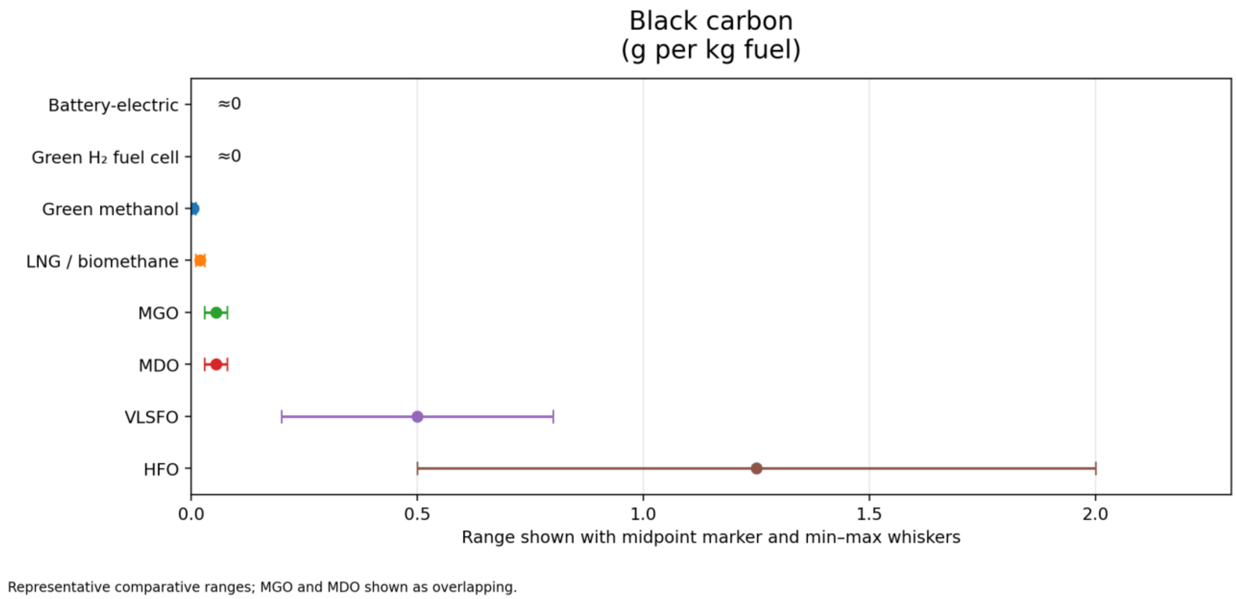


Figure 5. Comparative range graphic for Black carbon (g per kg fuel). Each graphic shows a midpoint marker with minimum–maximum whiskers; zero-emission vessel pathways are labeled separately.

6. Conclusions

From a port-air-quality perspective, battery-electric propulsion, green hydrogen fuel cells, green methanol, LNG/biomethane, and MGO are the strongest or most reasonable current options, with MGO being acceptable as the industry transitions to cleaner fuel options. By contrast, MDO, VLSFO, and HFO are less favorable because they perform worse on one or more of the principal local-pollutant measures emphasized in this report. HFO is the clearest candidate for avoidance in port areas.

The comparative graphics reinforce a broader policy point: local pollutant control and climate strategy should be addressed together but not collapsed into a single score. A robust port fuel policy should prioritize zero- or near-zero local emissions where feasible, require transparent lifecycle GHG accounting, and recognize that emissions performance depends on both the fuel pathway and the engine or power system in which that pathway is used. [5-8]

References

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Technical note. The comparative graphics use representative ranges for communication purposes. Actual emissions vary with engine type, load, fuel properties, pilot-fuel ratio, lubricant consumption, exhaust after-treatment, sampling method, and dilution conditions.

Use of Artificial Intelligence

Portions of this report were developed with the assistance of generative artificial intelligence to support drafting, organization, editing, and technical synthesis. An alternative generative tool was used to validate report contents in conjunction with review by Protect Virginia and other external reviewers. Generative AI is a powerful tool for synthesizing information but can sometimes produce erroneous results. Please contact Protect Virginia for any questions, corrections, or feedback.

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