

# Technical Model for Energy Transition in Small Vessels: Hydrogen and Gas Technologies

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## ABSTRACT:

The maritime and fluvial transport sectors are pivotal in achieving sustainable energy transitions, particularly for small vessels [1]. This study presents a comprehensive technical model focused on the integration of hydrogen and gas technologies tailored for small boat applications. Through an extensive technology review [2], scientific monitoring, and technical diagnostics, the model aims to facilitate the adoption of low-emission propulsion systems. Key technologies analyzed include Proton Exchange Membrane (PEM) fuel cells (e.g., [4] FCwave 200 kW), dual hydrogen-diesel engines (DF series) [5], high-pressure hydrogen storage (700 bar systems), and cryogenic liquid hydrogen storage. Additionally, methane reforming for onboard hydrogen generation is considered. The research integrates up-to-date international standards ([2], ISO 20519:2017) and aligns with the International Maritime Organization (IMO)'s 2023 GHG strategy [1], ensuring compliance and safety in hydrogen handling and storage. Safety protocols emphasize the importance of certified containment materials, hydrogen leak detection via electrochemical sensors, explosion-proof electrical equipment, and rigorous ventilation systems. Hydrogen leak detection is based on ISO 26142 standards for hydrogen detection apparatus [3]. Environmental impact assessments highlight hydrogen's potential to significantly reduce CO<sub>2</sub> emissions, emitting only water vapor during operation. However, potential atmospheric effects from hydrogen leaks require ongoing monitoring and mitigation strategies. A visual summary of the proposed technical framework is presented in Figure 1. This model serves as a foundational framework for stakeholders seeking to advance sustainable marine propulsion, supporting the development of regulatory frameworks and best practices for small vessel energy transition..

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**Keywords:** hydrogen technologies, energy transition, small vessels, maritime sustainability, PEM fuel cells, safety protocols, environmental impact.

## Introduction

This work focuses on designing a technical model for energy transition applicable to small vessels by analyzing hydrogen and gas technologies. The objective is to provide a structured framework based on technological referencing, scientific monitoring, and technical diagnostics for maritime and fluvial sectors.

This work addresses the decarbonization needs of small-scale maritime and fluvial transport systems. While large vessels have begun to adopt alternative fuels, small vessels remain underserved in current energy transition strategies. This study proposes a model for incorporating hydrogen and gas-based technologies in small vessels to support sustainable navigation and align with international decarbonization policies, and aligns with the IMO's 2023 Greenhouse Gas (GHG) Strategy [1]. The model aims to provide scalable and applicable solutions based on emerging technologies such as Proton Exchange Membrane (PEM) fuel cells, dual-fuel engines, and cryogenic hydrogen storage.

Maritime and fluvial transportation is vital for regional connectivity in countries like Colombia. However, small vessels operating with diesel engines contribute significantly to greenhouse gas emissions. The urgency of climate targets and international commitments requires a transition toward cleaner alternatives. Despite global momentum in maritime decarbonization, small vessels remain largely excluded from regulatory and technical models. This study aims to fill that gap by presenting a scalable and adaptable technical model for energy transition in vessels  $\leq 25$  meters in length.

## 2. Methodology

The technical model was developed using the following phases:

- **Technology Benchmarking:** Analysis of international hydrogen propulsion technologies through literature and patent databases (Scopus, Espacenet).

- **Scientific Monitoring:** Evaluation of case studies and pilot programs (ElbBlue, MSTX-22, FLAGSHIPS) [13].
- **Operational Diagnosis:** Profiling small vessels in Colombia by usage type (passenger, tourism), power requirements, and autonomy.
- **Infrastructure and Normative Review:** Assessment of existing hydrogen production, ISO/IMO standards, and bunkering infrastructure in Colombia.

Technology Readiness Level (TRL) levels were determined for each propulsion pathway, aligning model recommendations with feasible short-term and mid-term options.

## 3. Results

### 3.1 Technologies for Energy Transition

The integration of these technologies into a Proton Exchange Membrane (PEM) fuel cell hybrid propulsion architecture is illustrated in Fig. 10.

- **Sensor Integration:** Recent enhancements incorporate gas sensors specifically for hydrogen purity monitoring during production and fueling. These are integrated alongside existing current, pressure, temperature, and voltage sensors to ensure safe, efficient, and traceable operation in hybrid fuel cell systems.

- **PEM Fuel Cells:** e.g., Ballard FCwave 200 kW module with high-efficiency electric propulsion. Commercial validation of this system has been demonstrated in projects such as [12].

- **Dual-Fuel Engines:** Wärtsilä and other DF engines capable of operating on LNG or hydrogen blends, validated in ElbBlue retrofits and pilot maritime hybrid systems [6].

- **Hydrogen Storage:** High-pressure tanks (350–700 bar) or cryogenic LH2 tanks.

- **Onboard Reforming:** Methane reformers allow flexible hydrogen generation onboard.

A schematic of national hydrogen production and distribution pathways is shown in Fig. 2. The viability of hydrogen propulsion heavily relies on national production and distribution capabilities. Colombia currently produces hydrogen mostly via natural gas reforming (approx. 47,000 tonnes/year), with emerging interest in green hydrogen through solar-powered electrolysis [9]. Infrastructure remains limited, with pilot bunkering systems under study in Buenaventura and Barranquilla. A recent report by [8] notes that without supportive policy and financial incentives, hydrogen uptake in transportation sectors will remain marginal.

### 3.2 Dependency on Hydrogen Infrastructure

Despite Colombia's early exploration of hydrogen integration, infrastructure readiness remains a key limitation. Small vessels require localized and adaptable hydrogen refueling solutions. Therefore, the model recommends:

- Mobile and modular hydrogen bunkering stations that can service rural fluvial ports with minimal installation.
- Integration of solar-powered PEM electrolyzers in coastal regions like La Guajira, enhancing off-grid hydrogen generation aligned with renewable energy availability.
- Interconnection between hydrogen production hubs and minor ports, enabling feasible logistics for liquid or compressed H<sub>2</sub> transportation.
- Monitoring infrastructure including hydrogen flow, temperature, and leakage sensors at fueling sites to ensure safety and efficiency.

While this study is centered on Colombia, the proposed infrastructure approach is scalable and applicable in other regions facing similar geographic and economic conditions. Countries

like Chile, Indonesia, and India with fragmented riverine or island systems could adapt these mobile and off-grid solutions. Europe, while more advanced in hydrogen logistics, continues to develop modular port bunkering facilities for inland vessels, providing valuable lessons for adaptation.

In comparison to global efforts, such as the H2PORTS initiative in Europe, Colombia's hydrogen refueling network is still at the pilot stage. Accelerating infrastructure deployment will be crucial to scale the proposed model.

### 3.3 Infrastructure Needs

While Colombia's progress remains incipient, it is imperative that each country builds the capability to generate its own hydrogen sustainably, tailored to its local geographic, economic, and environmental conditions. National hydrogen production and distribution systems are fundamental not only to energy sovereignty but also to ensure continuous operation of hydrogen-powered small vessels.

Establishing region-specific electrolyzer installations and decentralized bunkering terminals strengthens the autonomy and viability of the transition. In regions such as Chile and parts of Africa and Asia, where fluvial or island transport is essential, similar efforts in local hydrogen generation have demonstrated early success, such as the H2PORTS initiative in Europe. Colombia's hydrogen refueling network is still at the pilot stage. Accelerating infrastructure deployment will be crucial to scale the proposed model.

### 3.4 Safety Considerations

Hydrogen presents unique operational hazards that require robust mitigation systems. The model adopts a layered safety approach, drawing from ISO and IEC standards:

- **Gas detection systems** using electrochemical and catalytic sensors are installed on board and at refueling points to detect leaks below 10% LIE.

- **Explosion-proof components** (International Electrotechnical Commission Explosive Atmospheres Certification System (IECEX)-certified) and intrinsically safe electronics are included in propulsion and monitoring systems.
- **Redundant safety valves**, emergency cut-off circuits, and forced ventilation mechanisms are mandated to reduce ignition risks.
- **Material compatibility protocols**, especially for high-pressure tanks and tubing, follow ISO 11114 standards to prevent hydrogen embrittlement.

Although advanced economies have adopted many of these safety protocols in large-scale applications, transferring them to small vessel contexts is still limited. Projects like FLAGSHIPS and [13] in Europe offer precedents, but regional customization is necessary due to differing regulatory enforcement and operational profiles.

While industrial-scale vessels have begun integrating these safeguards, their application in small vessels remains limited, underscoring the novelty and relevance of this model. The system layout and integration are presented in Fig. 3.

To validate the technical model, a scaled 1-meter prototype was developed simulating the energy demands of a 12-passenger vessel:

- **Architecture:** Brushless DC propulsion powered by a 1.2 kW PEM fuel cell (Horizon H-1000XP) and 24V lithium-ion battery pack.
- **Instrumentation:** Real-time monitoring via LoRa-based telemetry, capturing hydrogen pressure, production rate, motor RPM, GPS position, battery SOC, and ambient conditions.
- **Hydrogen production sensor** (based on flow and differential pressure) enables

performance diagnostics of onboard reformer or storage release.

- **Safety sensors** include LIE gas leak detector and high-temperature alarm, validated during prototype docking simulations.

This methodology not only validates the technical performance in Colombian conditions but also reflects approaches from global pilots in similar size vessels. For instance, the MSTX-22 program in Germany developed micro-propulsion testbeds for urban ferries, demonstrating the value of scaled testing prior to commercialization.

This prototype mirrors the validation methodologies of [13] and MSTX-22 programs in Europe and is pivotal for assessing feasibility before full-scale deployment. See Figs. 4 and 5 for baseline and sensor-enabled comparative emissions profiles.

Hydrogen yields only water vapor; LNG reduces CO<sub>2</sub> by 25% compared to diesel. Prototype trials confirm reduced acoustic signature and near-zero NO<sub>x</sub>. A comparative lifecycle analysis from the supports that hydrogen PEM systems achieve up to 70% GHG reduction versus marine diesel when supplied from electrolysis [11]. The architecture and regulatory layout of the proposed model is shown in Fig. 7.

The proposed model incorporates not only the technical configuration of propulsion and storage systems, but also accounts for the state of hydrogen production and distribution in Colombia. As hydrogen production scales up—especially green hydrogen from renewable sources—the viability of this model improves significantly. Government-backed projects and private investments in electrolysis plants, port terminals, and distribution corridors are key. Moreover, the model is built upon strict adherence to ISO standards such as ISO 19880-1 and ISO 26142, and aligns with IMO GHG reduction goals. Environmental regulation, occupational safety, and risk management are embedded in the design. The model provides a

modular and adaptive structure, capable of integrating future innovations in hydrogen logistics and bunkering systems.

While focused on Colombia, this framework has broader international relevance. Regions with decentralized riverine or island transport systems—such as Southeast Asia, Sub-Saharan Africa, and parts of Central America—can adapt the model to their contexts. Europe and Japan, although more advanced in hydrogen policy, are only beginning to address small vessel use cases, making this model a reference point for niche but critical maritime applications

### 3.7 Model Discussion and Regulatory Framework

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### 3.8 Lifecycle Considerations and Limitations

For small vessels (~12 passengers), lifecycle emissions vary significantly depending on hydrogen source:

- **Green hydrogen (electrolysis + solar):** Highest lifecycle benefit but currently limited by cost and infrastructure. Requires robust electrolyzer deployment.
- **Blue hydrogen (Steam Methane Reforming (SMR) with CCS):** Moderate reduction potential, but infrastructure is centralized and not ideal for fluvial distribution.
- **Grey hydrogen (from natural gas):** Least favorable in emissions impact; viable only as interim measure with planned transition.

Disadvantages of underdeveloped infrastructure include high transport costs, safety risks during handling, and low availability at ports. Without dedicated bunkering and regulatory incentives, small vessel operators cannot rely on hydrogen propulsion viability. Aligning local capabilities with vessel operational profiles (e.g., 4-5 hour range, sub-15 knot speeds) is essential.

Recent academic literature [16, 15] notes potential environmental risks associated with widespread hydrogen use. Hydrogen leakage can indirectly affect atmospheric chemistry by increasing stratospheric water vapor and altering methane lifetime, potentially warming the atmosphere. Furthermore, large-scale electrolysis demands significant water and energy resources. In regions with freshwater scarcity, this may compete with agricultural and human consumption needs. Also, the mining and processing of critical materials for electrolyzers and fuel cells (e.g., platinum, iridium, rare earths) raise concerns of environmental degradation and geopolitical dependencies.

These lifecycle limitations necessitate continuous monitoring, responsible sourcing, and integration

of circular economy principles in hydrogen technology deployment.

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#### 4. Implementation and Operational Model Framework

To facilitate the practical deployment of this energy transition model for small vessels, a structured implementation and operation framework is proposed:

##### A. Pre-Implementation Phase:

- **Policy Alignment:** Confirm alignment with IMO GHG Strategy and national hydrogen roadmaps.
- **Site Feasibility:** Identify ports and fluvial terminals with potential for hydrogen bunkering.
- **Stakeholder Engagement:** Coordinate with port authorities, vessel operators, and technology providers.

##### B. Design and Engineering Phase:

- **System Selection:** Choose propulsion configuration (PEM FC, dual-fuel, battery hybrid).
- **Hydrogen Supply Chain:** Define source (electrolysis, SMR, LOHC) and transport method (compressed, cryogenic).
- **Infrastructure Requirements:** Plan for bunkering skids, safety equipment, and ventilation systems.
- **Regulatory Compliance:** Ensure adherence to ISO 19880-1, ISO 26142, ISO 20519, IECEx.

##### C. Implementation Phase:

- **Prototype Deployment:** Construct and test scaled prototype (e.g., 1-meter hybrid).
- **Sensor Integration:** Install hydrogen flow, purity, leak, and propulsion telemetry sensors.
- **Training and Safety:** Conduct training for crew and maintenance personnel on hydrogen safety protocols.

##### D. Operational Phase:

- **Monitoring and Telemetry:** Use real-time DAQ systems to monitor hydrogen usage, emissions, and propulsion status.
- **Lifecycle Assessment:** Perform periodic GHG audits based on fuel source and operational efficiency.
- **Infrastructure Maintenance:** Routine checkups of storage tanks, dispensers, and sensors.

##### E. Regulatory and Strategic Implications:

- Regulatory bodies must define clear standards for hydrogen usage in small-scale maritime contexts, which are currently underrepresented in international frameworks.
- Despite automotive sector maturity in hydrogen deployment, maritime implementation remains technologically lagging. This model helps fill that void, building on commercial interest while promoting public regulatory progress.
- Aligning implementation with the SDGs, especially Goal 13 (Climate Action) and Goal 9 (Industry, Innovation, and Infrastructure), creates a compelling case for investment and cross-sector collaboration.

This framework offers a replicable path for maritime energy transition at the small vessel scale, balancing technological feasibility, safety,

regulatory compliance, and environmental responsibility.

### 3.9 Additional Technological Pathways

To expand the array of technical routes for hydrogen integration in small vessel propulsion, four additional schematic pathways are proposed:

- **Hybrid System with Natural Gas (LNG/CNG) + Gaseous Hydrogen (H<sub>2</sub>):** This system involves either blending hydrogen directly with LNG/CNG for use in a modified internal combustion engine or operating a dual-fuel switched configuration. It leverages existing LNG infrastructure, reduces emissions, and offers an intermediate step for gradual energy transition.
- **Hydrogen + Battery Hybrid System:** Hydrogen powers a PEM fuel cell, generating DC current, which is managed by an inverter/controller and optionally stored in a battery bank. This setup enhances energy efficiency, allows plug-in recharging, and ensures redundancy.
- **Onboard Electrolysis System:** Renewable sources (e.g., solar, wind) generate electricity to power an electrolyzer. The resulting hydrogen is stored under low pressure and converted into electricity via a PEM fuel cell. It's a self-sufficient model ideal for slow scientific vessels.
- **Compressed Gaseous Hydrogen System:** Hydrogen is stored in high-pressure tanks (200–700 bar), regulated, and fed to a PEM fuel cell. It offers a lightweight solution but requires significant pressure management and cylinder integrity.

These configurations are shown in Figures 9–12 and complement the previously proposed implementations by accommodating diverse operational, geographic, and regulatory constraints.

Each provides flexibility based on port infrastructure availability, autonomy needs, and vessel retrofitting capacity.

### 5. Conclusion

This technical model demonstrates a clear path for energy transition in small vessels, emphasizing modularity, safety, and environmental compliance. However, real-world deployment will critically depend on Colombia's hydrogen development roadmap, infrastructure investment, and international regulatory harmonization.

Advantages of the proposed approach include reduced emissions, potential integration with renewable hydrogen, and alignment with IMO and ISO norms. Moreover, scalable modular designs allow adaptation across diverse geographies. On the other hand, limitations arise from the high cost of hydrogen fuel cells, the scarcity of refueling infrastructure, and limited technical maturity in maritime applications compared to automotive sectors.

While vehicle-based hydrogen solutions are gaining momentum globally, implementation in maritime contexts—especially for small vessels—remains rare. Most academic publications focus on large commercial ships or port operations, leaving a research gap in fluvial and regional vessel strategies. Nevertheless, commercial innovation is being driven by sustainability mandates, notably the UN's Sustainable Development Goals (SDGs), pushing forward investments in fuel cell systems, hybrid engines, and hydrogen bunkering by private firms (Ballard, Wärtsilä, Kawasaki).

Hence, broader academic contributions and pilot testing in this segment are essential to build a robust policy, technical, and commercial foundation.

An essential component of successful implementation lies in a country's ability to generate and distribute hydrogen locally. Without dedicated national infrastructure, small vessels remain dependent on imported fuels, undermining

cost-efficiency and operational feasibility. While global leaders like Japan, Germany, and Norway have established robust hydrogen ecosystems with port-side bunkering systems, nations like Colombia must prioritize localized electrolyzer deployment and off-grid solutions. This will allow for flexible adaptation of the model proposed here and ensure self-reliance in maritime energy systems. and pilot testing in this segment are essential to build a robust policy, technical, and commercial foundation. An additional advantage identified in this study is the use of hydrogen-enriched natural gas propulsion systems. These systems operate under lower pressures compared to pure hydrogen (typically below 350 bar), simplifying storage and distribution. Moreover, they are compatible with existing internal combustion engine infrastructure—similar to hydrogen-enriched combustion in automotive applications—facilitating retrofitting in small vessels without significant redesign. This characteristic makes dual-fuel approaches (e.g., hydrogen and natural gas) attractive for initial implementation in regions lacking advanced hydrogen infrastructure, enabling emissions reduction with more accessible integration. The feasibility of implementing this model for small vessels depends heavily on national readiness in infrastructure, regulatory frameworks, and stakeholder collaboration. In optimal conditions, full deployment—including production facilities, retrofitting of small vessels, and port-based bunkering—may require 3 to 5 years. This

estimation is tailored specifically for small-scale maritime transport. Key variables influencing this timeline include political commitment, access to financing, local engineering capabilities, and regional logistical challenges. Countries with prior experience in hydrogen transportation, such as in the automotive sector, may shorten this timeline, while regions with limited baseline infrastructure may require longer-term planning and demonstration phases. Despite these hurdles, early investment and coordinated action can enable a progressive rollout, providing scalable and adaptable decarbonization pathways in the small vessel segment. Despite these challenges, early investment and coordinated action can accelerate deployment and create a long-term decarbonization pathway for small maritime transport.

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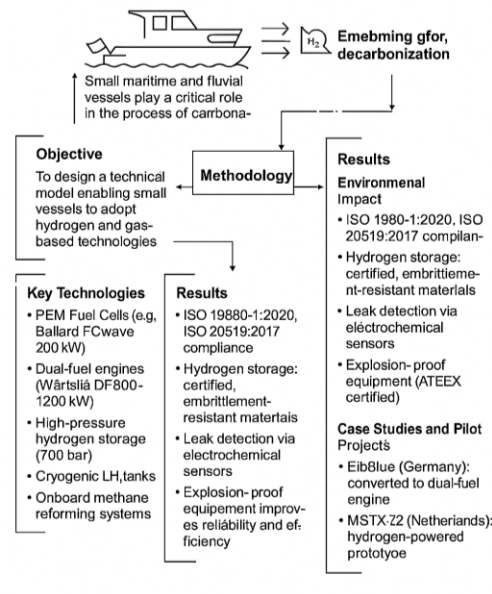
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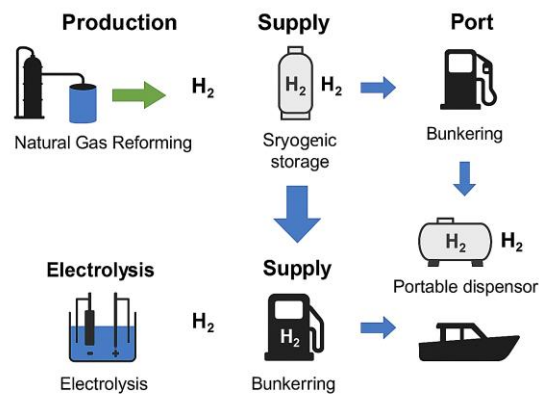
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### Figures:

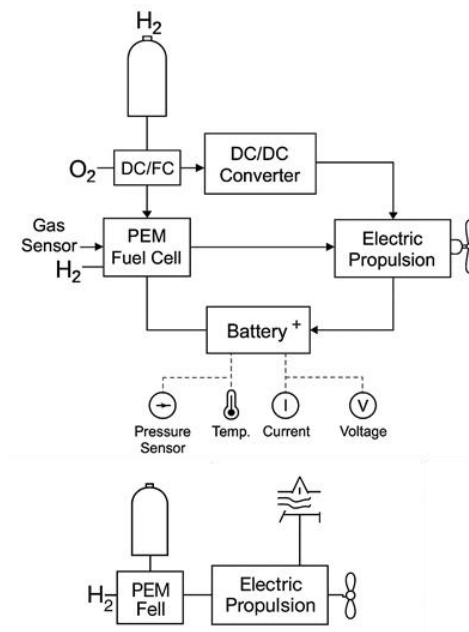
• Figure 1: Graphical Abstract



• Figure 2: Hydrogen Production and Distribution Flow



- Figure 3: Hybrid H<sub>2</sub> + Battery System Prototype



- Figure 4: Comparative Emissions Profile (Baseline)

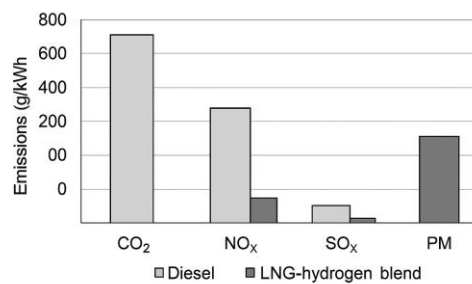
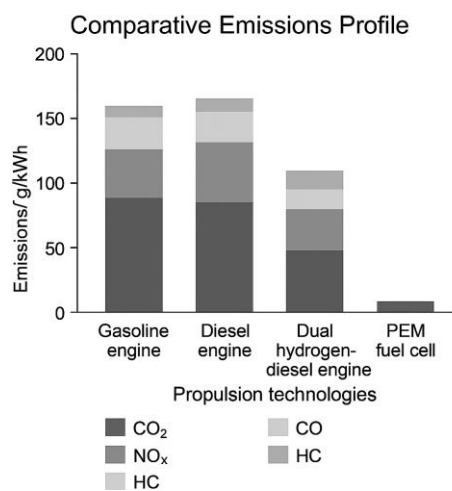
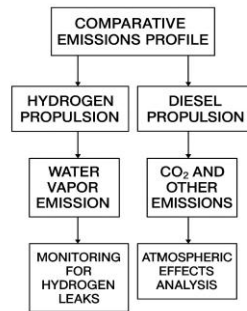


**Figure 4** Comparative Emissions Profile (Baseline)

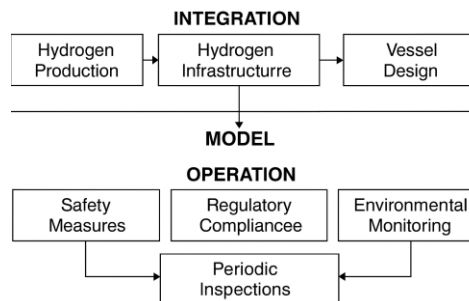
- Figure 5: Comparative Emissions Profile Including Sensor



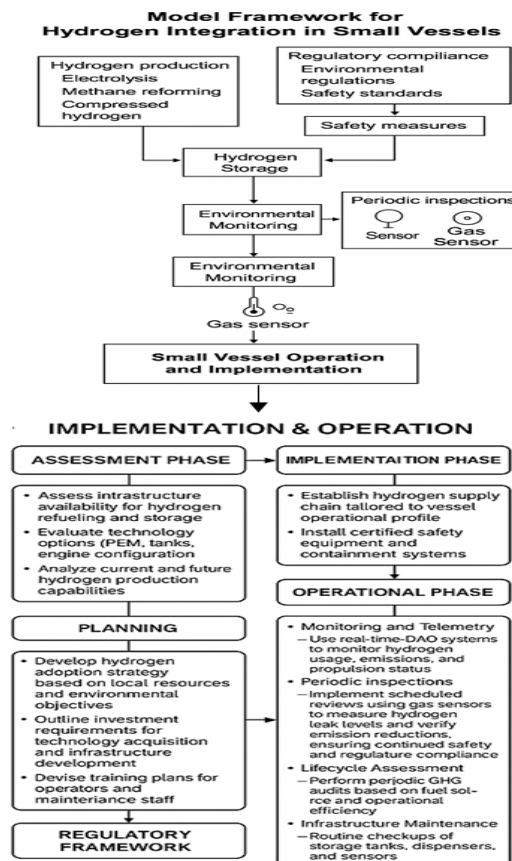
- Figure 6: PEM Hybrid Propulsion System with Sensor Integration



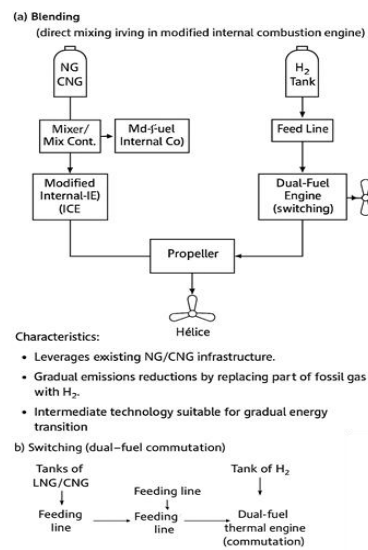
- Figure 7: Schematic Overview of the Technical Model



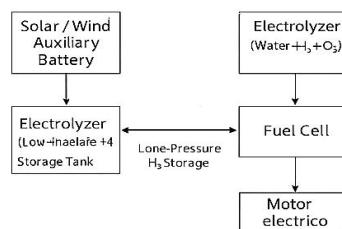
- Figure 8: Implementation and Operation Framework Schematic



- Figure 9: Hybrid LNG/CNG + Hydrogen System (Blending and Dual-Fuel Modes)



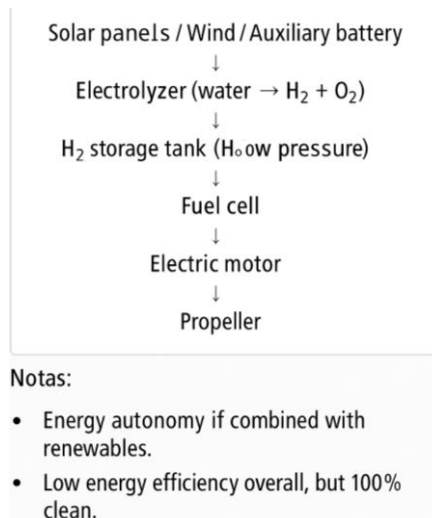
- Figure 10: Hydrogen + Battery Hybrid Architecture



**Notes:**

- High efficiency by combining storage and fuel cell
- Plug-in capability at ports
- Redundant power system for safety

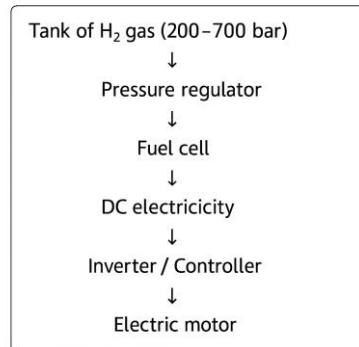
- Figure 11: Onboard Electrolysis for Hydrogen Production



- Figure 12: Compressed Hydrogen Gas Propulsion System

### **Compressed Hydrogen Gas Propulsion (200–700 bar)**

Diagram:



Notes:

- Requires high-pressure cylindrical tanks.
- Lightweight but bulky.