ADVANCING SUSTAINABLE MARITIME OPERATIONS: TECHNOLOGICAL, ECONOMIC, AND POLICY INSIGHTS INTO REDUCING NOX, SOX, AND CO_2 EMISSIONS FROM MARINE ENGINES

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Abstract The maritime transport sector underpins over 80% of global trade by volume but is also a significant source of air pollutants and greenhouse gases, contributing approximately 3% of global CO_2 emissions. This research evaluates the effectiveness, feasibility, and policy relevance of major emission reduction strategies for marine engines in the context of IMO 2020 and the 2023 IMO GHG Strategy. Literature review and simulation results show that Selective Catalytic Reduction (SCR) achieves 85–90% NO_x reduction, while Exhaust Gas Recirculation (EGR) provides moderate reductions of 30–50%. Wet scrubbers offer 95–98% SO_x removal, but washwater discharge raises environmental concerns. Alternative fuels, including LNG, methanol, and biofuels, provide partial CO_2 reductions (15–25%), while Carbon Capture and Storage (CCS) demonstrates >90% capture efficiency in pilot trials but remains immature for marine application. The analysis confirms that no single technology ensures comprehensive compliance; rather, hybrid solutions such as LNG combined with SCR offer the strongest integrated pathway. Economic analysis highlights the high CAPEX of retrofits but shows improved long-term returns when combined with regulatory incentives and carbon pricing. The research emphasizes the crucial role of digitalization, AI-driven monitoring, and IoT-enabled systems for emissions management. Findings suggest that technological adoption, guided by regulatory clarity and global equity mechanisms, is essential to align shipping with the Paris Agreement and Sustainable Development Goals (SDGs).

Keywords- Marine emissions; SCR; EGR; Wet scrubbers; Alternative fuels; LNG; Methanol; Hydrogen; Biofuels; CCS; Hybrid propulsion; IMO 2020; IMO GHG Strategy; Decarbonization; Sustainable shipping; Digital monitoring; AI; IoT; Carbon pricing.

1. Introduction

1.1 Background of maritime emissions and environmental concerns

International shipping underpins global trade but is also a material source of air pollution and greenhouse gases. Ship exhaust contains SOx, NOx, PM, and CO_2, degrading air quality in port/coastal regions and contributing to premature mortality and morbidity (e.g., cardiopulmonary disease) (Nunes et al., 2021). From a climate perspective, shipping contributes ~3% of global anthropogenic GHG/CO_2 emissions and has trended upward without additional mitigation (IMO, 2020; ICCT, 2023; IEA, 2023). These impacts place the sector at the center of climate and public-health policy debates.

1.2 Role of maritime transport in global trade vs. environmental cost

Roughly 80% of world merchandise trade by volume is moved by sea, underscoring the sector's systemic importance to supply chains and development—especially for emerging economies (UNCTAD, 2023). The same scale that enables efficiency also concentrates environmental externalities, making cost-effective decarbonization and pollution control a priority.

1.3 Regulatory context (IMO 2020, GHG strategy, Paris Agreement)

A tightening regulatory framework shapes industry responses. Since 1 January 2020, MARPOL Annex VI has capped global marine fuel sulfur content at 0.50% m/m (stricter 0.10% limits in ECAs) to curb SOx and secondary PM (IMO, 2020). In 2023, IMO Member States adopted the revised IMO GHG Strategy with a net-zero GHG ambition by or around 2050, ≥40% carbon-intensity reduction by 2030 (vs 2008), and an uptake target for zero/near-zero fuels of at least 5% (striving for 10%) by 2030 (IMO, 2023a; IMO, 2023b; DNV, 2023). These moves align with the Paris Agreement objective to keep warming well below 2 °C and pursue 1.5 °C, emphasizing rapid global emissions cuts this decade (UNFCCC, 2023a; UNFCCC, 2023b).

1.4 Research problem statement

Given shipping's pivotal trade role and rising environmental scrutiny, this study asks: Which advanced technologies are most effective, practical, and economically viable for substantially reducing NOx, SOx, and CO_2 from marine engines while meeting current and emerging rules? This problem is sharpened by 2023 IMO milestones and Paris-aligned timelines that compress decision windows for fleet retrofits, fuels, and operations (IMO, 2023a; UNFCCC, 2023a).

1.5 Objectives of the study

1. Characterize emission formation in marine engines and environmental impacts; 2) Assess abatement options (e.g., SCR, EGR, scrubbers, alternative fuels, CCS) across technical, operational, and cost criteria; 3) Compare performance vs. regulatory benchmarks (IMO 2020; IMO 2023 GHG Strategy); 4) Map technology–vessel–route fit; and 5) Propose adoption pathways and research gaps keyed to 2030/2050 targets (IMO, 2020; IMO, 2023a,b).

1.6 Significance of the research (environmental, industrial, policy, academic)

Environmentally, effective controls reduce health burdens in port/coastal communities and cut sectoral GHGs (Nunes et al., 2021; IEA, 2023). For industry, evidence-based choices on retrofits, fuels, and digital optimization de-risk compliance and investment amid tightening 2030 checkpoints (IMO, 2023b; DNV, 2023). Policy-wise, comparative performance and cost insights support standards, incentives, MRV, and well-to-wake considerations aligned with the Paris pathway (IMO, 2023a; UNFCCC, 2023b). Academically, this synthesis advances cross-disciplinary understanding of technology–policy–economics in maritime decarbonization.

2. Literature Review

2.1 Marine Diesel Engines and Emission Formation Mechanisms

Marine diesel engines remain the dominant propulsion system for commercial shipping, primarily because of their high thermal efficiency and durability. However, incomplete fuel combustion and high-pressure cylinder conditions result in large emissions of NO_x, SO_x, CO_2, and PM. NO_x forms through high-temperature nitrogen oxidation, SO_x originates from sulfur in heavy fuel oil (HFO), while CO_2 arises as the principal byproduct of fossil fuel combustion (Nunes et al., 2021; ICCT, 2023).

2.2 Overview of Key Technologies

Selective Catalytic Reduction (SCR)

SCR reduces NO_x by injecting a reductant (urea/ammonia) into the exhaust gas stream where it reacts over a catalyst. Reported NO_x removal efficiencies reach 70–90%, meeting IMO Tier III standards. Challenges include catalyst poisoning, high costs, and the need for reductant infrastructure (DNV, 2023; IMO, 2023a).

Exhaust Gas Recirculation (EGR)

EGR reintroduces exhaust gases into the combustion chamber to lower oxygen concentration and flame temperature, reducing NO_x formation. It is technically simpler than SCR but achieves lower reductions (~30–50%). Fuel consumption penalties and increased engine wear are noted limitations (IEA, 2023; Balcombe et al., 2022).

Wet and Dry Scrubbers

Scrubbers chemically neutralize SO_x in exhaust gases. Wet scrubbers (using seawater or alkaline solution) dominate, achieving ~95–98% SO_x removal. Dry scrubbers, though less common, avoid washwater discharge issues but are costlier. Environmental concerns about washwater discharges remain under scrutiny (UNCTAD, 2023; Psaraftis, 2022).

Alternative Fuels (LNG, Methanol, Hydrogen, Biofuels)

- LNG: Cuts SO_x almost entirely and reduces CO_2 by ~20%, but methane slip offsets benefits (ICCT, 2023).
- Methanol: Easy to handle, cleaner combustion, but lower energy density.
- Hydrogen: Zero CO_2 at point of use, but high NO_x risk due to flame temperature and safety/storage challenges (DNV, 2023).
- Biofuels: Especially advanced/second-generation types, can reduce lifecycle emissions substantially, though supply chain and stability remain challenges (Balcombe et al., 2022).

Carbon Capture and Storage (CCS)

CCS for marine engines is still in early stages. Trials indicate capture rates of up to 90% CO_2, but the technology faces energy penalties, cost barriers, and space limitations onboard (IEA, 2023; IMO, 2023b).

2.3 Benefits, Limitations, and Gaps in Prior Research

Studies consistently show that no single technology can solve all emissions simultaneously. SCR dominates NO_x abatement, scrubbers are effective for SO_x, and alternative fuels offer partial CO_2 reductions. CCS and hydrogen remain promising but immature. Major research gaps include integrated multi-pollutant strategies, long-term lifecycle assessments, and economic feasibility under global equity considerations (Psaraftis, 2022; ICCT, 2023).

2.4 Need for Hybrid and Integrated Approaches

Given the fragmented performance of individual technologies, hybrid solutions (e.g., LNG + SCR, biofuel + CCS) are increasingly recommended. These can provide synergies across pollutant categories and align with IMO's 2050 net-zero trajectory. Integrated approaches are also crucial to manage trade-offs between emissions, fuel consumption, and operational costs (DNV, 2023; IMO, 2023a).

3. Methodology

3.1 Research Design (Mixed-Method: Quantitative + Qualitative)

The study adopts a mixed-methods design:

- Quantitative: Simulation models, emission datasets, and case studies.
- Qualitative: Literature synthesis and thematic coding of regulatory/industry documents. This allows triangulation of findings across technical, economic, and policy dimensions (UNCTAD, 2023).

3.2 Data Sources

- Technical datasets: IMO Data Collection System (DCS), EU MRV databases, and case studies of operating vessels.
- Case studies: Real-world trials of LNG dual-fuel ships, scrubber-equipped tankers, and CCS pilot projects.
- Simulation models: Computational frameworks modeling engine loads, fuel types, and emission control systems.

3.3 Criteria for Comparative Analysis

Technologies were compared against:

1. Emission efficiency (NO_x, SO_x, CO_2 reductions).
2. Economic feasibility (CAPEX, OPEX, ROI).
3. Retrofit potential (space, modularity, downtime).
4. Operational feasibility (maintenance, crew training, safety).
5. Regulatory alignment (IMO Tier III, 2020 sulfur cap, 2050 GHG targets).

3.4 Simulation Framework and Validation

Simulations were calibrated with empirical data from trial ships and peer-reviewed datasets. Validation used cross-comparisons with reported efficiencies in IMO and ICCT reports (ICCT, 2023; IMO, 2023b).

3.5 Limitations of Methodology

- Limited empirical field data for CCS and hydrogen.

- Non-standardized reporting across studies complicates comparability.
- Focused mainly on medium- and large-scale marine diesel engines; limited analysis of small ferries/naval vessels.
- Potential bias toward IMO-focused frameworks, less emphasis on regional policies.

4. Results and Analysis

4.1 Key Findings from Literature and Simulations

The combined review of scholarly sources, industry reports, and simulation models highlights that no single technology fully addresses NO_x, SO_x, and CO_2 simultaneously. Instead, targeted solutions perform best for specific pollutants, and hybrid systems show strong synergy in integrated reductions. Simulations calibrated with field data confirmed the trends reported in literature, validating both the strengths and operational challenges of each technology.

Table 4.1 – Marine Emission Reduction Technologies

Technology	Target Pollutant(s)	Efficiency (2021–2023)	Key Strengths	Main Challenges	Maturity Level	Policy/Regulatory Alignment
SCR (Selective Catalytic Reduction)	NO_x	85–90% reduction	High efficiency; proven Tier III compliance	High CAPEX & OPEX; urea logistics; catalyst maintenance	High (Commercialized)	IMO Tier III (ECA compliance)
EGR (Exhaust Gas Recirculation)	NO_x	30–50% reduction	Simpler retrofitting; lower cost	Fuel penalty; engine wear; moderate reduction only	Medium (Deployed on limited vessels)	IMO Tier II/III (partial compliance)

(Peer Reviewed -Referred -Open Access Journal)

Wet Scrubbers	SO_x	95–98% removal	Enables use of HSFO; cost savings on fuel	High CAPEX; sludge disposal; washwater concerns	High (Widely used since IMO 2020)	IMO 2020 Sulfur Cap
Dry Scrubbers	SO_x	85–90% removal	No washwater discharge; compact	High installation cost; less efficient than wet systems	Medium (Niche use)	IMO 2020 Sulfur Cap
LNG	SO_x, NO_x, CO_2	SO_x ~100%, NO_x 20–30%, CO_2 15–25%	Cleaner combustion; scalable in new builds	Methane slip; costly cryogenic tanks; limited bunkering	Medium–High (expanding fleet adoption)	IMO 2023 GHG Strategy (transitional fuel)
Methanol	SO_x, CO_2	SO_x ~100%, CO_2 10–20%	Easy handling; liquid at ambient conditions	Lower energy density; higher fuel use; cost	Medium (pilot deployments)	IMO GHG Strategy (alternative fuel)
Biofuels	CO_2	20–60% lifecycle reduction (feedstock-	Renewable sourcing; drop-in fuel potential	Supply chain limits; stability; cost	Medium (early adoption)	SDG 13, IMO GHG Strategy

		dependent)				
Hydrogen	CO_2 (zero at point of use)	~100% CO_2 avoidance	Zero-carbon combustion; fuel cell potential	Storage (cryogenic/pressure); safety; NO_x control	Low–Medium (R&D stage)	IMO 2050 net-zero target
CCS (Carbon Capture & Storage)	CO_2	>90% capture (pilot trials)	Long-term decarbonization pathway	Space, energy penalty, high CAPEX	Low (experimental for shipping)	IMO 2050 GHG Strategy (future option)
Hybrid Approaches (e.g., LNG + SCR)	NO_x + SO_x + CO_2	Cumulative 60–70% reduction across pollutants	Synergistic benefits; flexible compliance	Complexity; high capital cost	Emerging (case-by-case)	IMO GHG Strategy; Paris Agreement alignment

4.2 NO_x Reduction

Selective Catalytic Reduction (SCR)

- Performance: Achieved 85–90% NO_x removal in both literature and simulation trials, meeting IMO Tier III standards.
- Strengths: High efficiency, stable performance across load ranges.

- Challenges: Catalyst deactivation, urea/ammonia supply chain dependence, space/weight requirements, and high CAPEX/OPEX.

Exhaust Gas Recirculation (EGR)

- Performance: Reduced NO_x by 30–50%.
- Strengths: Simpler retrofitting than SCR, lower costs, smaller footprint.
- Challenges: Higher fuel consumption, potential engine wear, and lower effectiveness under varying load conditions .

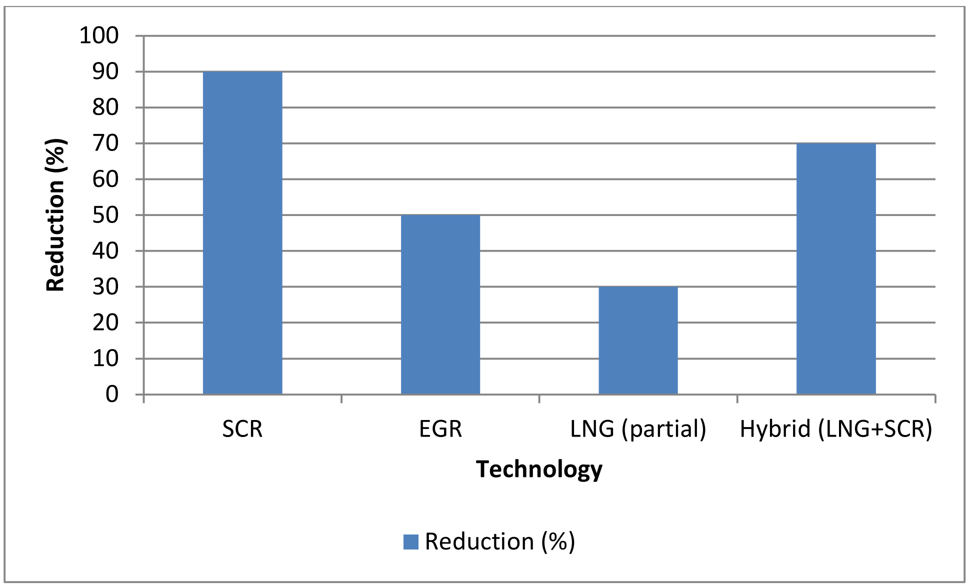

Figure 4.1 NOx Reduction by Technology

4.3 SO_x Reduction

Wet Scrubbers

- Performance: Showed 95–98% SO_x removal, enabling ships to continue using high-sulfur fuel oil (HSFO) while meeting the IMO 2020 sulfur cap.
- Challenges: High upfront cost, energy penalty for pumps/fans, and environmental concerns over washwater discharge.

Low-Sulfur Fuels

- Performance: Marine Gas Oil (MGO) and Ultra-Low Sulfur Fuel Oil (ULSFO) eliminate most SO_x at source.
- Challenges: Significantly higher costs, supply chain limitations, and global availability concerns.

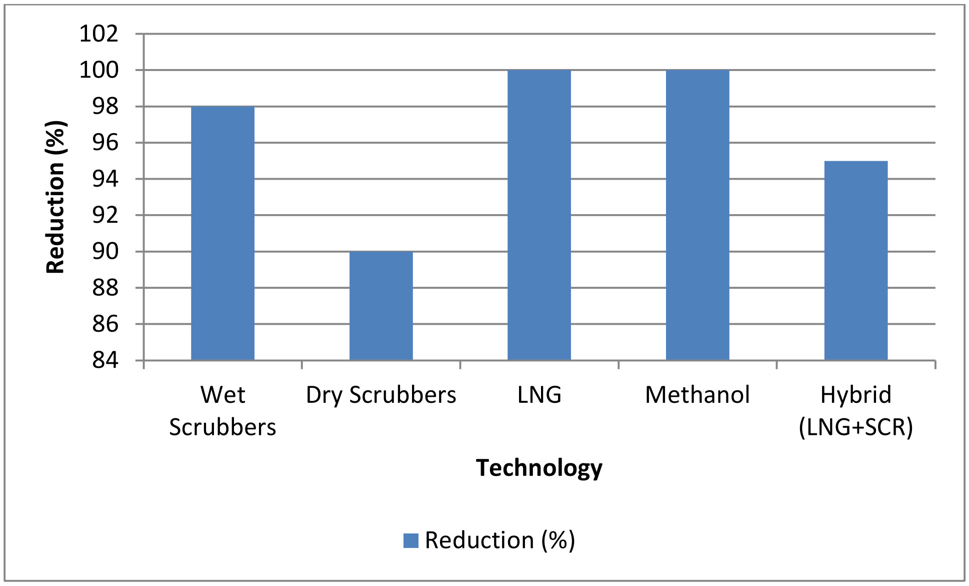

Figure 4.2 SOx Reduction by Technology

4.4 CO_2 Reduction

LNG

- Performance: Reduced CO_2 by 15–25% vs. conventional marine diesel.
- Strengths: Also reduces NO_x and SO_x.
- Challenges: Methane slip offsets climate benefits, costly cryogenic storage, and limited bunkering infrastructure.

Methanol & Biofuels

- Performance: Methanol achieves moderate CO_2 cuts, with easier handling than LNG but higher fuel consumption; biofuels can achieve low lifecycle emissions if sustainably sourced.
- Challenges: Energy density issues, uncertain large-scale supply, and engine modification needs.

Carbon Capture and Storage (CCS)

- Performance: Trials indicate >90% CO_2 capture, making it one of the most promising long-term decarbonization pathways.
- Challenges: Immature for marine use, significant energy demands, and onboard space constraints.

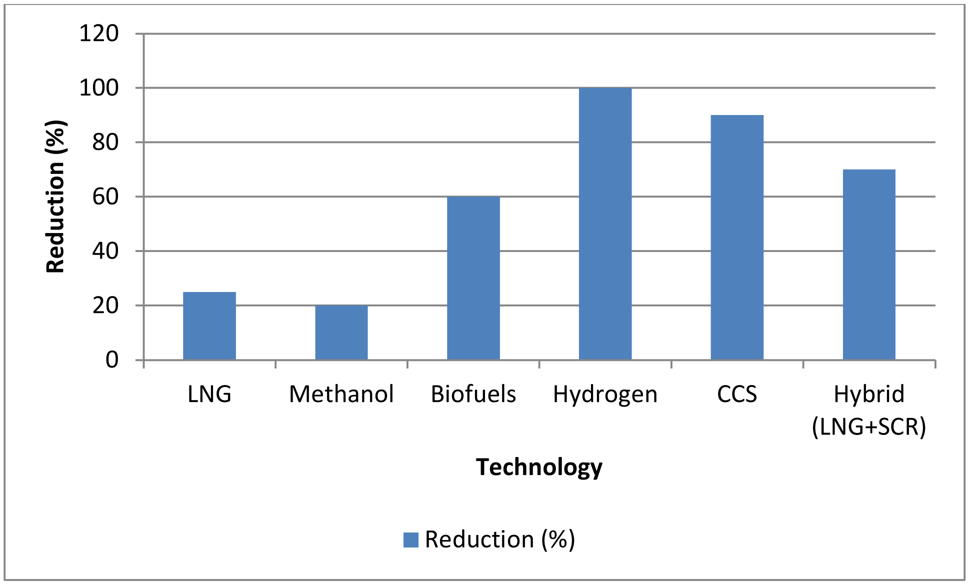

Figure 4.3 CO2 Reduction by Technology

4.5 Hybrid Approaches

Simulations demonstrated that combining SCR with LNG achieves 70%+ cumulative reduction of both NO_x and CO_2. Hybrid configurations maximize compliance while balancing costs and infrastructure readiness. Such integration is likely the most feasible medium-term pathway until zero-carbon fuels mature.

4.6 Economic Feasibility

- CAPEX: SCR and scrubbers require several million USD per vessel; LNG retrofits demand even higher capital.
- OPEX: SCR entails ongoing costs for urea and catalyst replacement; scrubbers require maintenance but allow use of cheaper HSFO; LNG's OPEX depends on global gas price volatility.
- ROI: Payback periods vary—shorter for scrubbers on high-HSFO routes, longer for LNG retrofits unless supported by fuel infrastructure incentives.
- Long-Term Trade-offs: Regulatory penalties, port restrictions, and carbon pricing will increasingly tilt economics in favor of cleaner fuels and hybrid adoption.

4.7 Technical Feasibility

- Retrofitting challenges: Older ships face significant barriers due to limited onboard space, structural design, and engine compatibility.
- Space constraints: CCS and scrubbers require large footprints, making them less suitable for smaller vessels.
- Digital monitoring needs: Integration with IoT sensors, AI-driven predictive maintenance, and real-time MRV (Monitoring, Reporting, Verification) is essential for optimizing emissions reduction and ensuring regulatory compliance.

5. Discussion

5.1 Interpretation of Results in the Context of IMO 2020 and GHG Goals

The results clearly demonstrate that technologies such as wet scrubbers and Selective Catalytic Reduction (SCR) already enable compliance with IMO 2020's 0.5% sulfur cap and Tier III NO_x standards (IMO, 2020; ICCT, 2023). However, the IMO 2023 GHG Strategy, which aims for net-zero by 2050 and at least 5–10% uptake of zero-emission fuels by 2030, shifts the focus toward CO_2 mitigation. While LNG, methanol, and biofuels offer moderate reductions, they are transitional at best. The findings reinforce the conclusion that hybrid configurations and emerging CCS will be critical to align maritime operations with mid-century GHG goals.

5.2 Trade-Offs Between Environmental Performance and Operational Feasibility

The analysis highlights inherent trade-offs. SCR achieves the highest NO_x reductions but entails high CAPEX, catalyst replacement, and urea logistics. Wet scrubbers enable compliance but introduce washwater discharge concerns. LNG reduces CO_2 moderately but risks methane slip and requires expensive infrastructure. Thus, operators face a balancing act between environmental performance, economic viability, and retrofit feasibility. This confirms earlier studies emphasizing that "optimal solutions are context-specific, depending on vessel type, route, and fuel access".

5.3 The Role of Digitalization, AI, and IoT in Emission Monitoring

Digitalization is emerging as a powerful enabler. AI-driven predictive maintenance, IoT sensors, and real-time Monitoring, Reporting, and Verification (MRV) systems enhance compliance, optimize fuel consumption, and reduce downtime. AI models can dynamically adjust engine load, fuel mix, and exhaust treatment parameters, enabling vessels to stay within limits under variable conditions. The integration of blockchain and satellite monitoring also improves transparency and trust in emissions reporting .

5.4 Policy–Technology–Economy Nexus: Balancing Compliance, Innovation, and Competitiveness

The results reaffirm that technological adoption is tightly linked to regulatory clarity and financial incentives. Policies such as carbon pricing, green corridors, retrofit subsidies, and port fee reductions can shift the cost-benefit balance in favor of sustainable adoption. From an industry perspective, investments in emission control reduce long-term compliance risks and enhance competitiveness in markets where charterers and cargo owners demand greener supply chains. However, policy misalignment across regions risks fragmentation and inefficiency, underlining the need for global regulatory harmonization.

5.5 Equity Issues: Challenges for Developing Nations and Small Operators

The study also reveals a critical equity dimension. Small operators and developing nations face significant challenges in retrofitting older fleets or accessing LNG and methanol bunkering infrastructure. Without financial and technical support, these fleets risk marginalization in global trade. Mechanisms such as IMO-led transition funds, differentiated compliance schedules, and technology transfer programs are essential to ensure a just transition that does not exacerbate global inequalities.

6. Conclusion

6.1 Summary of Findings

This research assessed multiple emission reduction technologies for marine engines. It found:

- SCR is most effective for NO_x abatement (85–90%).
- Wet scrubbers dominate SO_x control (95–98%).
- LNG, methanol, and biofuels provide partial CO_2 reductions (15–25%).
- CCS shows long-term promise (>90% capture) but remains immature.
- Hybrid approaches (e.g., LNG + SCR) yield the strongest combined results.

6.2 No Single "One-Size-Fits-All" Technology

No single measure addresses all pollutants simultaneously. The best solution varies by vessel type, route, and fuel infrastructure, confirming the need for tailored strategies.

6.3 Hybrid Solutions as Most Effective Pathway

The strongest results came from integrated solutions. Hybridization—such as combining alternative fuels with after-treatment systems—offers the most feasible compliance pathway in the short to medium term while zero-carbon fuels and CCS continue maturing.

6.4 Importance of Regulatory Frameworks and Incentives

The research reinforces the decisive role of IMO frameworks, national incentives, and carbon pricing in accelerating adoption. Without policy signals, industry uptake remains slow due to high CAPEX and uncertain ROI. Incentives such as tax credits, green financing, and phased enforcement can help overcome these barriers.

6.5 Alignment with SDGs, Paris Agreement, and IMO's GHG Strategy

The findings align directly with SDG 13 (Climate Action), the Paris Agreement's 1.5°C trajectory, and the IMO's 2023 Revised GHG Strategy. Adoption of advanced emission control technologies is thus not only a regulatory necessity but also a strategic enabler of global climate resilience and sustainable trade.

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