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Bridging Hydrogen Policy and Regulatory Implementation: A Governance Framework for Colombia's Maritime and Inland Waterway Sector

Paula Cuervo Velásquez [1,*], Carlos Andrés Cuervo Velásquez [2] and Luis Martínez Palmeth [1]

[1] Grupo de Investigación en Diseño y Manufactura—DIMA, Escuela de Ingeniería Mecánica, Facultad de Ingenierías Fisicomecánicas, Universidad Industrial de Santander, Bucaramanga 680002, Colombia; lhmarpal@uis.edu.co

[2] Facultad de Ingenierías, Universidad de San Buenaventura Medellín, Medellín 050010, Colombia; carlosc789@hotmail.com

* Correspondence: pacuevel@uis.edu.co; Tel.: +57-304-291-3381

Abstract

Hydrogen has emerged as a strategic energy vector for hard-to-electrify sectors, including maritime and inland waterway transport. However, important gaps remain between hydrogen policy frameworks and the practical conditions required for implementation in specific territorial and sectoral contexts. This study analyzes this policy–implementation gap using small-scale maritime and inland waterway vessels in Colombia, which fall outside the scope of SOLAS and the IGF Code, as a case study. The research combines literature review, policy and regulatory analysis of 40 instruments, technological surveillance and a 12-passenger vessel case to evaluate the conditions required for responsible hydrogen deployment. The study proposes an integrated framework that connects hydrogen implementation with territorial resource availability, water sustainability, safety requirements, regulatory conditions, industrial capabilities, infrastructure constraints, and energy security. Particular attention is given to water resource management for green hydrogen production, a factor often insufficiently incorporated into hydrogen policy despite its relevance to sustainable development. Results show that 71% of applicable national regulatory requirements are missing (20% internationally) and that hydrogen should complement an electricity system that is already 70–87% renewable. The findings show that hydrogen deployment cannot be treated only as a technological or decarbonization strategy; it requires coordinated governance mechanisms capable of aligning policy ambition with territorial, environmental, industrial, and operational realities.

Keywords: hydrogen policy; energy transition; territorial implementation; water footprint; maritime decarbonization; inland waterway transport; regulatory gap; Colombia

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1. Introduction

The transition toward low-emission energy systems represents one of the major challenges facing contemporary energy systems, particularly in sectors where direct electrification presents technical, operational, or economic limitations. In this context, low-emission hydrogen has emerged as a strategic energy vector capable of facilitating the decarbonization of hard-to-electrify sectors such as heavy industry, freight transport, and maritime transport. Its ability to store energy derived from renewable sources and convert it into

electricity through fuel cells positions hydrogen as a relevant alternative within global climate mitigation strategies [1–5].

At the international level, various energy strategies have incorporated hydrogen into their energy transition and decarbonization policies. In particular, the maritime sector has begun exploring alternative fuels and hydrogen-based energy solutions and their derivatives to reduce emissions from global maritime transport [6,7]. However, many of these strategies have focused primarily on technological development and emission reductions, while aspects related to territorial implementation, the selection of appropriate energy technologies according to regional conditions, and the sustainability of critical resources—such as the water resources required for green hydrogen production—have received comparatively less attention in public policy frameworks [2,4].

In the Colombian context, the energy transition has been progressively incorporated into the regulatory and energy planning framework through several normative and strategic instruments. These include Law 1715 of 2014, which promotes the integration of non-conventional renewable energy sources; Law 2099 of 2021, which formally introduced the categories of green and blue hydrogen within the national energy system; and Law 2169 of 2021 on climate action, which establishes carbon-neutrality targets and recognizes green hydrogen production as an activity of public interest. These legal instruments have been complemented by regulatory decrees and policy initiatives aimed at promoting the development of the hydrogen value chain in the country [8,9].

Colombia also adopted the National Hydrogen Roadmap in 2021 as a strategic instrument to guide the development of hydrogen technologies as part of the national energy transition and reindustrialization strategy [8]. The roadmap establishes production and technological development targets that project an increasing role for hydrogen in industrial and energy sectors by 2030 and 2050. Nevertheless, the national policy diagnosis recognizes that the country still exhibits a limited development of the low-emission hydrogen value chain, revealing significant gaps in infrastructure, technological development, financing, governance, and institutional coordination required for its deployment [9].

Among these gaps, challenges related to national industrial and technological capacity are particularly relevant. Currently, many of the critical components required for the hydrogen value chain—such as electrolyzers, high-pressure storage tanks, fuel cells, and specialized safety systems—are not produced at industrial scale within the country. This situation implies a strong dependence on imported technologies for the development of hydrogen projects, generating challenges related to technology transfer, industrial development, and the adoption of international technical standards that ensure the safety and reliability of hydrogen-based systems [2,7].

In this context, the adoption of hydrogen-based technologies requires not only the development of energy infrastructure but also the establishment of regulatory, normative, and technical frameworks that enable safe and efficient implementation. This includes the adoption of international standards related to hydrogen production, storage, transport, and utilization, as well as strengthening national capacities in certification, human capital training, applied research, and industrial development [1,10].

Despite the regulatory and strategic progress achieved in recent years, an important gap remains between hydrogen policy frameworks and the practical processes required for technological implementation. Current policy instruments primarily focus on promoting hydrogen production and enabling market development, while providing limited guidance on the technical criteria needed to select appropriate energy transition technologies according to territorial conditions, resource availability, and sector-specific operational requirements [1,4]. This gap is particularly relevant in the Colombian maritime and inland water transport sector, where waterborne transport plays a critical role

in connecting regions with limited terrestrial infrastructure. In these areas, small-scale vessels are essential for passenger and cargo transport but rely predominantly on internal combustion engines powered by fossil fuels, generating significant environmental impacts and limiting the transition toward more sustainable mobility systems [7].

Furthermore, the implementation of green hydrogen technologies requires consideration of critical variables such as the sustainable availability of water resources, regional energy capacity, existing logistical infrastructure, social impacts on local communities, and the operational safety of energy systems. Although green hydrogen production depends directly on water use in electrolysis processes, this factor has not yet been fully incorporated into energy planning criteria in many international strategies, despite its direct relationship with Sustainable Development Goal 6 (clean water and sanitation), in addition to SDG 7 (affordable and clean energy) and SDG 13 (climate action) [2,11].

In this context, there is a need to develop methodological approaches that guide the selection and implementation of energy transition technologies by considering technical, territorial, environmental, and social variables. Based on a case study applied to the Colombian maritime and inland water transport sector—particularly small-scale vessels—this article proposes a technical pathway for the progressive adoption of hydrogen-based technologies, integrating criteria related to energy sustainability, operational safety, natural resource availability, and alignment with national energy transition policies.

Additionally, energy planning processes still present gaps in defining technical criteria for selecting the most appropriate hydrogen production pathways according to the country's territorial and energy conditions. In particular, the choice between green hydrogen—produced through electrolysis using renewable energy—and blue hydrogen—produced from natural gas with carbon capture and storage—depends on factors such as regional energy resource availability, existing infrastructure, proximity to demand centers, production costs, and the sustainability of water resources required for electrolysis processes. However, these criteria have not yet been fully systematized within public policy instruments or technical methodologies guiding sectoral implementation. In some contexts, hydrogen technologies have been implemented in vehicular systems through adaptations or components that are not fully certified or regulated, potentially creating safety risks associated with hydrogen storage and high-pressure operation. Consequently, the development of a hydrogen-based energy transition requires not only policies that promote technological adoption but also technical procedures, safety standards, and regulatory frameworks that ensure safe and responsible implementation aligned with the country's energy and territorial conditions.

Hydrogen is commonly classified by its production route and associated emissions (Table 1). Green hydrogen is produced by water electrolysis powered by renewable electricity; blue hydrogen is produced from natural gas by steam methane reforming (SMR) or autothermal reforming combined with carbon capture and storage (CCS); grey hydrogen is produced from natural gas without capture and currently dominates global supply; brown or black hydrogen is obtained from coal gasification; turquoise hydrogen is produced by methane pyrolysis with solid carbon as a by-product; and pink hydrogen uses nuclear electricity for electrolysis [12–14]. Colombian legislation formally recognizes only the green and blue categories [15], which is why this study focuses on these two pathways while using grey hydrogen as a reference.

Table 1. Main hydrogen production pathways ("colours"), nature and typical uses.

Type	Production Route and Nature	Main Emission or Resource Issue	Typical Use and Status
Green	Water electrolysis (alkaline, PEM, solid oxide) with renewable electricity	Near-zero direct CO_2; water ($\geq$9 L/kg H_2) and renewable electricity demand	Fuel cells, synthetic fuels, industry; scaling up
Blue	SMR/ATR of natural gas with CCS	Residual CO_2 and upstream methane; geological storage required	Refining, ammonia; transitional option in the Colombian Roadmap
Grey	SMR of natural gas without capture	$\approx$9–12 kg CO_2/kg H_2	Dominant current industrial supply
Brown/black	Coal or lignite gasification	Highest CO_2 intensity	Industrial supply in coal-based economies
Turquoise	Methane pyrolysis	Solid carbon by-product; upstream methane	Pilot/demonstration
Pink	Electrolysis with nuclear electricity	Low CO_2; nuclear governance	Limited; not applicable to Colombia

Sources: compiled from [12–14,16].

Colombia's maritime and inland waterway sector was selected as the study context for three reasons. First, waterborne transport is the only practical means of mobility for many communities in the Pacific coast, the Amazon and Orinoco basins and the Magdalena and Atrato river systems, where small-scale vessels transport passengers and goods and depend almost entirely on gasoline and diesel engines [17]. Second, Colombia combines a hydropower-dominated electricity system with natural gas resources, so it can in principle pursue both green and blue hydrogen, which makes the pathway-selection problem particularly relevant [8,18]. Third, the country has a national naval science and technology corporation (COTECMAR) and an active hydrogen policy process, which provides an institutional setting in which the transition from policy to regulation can be observed while it is happening.

Despite the growing literature on maritime hydrogen, most studies address large ocean-going ships, techno-economic comparisons of fuels or national strategies in industrialized economies [19–22]. Far fewer examine how national hydrogen policies are translated into technical criteria and enforceable regulation for small domestic craft, and almost none address this question for an emerging economy. A structured search conducted in this research (Scopus, Web of Science and Google Scholar, 2010–2024) identified only four peer-reviewed articles specifically addressing hydrogen propulsion in small vessels (Section 3.2). This research gap is relevant because small domestic vessels typically fall outside the mandatory scope of international maritime conventions, so the regulatory pathway for hydrogen on board depends entirely on national authorities.

This study therefore addresses three research questions: (RQ1) Which gaps separate Colombia's hydrogen policy instruments from the conditions required to implement hydrogen technologies in small-scale maritime and inland waterway vessels? (RQ2) How complete is the regulatory coverage of the hydrogen value chain for these vessels at the international and national levels? (RQ3) Which technical criteria and governance arrangements are needed to close these gaps?

The study contributes to the energy policy literature in three ways. First, it frames hydrogen deployment as a gap between strategic policy and sectoral implementation. Second, it integrates territorial resource availability, water sustainability, safety, regulation and industrial capabilities into a single technical pathway for small vessels. Third, it links this pathway to institutional responsibilities, measurable indicators and a prioritized roadmap that can be applied in other emerging economies. Section 2 reviews the literature; Section 3 describes the materials and methods; Section 4 presents the results; Section 5 discusses the role of hydrogen in a renewable-dominated electricity system, energy security and policy implications; and Section 6 presents the conclusions.

2. Literature Review

2.1. Decarbonization Options and Emerging Trends in Maritime Propulsion

The International Maritime Organization (IMO) adopted in 2023 a revised strategy that targets net-zero greenhouse gas (GHG) emissions from international shipping by or around 2050, with indicative checkpoints for 2030 and 2040 and an uptake target for zero or near-zero emission fuels [23]. Reviews of the available options show that no single measure is sufficient: operational and design efficiency, alternative fuels and new power systems must be combined [19–21]. Among the alternative fuels, hydrogen and its derivatives (ammonia, methanol, synthetic fuels) offer the deepest reductions when produced from renewable electricity, but they face lower volumetric energy density, higher costs and safety rules that are still under development [20,22,24].

For short-sea, harbour and inland vessels, the most dynamic trend is electrification. Battery–electric and hybrid power systems combine batteries with engines or fuel cells through DC or AC grids and an energy management system, allowing peak shaving, improved energy management and zero-emission operation in ports when operating on battery or fuel-cell power [25]. Fuel cells—mainly proton exchange membrane fuel cells (PEMFCs)—have been utilized in ferries, passenger boats and research vessels; their advantages include quiet operation and zero local emissions, while durability, cost, hydrogen storage and the integration of safety systems remain the main barriers [25,26]. Techno-economic studies of inland shipping indicate that battery–electric propulsion is usually the most cost-effective option for short, regular routes with access to low-carbon electricity, whereas hydrogen becomes competitive for longer autonomy requirements or where charging infrastructure is limited [27]. Emerging trends include modular PEMFC–battery architectures, hydrofoil craft that reduce energy demand, and university-led demonstrators such as those competing in the Monaco Energy Boat Challenge, which were observed during the technological surveillance of this research.

2.2. Hydrogen Policy, Governance and the Implementation Gap

Policy implementation research has long shown that objectives formulated at the central level are frequently diluted or blocked when their execution depends on multiple agencies, legal instruments and local actors [28]. Hydrogen is a typical example: national strategies set production targets and incentives, but deployment requires the coordination of energy, environmental, transport, industrial and quality-infrastructure authorities [3,29]. The literature on hydrogen governance has focused mainly on geopolitics, international trade and certification of low-carbon hydrogen [2,29], and on the risk of overestimating hydrogen's role in sectors that can be electrified directly [5,24]. Few studies analyze the intermediate level at which policy goals become technical criteria, regulation and conformity assessment in a specific sector, or how global transition narratives should be adapted to the resources and industrial capacities of each country. This is the level addressed in the present study.

2.3. Regulatory Landscape for Hydrogen as a Marine Fuel

The International Convention for the Safety of Life at Sea (SOLAS) and the International Code of Safety for Ships Using Gases or Other Low-Flashpoint Fuels (IGF Code) form the international regulatory basis for alternative fuels on ships [30,31]. The IGF Code contains detailed requirements for natural gas, but hydrogen is currently addressed through the alternative-design procedure, supported by IMO interim guidelines for fuel cell power installations and for ships using hydrogen as fuel [32,33]. Classification societies such as DNV, ABS, Bureau Veritas and Lloyd's Register have issued rules and guidance for fuel cells and hydrogen systems, and industry handbooks summarize hazards, ventilation,

leak detection and risk-assessment practices [34]. At the component level, ISO/TC 197, the technical committee responsible for hydrogen technologies, and IEC provide standards for hydrogen quality (ISO 14687:2025), refuelling stations (ISO 19880-1:2020), storage containers and pressure-relief devices (ISO 19881:2025 and ISO 19882:2025), hydrogen generators using water electrolysis (ISO 22734-1:2025), and fuel cell modules (IEC 62282-2-100:2020) [10,35–40]. Importantly for this study, SOLAS defines a passenger ship as one carrying more than 12 passengers, and the IGF Code applies to ships covered by SOLAS [30,31]; domestic vessels carrying up to 12 passengers and crafts operating on inland waters therefore fall outside the mandatory scope of these instruments and must be regulated by national authorities.

2.4. The Water–Energy Nexus of Hydrogen Production

Electrolysis requires 9 kg of water per kilogram of hydrogen stoichiometrically; when losses in water purification are included, practical consumption is typically 10–15 L/kg H_2, and considerably more when evaporative cooling is used [16,41]. Although this demand is small at the national scale, it can be significant locally, in water-stressed basins or where access to drinking water is precarious [41,42]. ISO 14046 provides a framework for water footprint assessment [43], but few national hydrogen strategies translate water availability into binding siting or approval criteria.

2.5. Synthesis and Research Gap

The literature includes (i) a strong technological and techno-economic body of work on maritime hydrogen, centred on large ships; (ii) a policy literature focused on national strategies, trade and certification; and (iii) an international regulatory framework that is still interim and does not cover small domestic craft. What is missing is an analysis that connects these strands for a specific sector of an emerging economy, identifies the concrete gaps between policy and implementation, and proposes technical criteria and governance arrangements adapted to the territory. This study addresses that gap.

3. Materials and Methods

3.1. Research Design

This study adopts a qualitative and comparative approach to examine the gap between hydrogen public policies and the regulatory frameworks required for their practical implementation, considering Colombia's energy, territorial, and industrial conditions. The methodology combines scientific literature, national and international regulatory analysis, and technological surveillance to identify limitations in the integration of hydrogen technologies, using Colombia's maritime and inland waterway sector as a case study [1–4,7].

The four analytical components are integrated sequentially (Figure 1): (1) a documentary and regulatory analysis of a defined corpus of instruments (Section 3.2); (2) a comparative gap analysis using an explicit coding scheme (Section 3.3); (3) technological surveillance, a case study of a small vessel and contextual validation with stakeholders (Sections 3.4 and 3.5); and (4) the synthesis of the results into a technical pathway and governance framework. Components (1) and (2) identify the gaps, component (3) verifies whether they matter for concrete design and investment decisions, and component (4) proposes how to close them. The study was carried out between 2024 and 2026 within a postdoctoral research project hosted by COTECMAR.

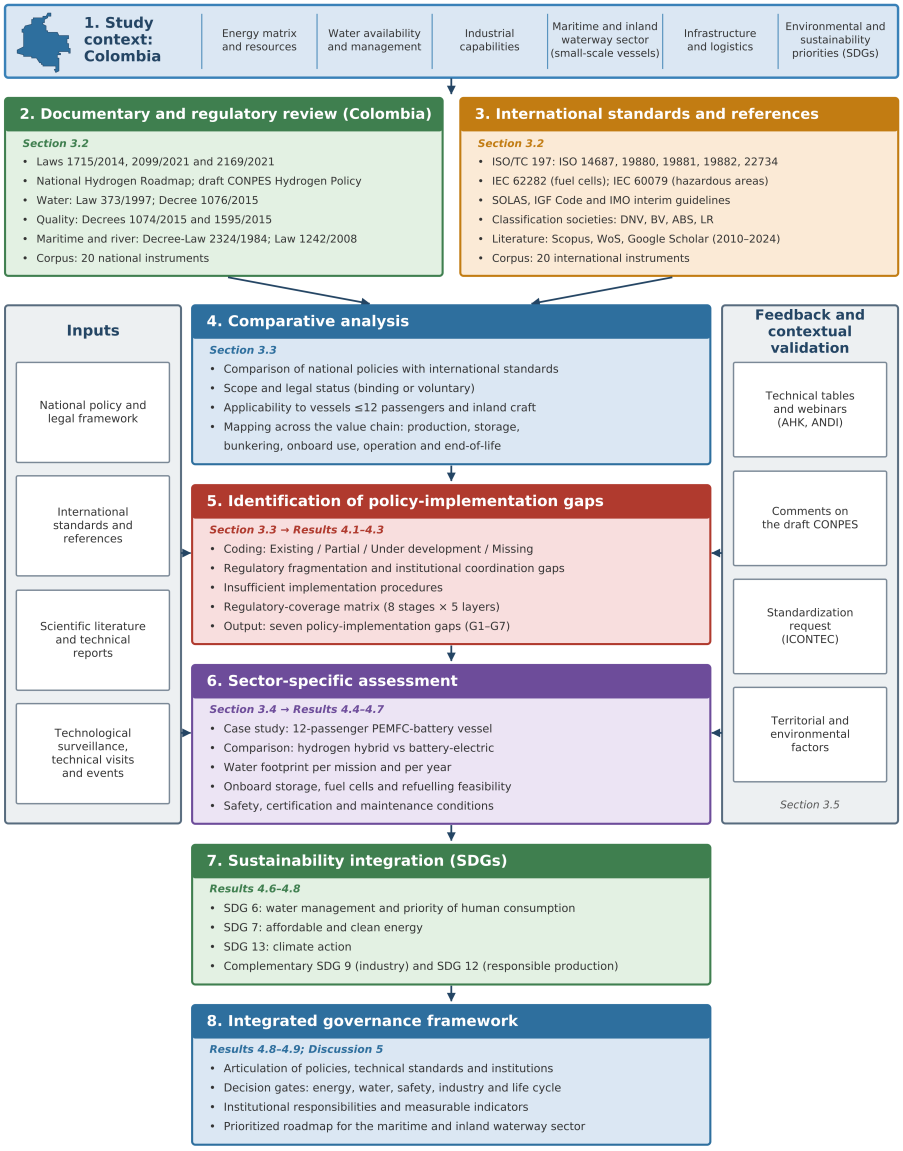


Figure 1. Country-contextualized methodological framework for identifying hydrogen policy–regulatory implementation gaps and developing an integrated governance framework adapted to Colombia's energy resources, territorial conditions, and sustainability priorities. Stages 2–3 correspond to Section 3.2, stages 4–5 to Section 3.3, stage 6 to Section 3.4 and stages 7–8 to Section 3.5. Source: authors' elaboration. Base map of Colombia: Natural Earth (public domain).

3.2. Document Corpus and Selection Criteria

First, a documentary review was conducted of Colombian energy transition policies, including Laws 1715 of 2014, 2099 of 2021, and 2169 of 2021, the National Hydrogen Roadmap, and the draft CONPES National Hydrogen Policy [8,9,15,44,45]. These instruments were compared with international technical standards developed by ISO/TC 197, maritime safety requirements, and classification society guidelines [10,22]. The analysis examined their scope, regulatory status, and applicability to different stages of the hydrogen value chain, distinguishing existing technical standards from integrated implementation requirements.

Documents were included when they met at least one of the following criteria: (i) a law, decree, policy or official strategy in force or under formal consultation in Colombia that governs hydrogen, energy planning, water resources, quality infrastructure or maritime and river transport; (ii) an international convention, code, guideline or standard

applicable to a stage of the hydrogen value chain or to ships using hydrogen; or (iii) a classification-society rule or guidance document for hydrogen or fuel cells on ships. Documents were obtained from official repositories (Congress, ministries, DNP, ICONTEC, ISO, IEC and IMO) and from the classification societies; commercial brochures and non-official summaries were excluded. The final corpus comprised 40 instruments (20 national and 20 international), summarized in Table 2. The scientific literature was searched in Scopus, Web of Science and Google Scholar for 2010–2024 using iterative keyword Equations (e.g., boat OR vessel AND small AND hydrogen AND propulsion), refined over up to six search cycles per thematic group; patent databases were also consulted. Only four peer-reviewed articles dealing specifically with hydrogen propulsion in small vessels were found in Scopus.

Table 2. Document corpus analysed ($n = 40$).

Group	Instruments	Role in the Analysis
Hydrogen and energy policy (CO)	Laws 1715/2014, 2099/2021, 2169/2021; National Hydrogen Roadmap (2021); draft CONPES National Hydrogen Policy (2025); Plan Energético Nacional 2022–2052; Law 143/1994	Strategic objectives, incentives, targets
Environment and water (CO)	Law 99/1993; Law 373/1997; Decree 1076/2015; Resolution 0631/2015; National Policy for Integrated Water Resource Management	Water concessions, licensing, reuse
Quality infrastructure and safety (CO)	Decree 1074/2015 (technical regulations); Decree 1595/2015 (national quality subsystem); Decree 1072/2015 (occupational safety); RETIE; Law 1523/2012 (disaster risk)	Path from standard to mandatory regulation
Maritime and river transport (CO)	Decree-Law 2324/1984 (DIMAR); Law 1242/2008 (river navigation code); Decree 1079/2015 (transport sector)	Competent authority and vessel rules
IMO instruments	SOLAS; IGF Code; interim guidelines for fuel cell installations and for hydrogen as fuel; 2023 IMO GHG Strategy	International maritime safety and climate rules
Technical standards	ISO 14687, ISO 19880 series, ISO 19881, ISO 19882, ISO 22734, ISO 13985, ISO/TS 19870, ISO 14046; IEC 62282 series; IEC 60079 series; NFPA 2	Component and system requirements
Classification societies	Rules and guidance of DNV, ABS, Bureau Veritas and Lloyd's Register for fuel cells and gaseous fuels	Design approval and certification practice

CO = Colombia. Each standard series and each classification society was counted as one instrument.

3.3. Comparative Gap Analysis and Coding Scheme

Subsequently, a comparative gap analysis was performed to identify regulatory fragmentation, insufficient coordination between institutions, and limitations in procedures for hydrogen production, storage, distribution, refuelling, and utilization. International technological experiences, supported by technical visits and participation in specialized hydrogen and maritime events, were examined in relation to Colombian territorial and industrial conditions. Small-scale maritime and inland waterway vessels were used to illustrate the challenges of integrating existing standards into sector-specific applications.

To make the gap identification traceable, two products were derived. First, each policy instrument was compared with the implementation requirements identified in the technical

literature and in the case study, and each missing requirement was recorded as a policy-implementation gap (G1–G7). Second, a regulatory-coverage matrix was built for eight value-chain stages (production, CGH_2 storage, LH_2 storage, refuelling/bunkering, fuel cell systems, hydrogen internal combustion, water supply and decommissioning) and five regulatory layers (ISO/IEC standards, IMO instruments, classification rules, Colombian standards and technical regulation, and Colombian maritime and river authority rules). Each cell was coded as existing (E), partial (P: requirements developed for other applications that need adaptation), interim or under development (U), missing (M) or not applicable. Coding was performed by the first author and cross-checked by the second author against the source documents.

3.4. Technological Surveillance and Case Study

The technological surveillance included participation in Connecting Hydrogen Europe 2025 (Madrid), Green Marine Med 2025 and Marina Port Forum (Barcelona), and the Monaco Energy Boat Challenge, as well as technical visits to the PiCoHiMA group and the Green Foiling Spain team of the Universidad Politécnica de Madrid. The case study is a 12-passenger vessel designed in the project for river, lake and coastal service (12 m length, 3.2 m beam, 0.6 m draught, 18 km/h service speed, 8 h autonomy, 80–100 km/day) with a PEMFC–battery hybrid system. It was used to apply the proposed criteria to a concrete decision and to compare the hydrogen configuration with a battery–electric alternative designed for the same mission. The vessel and its hydrogen-based propulsion and supply systems were developed as conceptual engineering designs. No physical equipment was procured, installed, or experimentally tested as part of this case study. Consequently, manufacturer names and equipment sourcing locations are not applicable to the proposed components.

3.5. Contextual Validation with Stakeholders and Synthesis

Preliminary gaps and recommendations were discussed in institutional settings in Colombia: the Ninth Technical Table on Sustainable Maritime Transport and Green Shipping organized by the German-Colombian Chamber of Commerce (AHK Colombia, September 2025), with participation of DIMAR, UPME, MinCIT, MinEnergía and industry; the webinar on regulatory progress of hydrogen in Colombia organized by ANDI (August 2025); and the Circuito H_2 meeting of the ANDI-Naturgas Hydrogen Chamber (Cali, November 2025). The recommendations were also submitted formally as technical comments on the draft CONPES National Hydrogen Policy (2026) and as a standardization request to ICONTEC (request No. 6247, May 2026). These activities were not a formal survey but served to verify that the gaps identified were recognized by the institutions concerned.

Finally, the identified gaps were examined considering energy resource availability, water sustainability, industrial capabilities, operational safety, and environmental impacts. These criteria were aligned with Sustainable Development Goals 6, 7, and 13, concerning water management, clean energy, and climate action, with complementary considerations related to SDGs 9 and 12 [11,16,17,42]. The findings were synthesized into a proposed governance framework aimed at articulating existing policies, technical standards, and institutional responsibilities to support safe and sustainable hydrogen implementation.

Figure 1 illustrates the methodological stages and their interconnections, from regulatory analysis and gap identification to the development of a governance framework adapted to Colombia's territorial and sustainability priorities.

4. Results: Regulatory Gaps and Implementation Criteria for Hydrogen Technologies in Small Vessels

4.1. Gap Between Public Policy and Sectoral Implementation

The transition toward low-carbon energy systems has driven the development of new policy strategies aimed at reducing greenhouse gas emissions in sectors where direct electrification presents technical, operational, or economic limitations. In this context, low-emission hydrogen has emerged as a strategic energy vector capable of facilitating the decarbonization of hard-to-abate sectors such as energy-intensive industry, heavy-duty transport, and maritime transport [3,4].

The structure of Colombia's electricity generation matrix plays a critical role in shaping the country's energy transition strategies. Unlike many regions where electricity production is largely dependent on fossil fuels, Colombia's power system has historically been dominated by hydropower generation. This characteristic has allowed the country to maintain a relatively low-carbon electricity mix compared with many other economies. However, thermal generation based on natural gas, coal, and liquid fuels continues to play an important role in providing system reliability and supply security. Understanding the composition of the national electricity matrix is therefore essential when evaluating the potential role of hydrogen technologies in the energy transition. In particular, the high participation of hydropower implies that new energy vectors such as hydrogen must be assessed in relation to an already renewable-dominant electricity system, rather than as a direct substitute for fossil-based electricity generation.

Figure 2 presents the approximate distribution of electricity generation sources in Colombia in 2024 and 2025, based on official data from the system operator XM [18].

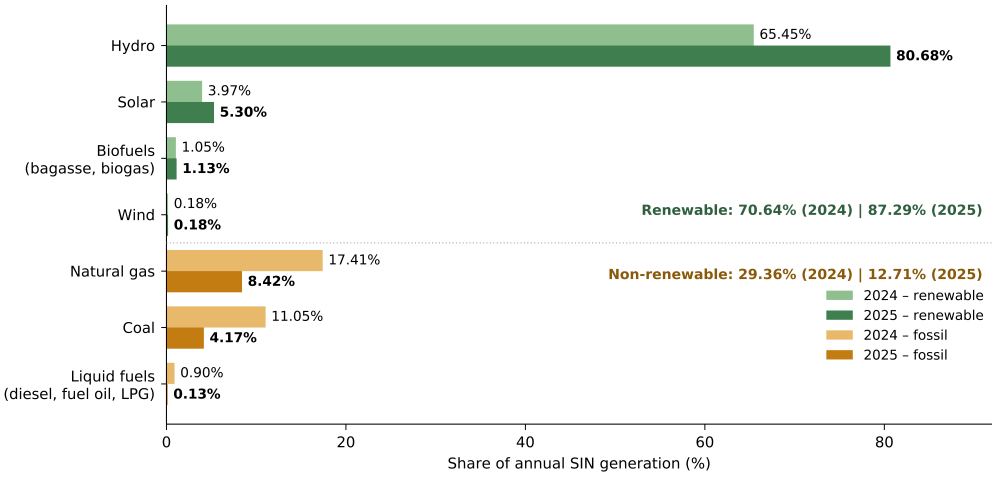


Figure 2. Electricity generation mix in Colombia by energy source in 2024 and 2025 (share of the annual generation of the National Interconnected System, SIN; total generation of 83,262.92 GWh in 2024 and 84,412.31 GWh in 2025). Source: authors' elaboration based on official data from XM [18].

The comparison of both years illustrates the dependence of the Colombian system on hydrology. In 2024, a dry year influenced by El Niño, hydropower supplied 65.45% of the electricity and thermal plants 29.36% (natural gas 17.41%, coal 11.05%, liquid fuels 0.90%). In 2025, with high inflows to the reservoirs, hydropower rose to 80.68% and thermal generation fell to 12.71%. Solar generation grew from 3.97% to 5.30%, whereas wind power remained marginal (0.18%), even though La Guajira concentrates several wind projects: in 2025 the operating wind plants (e.g., Guajira I and Carreto) generated only 154.85 GWh, none of the 41.5 MW of wind capacity expected for that year entered commercial operation, and the large wind generation planned for the Cuestecitas 500 kV node had not materialized [18]. This delay between planned and operating renewable

capacity is itself an example of the policy-implementation gap analysed in this study. This variability confirms that thermal generation is a reliability backup during dry periods and that the carbon intensity of grid electricity—and therefore of hydrogen produced from the grid—changes from year to year.

At the international level, numerous national and regional strategies have incorporated hydrogen into their energy transition and climate neutrality policies. However, several studies have highlighted that, despite significant technological progress in hydrogen development, important gaps remain in the implementation frameworks of these technologies. These gaps are particularly evident in aspects related to the territorial selection of projects, the sustainability of resources used in hydrogen production, and the sectoral integration of hydrogen-based energy solutions [2,3].

In the Colombian case, the country has developed in recent years a set of regulatory and policy instruments aimed at promoting the development of low-emission hydrogen as part of the national energy transition strategy. Among the main regulatory milestones are Law 1715 of 2014, which establishes the framework for the integration of non-conventional renewable energy sources into the national energy system; Law 2099 of 2021, which formally incorporates the categories of green and blue hydrogen into the Colombian energy system; and Law 2169 of 2021, which establishes national carbon neutrality goals and recognizes green hydrogen production as an activity of public utility and social interest [15,44,45].

In addition, the Colombian Hydrogen Roadmap, published by the Ministry of Mines and Energy in 2021, establishes production targets for low-emission hydrogen toward 2030, 2040, and 2050, while defining strategic pillars for the development of the hydrogen value chain in the country. The roadmap highlights the need to strengthen technological capabilities, develop infrastructure, and create market mechanisms that enable the gradual integration of hydrogen into the national energy matrix [8].

Within this policy framework, the draft National Hydrogen Policy currently under formulation through a CONPES document seeks to strengthen the technical, institutional, and productive capacities required for the deployment of the low-emission hydrogen value chain in Colombia. The policy diagnosis recognizes that the country still presents a limited level of development in this emerging industry and identifies significant gaps in infrastructure, governance, financing mechanisms, technological development, and institutional coordination required for the effective deployment of hydrogen projects [9].

Among the main challenges identified are the absence of intersectoral mechanisms for identifying optimal locations for hydrogen production projects, the lack of a comprehensive long-term strategy for the development of hydrogen transport and storage infrastructure, the absence of defined criteria for regulating and operating hydrogen distribution systems, and the limited adoption of technical and safety standards for hydrogen management [9].

However, the analysis conducted in this study shows that, although Colombia has made significant progress in establishing strategic policy instruments to promote hydrogen as part of the energy transition, a gap persists between the general policy guidelines and the technical procedures required for sectoral implementation. Existing instruments primarily focus on promoting hydrogen production and creating enabling market conditions, while providing limited guidance regarding the technical criteria required to support the selection of transition energy technologies based on territorial conditions, resource availability, sustainability considerations, and safety requirements.

This gap becomes particularly relevant in sectors such as maritime and inland waterway transport, where the adoption of new energy technologies depends on specific operational, territorial, and logistical conditions. In Colombia, waterborne transport plays a fundamental role in connecting regions with limited terrestrial infrastructure. In these areas, small-scale vessels are essential for the transportation of passengers and goods, yet

they remain largely dependent on internal combustion engines powered by fossil fuels, generating significant environmental impacts and limiting the transition toward sustainable mobility systems.

Furthermore, the implementation of hydrogen-based technologies requires the consideration of critical variables such as regional energy availability, existing logistics infrastructure, the sustainable management of water resources required for green hydrogen production, and the safety standards associated with hydrogen storage and handling. Although green hydrogen production relies directly on water through electrolysis processes, this factor has not yet been fully incorporated into energy planning criteria in many international strategies, despite its direct relationship with Sustainable Development Goal 6 (Clean Water and Sanitation), in addition to SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action). In this context, the present study argues that the effective implementation of hydrogen-based technologies requires the development of methodological approaches capable of integrating energy, territorial, environmental, and safety criteria into decision-making processes. Based on a case study focused on the Colombian maritime and inland waterway sector—particularly small-scale vessels—this research proposes a technical pathway for the progressive adoption of hydrogen-based technologies that aligns public policy frameworks with sustainability criteria, operational safety requirements, natural resource availability, and territorial energy planning.

Table 3 summarizes, for each main instrument, what it establishes and what it leaves undefined for small-scale vessels, and Figure 3 organizes the resulting seven gaps (G1–G7) in three levels: the strategic instruments that already exist (macro-level), the sectoral decisions that operators and authorities must take (micro-level), and the missing implementation layer between them (meso-level). Three of these gaps are specific to the waterborne sector and are not explicitly addressed in the draft policy: the absence of a regulatory pathway for vessels outside SOLAS/IGF scope (G2), the absence of binding water-security criteria (G4), and the absence of a defined division of responsibilities between energy, environmental, maritime and river authorities (G5).

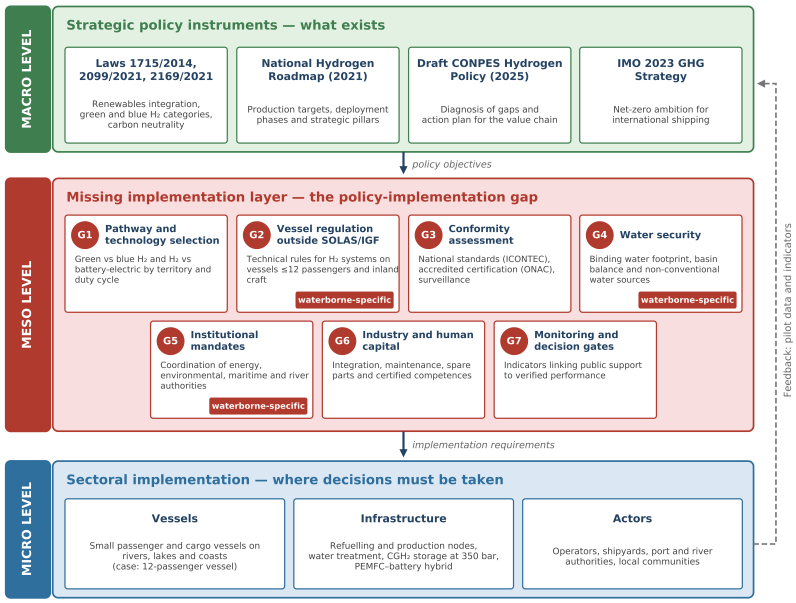


Figure 3. Conceptual model of the policy-implementation gap for hydrogen in Colombia's waterborne sector: macro-level (existing strategic instruments), meso-level (missing implementation layer, gaps G1–G7) and micro-level (sectoral decisions). Source: authors' elaboration.

Table 3. Policy instruments and the implementation elements they leave undefined for small-scale maritime and inland waterway vessels.

Instrument	What it Establishes	What Remains Undefined for Implementation	Gap
Law 1715/2014; Law 2099/2021	Green and blue hydrogen categories; fiscal incentives	Criteria to select a pathway by territory and application; conditions linking incentives to verified performance	G1, G7
Law 2169/2021	Carbon neutrality by 2050; hydrogen of public interest	Sectoral targets and indicators for waterborne transport	G7
National Hydrogen Roadmap (2021)	Production targets, phases for blue and green hydrogen, strategic pillars	Rules for maritime/river end use; responsible agencies for vessels	G2, G5
Draft CONPES (2025)	Diagnosis of gaps; action plan for value chain	Binding water-security criteria; explicit reference to IGF Code and non-SOLAS craft; conformity assessment chain	G2–G4
Decree 1076/2015; Law 373/1997	Water concessions and efficient use	Hydrogen-specific water footprint and basin-balance requirements	G4
Decree 1074/2015 and 1595/2015	Procedure for technical regulations and conformity assessment	A hydrogen technical regulation and adopted NTC standards	G3
Decree-Law 2324/1984; Law 1242/2008	Competences of DIMAR (maritime) and MinTransporte (river navigation)	Requirements for hydrogen fuel systems, bunkering and crew competence on small vessels	G2, G5, G6

Source: [8,9,15,44–51].

4.2. Absence of Technical Criteria for Selecting Green or Blue Hydrogen Pathways

One of the most significant findings of this research is that the selection between green hydrogen and blue hydrogen cannot be approached as a uniform, generalized, or purely technological decision. Instead, the results indicate that this choice depends on a combination of territorial, energy, industrial, and environmental conditions which, although partially acknowledged in policy frameworks, have not yet been translated into systematic technical procedures capable of guiding sector-specific decision-making. The Colombian Hydrogen Roadmap recognizes that the country possesses favorable conditions for both green and blue hydrogen development. On the one hand, Colombia has considerable potential for green hydrogen production supported by renewable energy resources such as solar, wind, and hydropower. On the other hand, the country also presents opportunities for blue hydrogen associated with the availability of natural gas resources and the potential development of carbon capture, utilization, and storage technologies [8]. The roadmap further outlines differentiated deployment phases, suggesting that blue hydrogen may play a transitional role in the short- and medium-term, while green hydrogen is expected to become the dominant pathway in the long-term.

However, when these strategic policy orientations are translated into specific sectoral applications—such as small vessels operating in coastal and inland waterway corridors—a significant methodological gap becomes evident. Current policy instruments do not clearly define the technical criteria required to determine which hydrogen pathway is more suitable for specific territorial contexts or operational applications. The analysis conducted in this study indicates that such decisions should consider multiple dimensions, including regional energy resource availability, access to and sustainability of water resources, existing infrastructure, proximity to demand centers, and logistical conditions for fuel supply systems.

In the case of green hydrogen, project feasibility is closely linked to the availability of renewable electricity and to the sustainable access to water resources required for electrolysis processes. This may involve the use of treated wastewater, desalinated seawater, or other alternative water sources depending on regional conditions. Recent studies have highlighted that water availability may become a critical constraint for large-scale green

hydrogen deployment, particularly in water-stressed regions [2,7,16,42]. In contrast, the viability of blue hydrogen depends primarily on the availability of natural gas infrastructure and the technical and geological feasibility of carbon capture and storage systems [4,52].

The results of this research also demonstrate that the Colombian energy system should not be interpreted as homogeneous across the national territory. Colombia has historically relied on a power system dominated by hydropower generation, which has allowed the country to maintain a relatively low-carbon electricity matrix compared to many economies undergoing energy transitions based on fossil fuel phaseout [7,17], while hydropower infrastructure is also associated with environmental impacts related to large-scale dam construction and ecosystem alteration, these impacts have been managed through environmental licensing, regulatory oversight, and territorial planning processes over several decades.

As a result, the energy transition challenge in Colombia differs from that of many European energy systems, where decarbonization strategies primarily focus on replacing fossil-fuel-based electricity generation. In the Colombian context, the transition challenge is more closely associated with identifying sectors where further decarbonization can be achieved through complementary technologies such as hydrogen, particularly in applications where direct electrification presents operational limitations.

Several international studies have emphasized that hydrogen should be understood as a complementary energy carrier within energy systems that already present a significant share of renewable electricity, targeting sectors that remain difficult to electrify directly, including heavy transport, industrial processes, and maritime applications [2–4]. Consequently, hydrogen deployment strategies should not be interpreted as a universal technological replacement for existing energy systems but rather as part of a sector-specific transition strategy based on technical feasibility and resource availability.

This issue becomes particularly critical in the case of small-scale vessels operating in maritime and inland waterway systems. In these applications, the entire implementation chain—including hydrogen production, storage, refueling infrastructure, and onboard energy systems—is constrained by factors such as vessel size limitations, weight restrictions, safety requirements, operational autonomy, and fuel supply logistics.

The technical pathway developed in this research indicates that viable implementation for these systems requires prioritizing specific operational scenarios, identifying navigation corridors, defining hydrogen refueling nodes, evaluating water treatment requirements for hydrogen production, and selecting onboard technological architectures compatible with vessel operational profiles. In this context, current policy frameworks do not yet provide sufficiently detailed technical guidance to support energy pathway selection for specific sectoral applications.

To quantify these differences, Table 4 compares green and blue hydrogen, with grey hydrogen as reference, in terms of cost, emissions, efficiency and water use. Three observations are relevant for policy. First, blue hydrogen is currently cheaper in Colombia, but its emissions depend strongly on the capture rate and on upstream methane emissions, which no hydrogen-specific instrument regulates [14]. Second, green hydrogen has the lowest emissions only if the electricity is renewable and traceable: each 0.1 kg CO_2/kWh of grid carbon intensity adds about 5.5–5.9 kg CO_2 per kilogram of hydrogen at 55–58.5 kWh/kg. Because Colombian grid intensity rises in dry years with thermal backup, grid-connected electrolysis without guarantees of origin may not be low-carbon. Third, both pathways consume water: electrolysis requires roughly twice the stoichiometric water of reforming, while blue hydrogen adds cooling water for capture [16,41].

Table 4. Indicative comparison of hydrogen production pathways.

Indicator	Green (PEM Electrolysis)	Blue (SMR + CCS)	Grey (SMR, Reference)
Production cost, USD/kg H_2 (Colombia, 2025)	4–6 (project estimate); <2 projected for 2030	3–4	≥2
Emission intensity, kg CO_2e/kg H_2	≈0.5–3 (life cycle, dedicated renewables); +5.5–5.9 per 0.1 kg CO_2/kWh if grid-powered	≈1–5, depending on capture rate and upstream methane	≈9–12
Conversion efficiency (LHV)	55–70% (case design: 68% stack, 56.9% incl. compression)	≈60–70%	≈70–76%
Water use, L/kg H_2	9 (stoichiometric); 10–15 practical; target ≤15	4.5 (stoichiometric) + process and capture cooling	4.5 (stoichiometric) + process cooling
Key infrastructure prerequisite	Renewable electricity with guarantees of origin; water treatment	Gas supply; CO_2 transport and geological storage	Gas supply
Policy instrument still missing	Traceability of electricity; water-footprint criterion	CO_2 storage regulation; methane-leakage limits	—

Source: cost values from the project techno-economic assessment for Colombia (see Data Availability Statement), consistent with ranges reported by IEA [3,7,52]; emissions and efficiency from [12,14,42]; water from [16,41]; case design values from Section 4.7. Values are indicative and site-specific.

4.3. Regulatory Gaps and the Absence of a Clear Regulatory Pathway for the Safe Implementation of Hydrogen Technologies

The results of this research show that safety constitutes one of the most critical aspects in the implementation of hydrogen-based technologies and, at the same time, one of the areas where significant sectoral regulatory gaps still persist. Although hydrogen has been identified as a key energy vector for the decarbonization of hard-to-electrify sectors, its implementation requires clearly defined regulatory frameworks, technical standards and operational procedures that ensure adequate conditions of safety, sustainability and operational feasibility [2,12].

At the international level, a growing set of technical standards related to hydrogen technologies has been developed, mainly by standardization bodies such as the International Organization for Standardization (ISO) and the International Electrotechnical Commission (IEC). In particular, the ISO Technical Committee ISO/TC 197 develops international standards covering different stages of the hydrogen value chain, including production, storage, transport, fuel quality and refuelling protocols [10]. These standards constitute an important technical foundation for the development of the hydrogen industry; however, they are essentially voluntary in nature and must be adopted or incorporated into national or sectoral regulatory frameworks to become legally binding.

The analysis of the international regulatory landscape also shows that existing standards are distributed across the entire hydrogen lifecycle—production, storage, transport, transfer or bunkering, use as fuel, and decommissioning—and many of them remain under development or technological revision. As a result, although a considerable number of technical standards exist, they do not necessarily constitute an integrated regulatory pathway capable of guiding the implementation of hydrogen technologies in specific applications, particularly in emerging sectors such as maritime and inland waterway transport [12,22].

Another relevant aspect identified in this research is that hydrogen technologies do not constitute a homogeneous technological system from either a technical or regulatory perspective. Depending on the form of storage and use of hydrogen—such as compressed gaseous hydrogen (CGH_2), liquid hydrogen (LH_2), or hydrogen production systems based on electrolysis—the safety requirements, design criteria, materials, storage systems and

operational procedures vary significantly. For instance, compressed hydrogen requires high-pressure storage systems, thermal pressure relief devices, leak detection sensors and specific refuelling protocols, while liquid hydrogen requires cryogenic systems with completely different thermal and structural requirements [12,22].

International technical standards reflect this technological diversity. Within the ISO/TC 197 framework, specific standards have been developed for different components of hydrogen energy systems, such as ISO 14687, which defines hydrogen fuel quality requirements; ISO 19880, related to gaseous hydrogen refuelling stations; ISO 19881 and ISO 19882, addressing high-pressure hydrogen storage systems; and ISO 13985, associated with the design and testing of liquid hydrogen tanks [35–38,53]. However, while these standards cover individual technical components, they do not establish an integrated procedure capable of guiding the implementation of hydrogen systems in sector-specific applications such as maritime or inland waterway transport.

In the maritime sector, the implementation of hydrogen as a fuel requires the articulation of multiple regulatory frameworks, including hydrogen technical standards, industrial safety regulations, international maritime conventions and certification schemes from maritime classification societies such as DNV, ABS, Bureau Veritas and Lloyd's Register. This regulatory overlap implies that technological adoption largely depends on processes of regulatory integration that are still evolving at the international level [12,22]. In the Colombian context, the country has made progress in developing policy instruments aimed at promoting the deployment of low-emission hydrogen. Among the most relevant are Law 1715 of 2014, which promotes the use of non-conventional renewable energy sources; Law 2099 of 2021, which introduces the categories of green and blue hydrogen within the national energy framework; and the National Hydrogen Roadmap published in 2021, which establishes strategic guidelines for the development of the hydrogen value chain in the country [8].

However, the national policy diagnosis itself acknowledges that significant regulatory, institutional and technological gaps remain for the effective deployment of hydrogen technologies. Although technical standardization processes have been initiated through institutional spaces such as the Hydrogen Technical Committee 259 within ICONTEC, aimed at developing standards related to the design, construction, operation and maintenance of hydrogen systems, these efforts are still at an early stage and do not yet constitute a complete regulatory pathway for sector-specific applications.

In Colombia, the path from a voluntary standard to a binding requirement runs through the adoption of standards as Colombian Technical Standards (NTC), their incorporation into a technical regulation issued under Decree 1074/2015, and conformity assessment by bodies accredited by ONAC under Decree 1595/2015 [48,49]. None of these steps has yet been completed for hydrogen systems on vessels. To initiate this path, the authors submitted a formal standardization request to ICONTEC in May 2026.

This gap becomes particularly relevant in the context of maritime and inland waterway transport in Colombia. In many regions of the country, particularly those with limited land-based transport infrastructure, small-scale vessels constitute an essential means of transportation for passengers and goods. However, the transition toward hydrogen-based energy systems for this type of vessel requires the simultaneous integration of naval design considerations, operational safety requirements, energy infrastructure, natural resource availability and environmental sustainability. In addition, the implementation of hydrogen technologies must incorporate sustainability criteria within the planning and deployment process. Although the production of green hydrogen directly depends on water use in electrolysis processes, international literature and policy frameworks still present limitations in the systematic incorporation of indicators related to water footprint,

water resource sustainability and territorial environmental impacts. These aspects are closely linked to several Sustainable Development Goals, particularly SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) [11].

Consequently, the findings of this research indicate that the energy transition based on hydrogen does not depend solely on technological development or the availability of isolated technical standards. Instead, it requires the development of integrated regulatory pathways and methodological implementation frameworks capable of articulating existing standards with territorial conditions, energy resources and sector-specific operational requirements. Without such frameworks, technological adoption may evolve in a fragmented manner, hindering the standardization of processes, the assessment of impacts and the consolidation of scalable implementation models for the sustainable development of maritime and inland waterway transport.

The regulatory-coverage matrix (Figure 4) quantifies these findings. Of the 34 applicable cells, 4 (12%) were coded as existing, 7 (21%) as partial, 9 (26%) as interim or under development and 14 (41%) as missing. The contrast between levels is the main result: at the international level (ISO/IEC, IMO and classification societies) 20% of the applicable cells are missing, whereas at the Colombian level, 71% are missing and none are fully covered. Decommissioning and end-of-life is missing in all layers, and bunkering lacks a complete IMO instrument. In addition, because SOLAS defines passenger ships as those carrying more than 12 passengers [30], a 12-passenger vessel on a domestic route, or any craft operating on Colombian rivers, is not required to comply with the IGF Code or the IMO interim guidelines [31–33]. Jurisdiction over these craft is split between the Maritime Authority (DIMAR) [50] and the Ministry of Transport under the river navigation code [51]; to the authors' knowledge, neither framework currently contains provisions for hydrogen fuel systems. An operator who wishes to install a hydrogen system on a small passenger vessel in Colombia therefore has no defined set of design, approval, inspection or crew-certification requirements to follow.

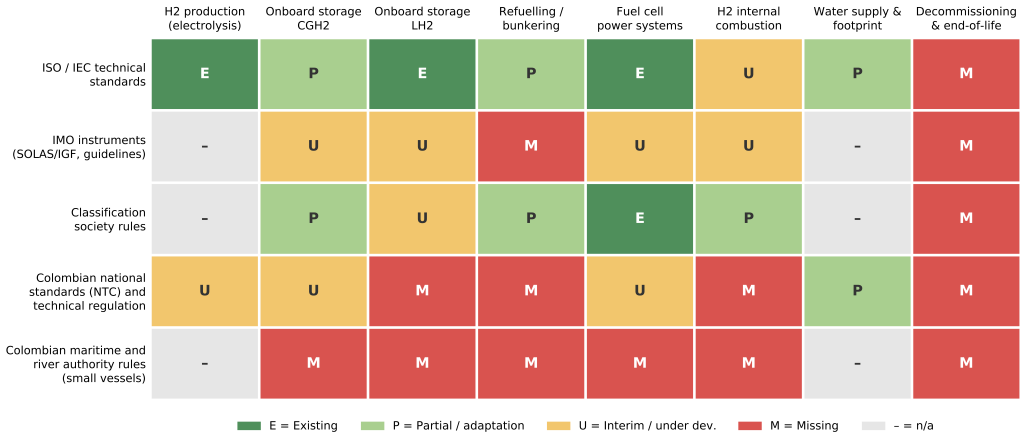


Figure 4. Regulatory-coverage matrix of the hydrogen value chain for small-scale vessels by regulatory layer (E = existing; P = partial, requires adaptation; U = interim or under development; M = missing; - = not applicable). Coding based on the corpus in Table 2 and the project's regulatory manual. Source: authors' elaboration.

4.4. Onboard Technical Feasibility: Storage, Fuel Cells and Refuelling

For small vessels, compressed hydrogen (CGH_2) at 350 bar in Type IV composite tanks is the most feasible storage option: the case design stores 16.8 kg H_2 in 0.42 m^3 with a tank system of 137 kg, a hydrogen mass fraction of 12.3%. Liquid hydrogen requires cryogenic tanks at −253 °C with boil-off management, which is not justified at this scale. PEMFC systems are commercially available in the 25–200 kW range and are mature in

road transport, but their integration in Colombian vessels remains at TRL 4–5 because there are no operational references, spare-parts supply or trained personnel. The safety design must include ventilation of tank and fuel cell spaces, hydrogen detection with alarm and shut-down, thermally activated pressure-relief devices, venting to a safe location and certified electrical equipment for hazardous areas (IEC 60079) [31,32,34]. For refuelling, no certified marine hydrogen dispenser or bunkering procedure exists in Colombia, and no IMO bunkering code for hydrogen is yet available (Figure 4). Feasibility is therefore limited less by the components than by the absence of integration experience, certification and refuelling infrastructure.

4.5. Industrial Constraints and Technological Dependency for Hydrogen Implementation

Another central result of this study is that the transition toward hydrogen-based technologies does not depend solely on the availability of energy resources or the existence of political commitment to promote their development. It also depends on the industrial capacity required to manufacture, adapt, certify, and integrate the technological components that constitute the hydrogen value chain. The draft National Hydrogen Policy currently under development in Colombia identifies significant limitations in regional industrial capabilities for the production and assembly of specialized equipment, as well as low levels of research, development and innovation (R&D&I), and the need to strengthen human capital and technical expertise to support the deployment of the hydrogen economy in the country [9].

These structural limitations are particularly evident in critical components of hydrogen energy systems, including electrolyzers, fuel cells, high-pressure hydrogen storage tanks, safety systems, sensors, specialized valves, and hydrogen dispensing equipment. At the global level, technological leadership and industrial manufacturing capacity remain concentrated in Europe, East Asia and North America [2,12,24] where hydrogen technologies have been supported through coordinated strategies integrating industrial policy, regulatory development, technological innovation, financing mechanisms, and market creation [2,12].

In the Colombian context, although progress has been made in developing scientific and technological capabilities related to the energy transition, these capacities remain at an early stage compared to more mature hydrogen innovation ecosystems. In recent years, the national government has promoted funding programs aimed at strengthening technological development in the field of clean energy and hydrogen through institutions such as the Ministry of Science, Technology and Innovation (Minciencias). These initiatives have supported research projects, pilot programs, and collaborative initiatives involving universities, research centers, and private sector actors, contributing to the development of applied research and the training of specialized human capital in hydrogen technologies and energy transition processes.

However, despite these efforts, the current level of technological maturity and industrial capacity in Colombia remains significantly lower than that observed in countries leading the development of hydrogen technologies. As a result, many initiatives remain concentrated in pilot-scale projects, demonstration systems, and early-stage integration experiences rather than in large-scale industrial manufacturing or deployment of hydrogen technologies [2,12,24].

Evidence collected during this research through international technology surveillance, participation in specialized conferences, and technical visits supports this conclusion. Participation in international events such as Connecting Hydrogen Europe 2025, Green Marine Med 2025, and the Monaco Energy Boat Challenge, as well as technical interactions with research and innovation groups such as PiCoHiMA and Green Foiling Spain, demonstrated that the most advanced hydrogen innovation ecosystems operate through strong integration between industrial manufacturers, research institutions, regulatory bodies,

financing mechanisms, and innovation networks. In contrast, in the Colombian context these elements remain partially fragmented, and technological development is still largely concentrated in pilot initiatives and early-stage demonstrations.

For the specific case of hydrogen applications in small-scale maritime and inland waterway vessels, this technological dependency has direct implications for the feasibility and scalability of implementation pathways. Reliance on imported components increases system costs, lengthens adoption timelines, and complicates operational maintenance and supply chain logistics. Moreover, the absence of local manufacturing capacity for key hydrogen technologies limits system standardization, component traceability, and the development of national technical capabilities required to operate, maintain, and scale hydrogen-based energy systems in the long term.

In this context, the findings of this research suggest that the implementation of hydrogen technologies in small-scale maritime transport should not be interpreted solely as an energy transition decision. Instead, it must also be understood as a broader challenge involving industrial policy, technology transfer, and the development of national technological capabilities. Studies on hydrogen value chains emphasize that successful deployment depends not only on energy availability but also on the development of domestic industrial ecosystems capable of supporting manufacturing, system integration, certification processes, and technological innovation [4,12].

Consequently, the effective deployment of hydrogen technologies in emerging markets requires coordinated efforts that go beyond pilot projects, including the strengthening of industrial capabilities, the development of local supply chains, and the promotion of collaborative innovation ecosystems capable of reducing technological dependency and enabling scalable hydrogen implementation pathways.

4.6. Water Resources as a Critical Criterion Not Yet Fully Incorporated into Hydrogen Planning

Another key finding of this research concerns the limited integration of water resource availability as a central criterion in hydrogen implementation planning, while green hydrogen is widely promoted as a strategic pathway for decarbonization, its production through electrolysis requires significant quantities of high-purity water—9 kg per kilogram of hydrogen stoichiometrically and typically 10–15 L/kg H_2 including purification losses [16,41]—making water availability a critical factor that must be considered in energy planning, particularly in regions where water resources are essential for ecosystems, food production and human consumption [2,12].

Despite this technical dependency, most hydrogen development strategies have primarily focused on the availability of renewable electricity—such as solar and wind resources—while paying comparatively less attention to the implications associated with water use. In many cases, hydrogen policy frameworks do not systematically incorporate assessments of regional water availability or the potential impacts of hydrogen production on water resources. This represents a significant gap in planning, particularly in countries where water resources play a fundamental role in environmental sustainability and territorial development. In the Colombian context, water resources constitute a strategic element of environmental governance and territorial planning. National environmental regulations recognize the priority of water use for human consumption, ecosystem preservation and food production. Therefore, any energy transition strategy involving large-scale water consumption must ensure that the implementation of hydrogen technologies does not compromise the availability of water resources necessary to sustain life and ecosystem functions. Based on the analysis conducted in this study, the results suggest that hydrogen deployment strategies should incorporate the systematic measurement and evaluation of the water footprint associated with hydrogen production. Water footprint assessment

would allow decision-makers to quantify water consumption in electrolysis processes, evaluate regional water availability, and determine whether hydrogen production is compatible with local environmental and social conditions.

Furthermore, hydrogen projects should prioritize the use of alternative water sources, such as treated wastewater, desalinated seawater in coastal regions, or other non-potable water sources, rather than relying on freshwater resources that are essential for human consumption and ecosystem sustainability. Incorporating such criteria into hydrogen planning would reduce potential conflicts over water use and improve the environmental sustainability of hydrogen deployment strategies.

This approach is consistent with the principles of sustainable development and with international commitments associated with the Sustainable Development Goals, particularly SDG 6 (Clean Water and Sanitation), SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action) [11]. Integrating water sustainability indicators into hydrogen planning frameworks would therefore strengthen the environmental legitimacy of hydrogen projects and contribute to more balanced and responsible energy transition strategies.

Finally, the deployment of hydrogen technologies should incorporate a broader framework of extended environmental and social responsibility, considering not only the water used during hydrogen production but also the environmental impacts associated with the entire lifecycle of the technologies involved. This includes the manufacturing, installation, operation and eventual decommissioning of hydrogen infrastructure and associated renewable energy systems. In this sense, hydrogen projects and industrial initiatives should be required to demonstrate compliance with sustainability criteria related to water management, lifecycle environmental impacts and responsible resource use as part of regulatory approval and project implementation processes.

4.7. Case Study: Water Footprint and Technology Selection for a 12-Passenger Vessel

The proposed vessel configuration considers a 25 kW PEMFC, a 40 kWh lithium-ion battery, a 30 kW permanent-magnet motor, and three Type IV hydrogen storage tanks operating at 350 bar, with a total usable hydrogen capacity of 16.8 kg (Table 5). These components represent conceptual engineering design specifications and were not physically installed or experimentally tested. At rated fuel cell power, the estimated hydrogen consumption is 1.65 kg H_2/h, equivalent to 13.2 kg H_2 for an 8 h mission. The proposed hydrogen supply system considers on-site production using a 50 kW PEM electrolyser, with an assumed specific energy consumption of 58.5 kWh/kg H_2, including compression and auxiliaries, and an estimated refuelling time of approximately 10 min at 350 bar. The electrolyser was not physically installed or experimentally evaluated.

Water footprint. Producing 13.2 kg H_2 per mission requires 119 L of water stoichiometrically and up to 198 L at the design target of 15 L/kg H_2. For 300 operating days per year, this corresponds to about 4.0 t H_2 and 36–59 m^3 of water. These volumes are small at basin level, but in riverine communities without reliable drinking water supply they are comparable to the daily consumption of several households, which supports the recommendation of Section 4.6 that hydrogen nodes use treated wastewater, rainwater or desalinated water and report their water footprint.

Comparison with battery–electric propulsion. A battery–electric version was dimensioned for the same conservative mission energy at the DC bus 25 kW × 8 h = 200 kWh. With 80% depth of discharge this requires a 250 kWh battery, which, using the specific mass of the project battery (5.5 kg/kWh), would weigh about 1375 kg compared with about 527 kg for the hydrogen hybrid energy system (fuel cell, tanks, hydrogen and buffer battery). Table 6 and Figure 5 summarize the comparison.

Table 5. Main design parameters of the case vessel and its hydrogen supply node.

Parameter	Value	Note
Passengers/crew	12/2	Below SOLAS passenger-ship threshold
Length × beam × draught	12.0 × 3.2 × 0.6 m	River, lake and coastal service
Service speed/autonomy/daily distance	18 km/h/8 h/80–100 km	Mission profile
Effective/installed power	12.5–14.2 kW/25 kW	15% margin
PEMFC (net) and mass	25 kW: 170 kg	Efficiency = 50% (LHV)
Battery (Li-ion NMC)	40 kWh: 220 kg: 400 V DC	80% depth of discharge
Hydrogen storage	3 × 140 L Type IV, 350 bar; 16.8 kg H_2: 120 kg empty	ISO 19881/19882 references
H_2 consumption	1.65 kg/h: 13.2 kg per 8 h mission	At rated power (conservative)
Electrolyser/specific electricity use	50 kW PEM/58.5 kWh/kg H_2	Incl. compression to 450 bar
Water footprint target	≤15 L/kg H_2	ISO 14046 indicator

Source: project design of the 12-passenger vessel (see Data Availability Statement).

Table 6. Indicative comparison of the PEMFC–battery hybrid and a battery–electric alternative for the case mission (200 kWh at the DC bus per 8 h mission).

Indicator	H_2 PEMFC–Battery Hybrid	Battery–Electric
Energy-system mass (excluding motor)	≤527 kg	≤1375 kg
Grid electricity per mission	≤772 kWh (13.2 kg × 58.5 kWh/kg)	≤217 kWh (charger 95%, battery 97%)
Electricity-to-shaft efficiency	≤23%	≤77%
Refuelling/recharging time	≤10 min	≤5 h at 50 kW; ≤1.7 h at 150 kW
Water per mission	119–198 L	≤0
CO_2 per mission with grid intensity g (kg CO_2/kWh)	$772g$	$217g$
Break-even g versus diesel (=150 kg CO_2/mission)	≈0.19	≈0.69
Infrastructure at the node	Electrolyser, water treatment, compressor, 350 bar dispenser	Grid connection ≥ 50–150 kW

Assumptions: drivetrain efficiencies from the project design (DC/DC 96%, inverter 96%, motor 92%, gearbox 95%; diesel baseline with 30% engine efficiency, 10 kWh/L and 2.68 kg CO_2/L (tank-to-wake). Values are indicative and intended to support technology selection criteria, not a full techno-economic assessment.

The comparison shows a clear trade-off. Battery–electric propulsion uses about 3.6 times less electricity, no water and simpler infrastructure, and it reduces emissions relative to diesel for any grid intensity below about 0.69 kg CO_2/kWh. The hydrogen hybrid weighs about 850 kg less and refuels in minutes, so it is better suited to long daily missions, multiple shifts or nodes without sufficient grid capacity, which are common in non-interconnected zones; however, it only reduces emissions relative to diesel if the electricity used for electrolysis is below about 0.19 kg CO_2/kWh. These results confirm the central argument of this study: hydrogen is not a universal solution but a complementary vector whose choice depends on the duty cycle, the territory and the electricity source, and this choice must be framed by explicit technical criteria that current policy does not yet provide.

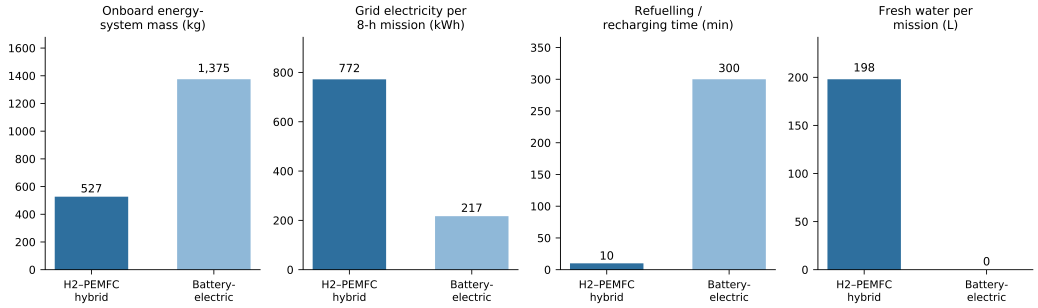


Figure 5. Indicative comparison of the H_2 PEMFC–battery hybrid and a battery–electric alternative for the 12-passenger case vessel (200 kWh per 8 h mission). Source: authors' calculations based on the project design.

4.8. Integrated Technical Pathway for the Implementation of Hydrogen Technologies in Small-Scale Vessels

Based on the results obtained in this research, an integrated technical pathway is proposed for the implementation of hydrogen-based technologies in small-scale maritime and inland waterway applications. This pathway aims to provide a structured framework capable of guiding technological adoption processes under conditions where energy, regulatory, environmental, industrial, and territorial factors interact simultaneously. The development of this pathway responds to the need to overcome fragmented approaches that have characterized many energy transition initiatives, in which hydrogen deployment is often analyzed primarily from the perspective of technological development or renewable energy availability. The findings of this study demonstrate that the effective implementation of hydrogen technologies requires a systemic planning approach capable of integrating multiple dimensions simultaneously, including territorial conditions, natural resource availability, existing infrastructure, industrial capabilities, regulatory frameworks, and sustainability considerations. The first component of the proposed pathway corresponds to the selection of the appropriate energy vector according to regional and sectoral conditions. The research shows that the choice between green hydrogen, blue hydrogen, or other energy alternatives cannot be addressed as a uniform or purely technological decision. Instead, it must be based on a multi-criteria technical assessment that considers factors such as regional energy resource availability, the structure of the national energy matrix, existing energy and logistics infrastructure, proximity to demand centers, production and transportation costs, and the operational requirements of the transport system where the technology will be implemented.

In the Colombian context, this analysis is particularly relevant due to the country's strong dependence on hydroelectric generation and the heterogeneous distribution of energy resources across regions. These conditions imply that the integration of hydrogen technologies must be evaluated under criteria of energy complementarity and systemic efficiency, avoiding simplified technological narratives that present hydrogen as a universal solution without considering the territorial and sector-specific characteristics of energy systems [4,5].

The second component of the pathway involves the assessment of water resources as a critical planning criterion, particularly for green hydrogen production through electrolysis. The findings of this research show that, despite the direct dependence of electrolysis on high-purity water, the sustainability and availability of water resources have not been systematically incorporated into hydrogen development strategies.

For this reason, the proposed pathway recommends that hydrogen project planning incorporate mandatory water footprint assessments, including regional water availability analysis and evaluation of potential water-use conflicts. Such assessments would ensure

that hydrogen deployment does not compromise water resources required for human consumption, food production, or ecosystem preservation.

In addition, the pathway recommends prioritizing alternative water sources, including treated wastewater, desalinated seawater in coastal regions, or non-potable water resources, in order to minimize pressure on freshwater resources essential for sustaining life and territorial development.

To complement the proposed technical pathway, this study introduces a conceptual framework that integrates key sustainability and governance criteria required for the responsible implementation of hydrogen technologies. Beyond technological feasibility, hydrogen deployment must incorporate systematic verification processes related to environmental, technical, and social sustainability throughout the entire lifecycle of the system.

As illustrated in Figure 6, the proposed pathway integrates multiple verification stages including water footprint assessment, carbon footprint evaluation, safety compliance, responsible resource management, and mitigation of environmental and social impacts. These elements are necessary to ensure that hydrogen implementation contributes effectively to decarbonization goals without generating unintended pressures on critical natural resources or local communities. The framework also incorporates operational considerations such as system monitoring, maintenance requirements, and timely decommissioning of technological infrastructure, promoting responsible lifecycle management of hydrogen technologies. This approach aligns with principles of extended social responsibility and circular economy, ensuring that the deployment of hydrogen systems considers not only their operational phase but also the long-term management of associated infrastructure and materials. Although some of these lifecycle aspects are further explored in complementary research, their inclusion in the proposed pathway highlights the importance of addressing hydrogen implementation as a systemic process that integrates technological innovation, resource governance, safety standards, and sustainability verification.

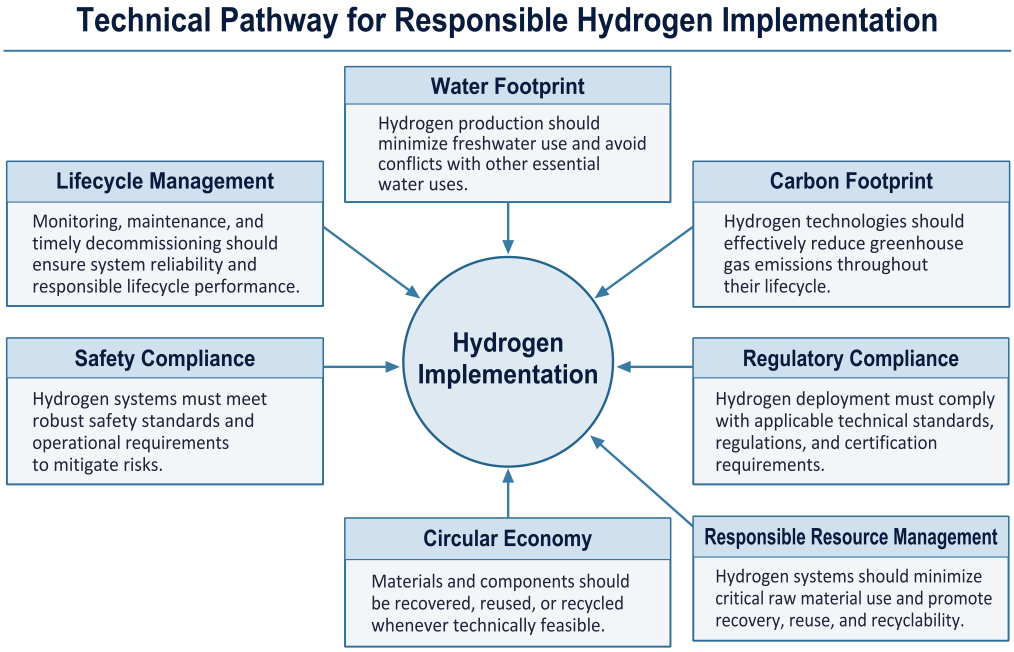


Figure 6. Technical pathway for hydrogen implementation incorporating sustainability verification criteria, including water footprint, carbon footprint, safety compliance, responsible resource management, lifecycle management, maintenance, and timely decommissioning under circular economy principles. Source: authors' elaboration with AI-assisted visualization tools (2026).

The third component of the technical pathway concerns the integration of safety requirements and regulatory frameworks. The regulatory analysis conducted in this research shows that although numerous international standards exist for hydrogen production, storage, transport, dispensing, and use, these standards are often dispersed and do not yet constitute a fully integrated regulatory pathway for specific applications such as small-scale maritime or inland navigation systems.

Consequently, the implementation of hydrogen technologies in small-scale vessels must incorporate safety requirements from the earliest design stages, including ventilation systems, hydrogen leak detection sensors, pressure relief valves, electrical protection systems, monitoring technologies, and operational testing protocols. These elements must be aligned with international standards and emerging technical regulations to ensure safe operation of hydrogen systems in maritime environments.

The fourth component addresses industrial and technological constraints in the national context. The study shows that the deployment of hydrogen technologies also depends on the availability of industrial capabilities to manufacture, integrate, certify, and maintain hydrogen system components. In the Colombian case, many of the critical technologies associated with the hydrogen value chain—such as electrolyzers, fuel cells, and high-pressure hydrogen storage systems—are currently produced primarily within international industrial ecosystems. As a result, the implementation of hydrogen technologies requires complementary strategies focused on technology transfer, development of local industrial capabilities, and strengthening of national innovation ecosystems, which would allow gradual integration of domestic capabilities into the hydrogen value chain and reduce long-term technological dependency.

Finally, the technical pathway incorporates a comprehensive sustainability and extended social responsibility approach, considering not only the operational phase of hydrogen technologies but also the environmental and social impacts associated with their entire lifecycle. This includes the installation of energy infrastructure, sustainable resource management, safe system operation, and the responsible decommissioning or repurposing of hydrogen-related technologies at the end of their operational life.

Taken together, these elements define a structured technical pathway for hydrogen technology implementation in small-scale maritime and inland waterway applications, integrating energy, environmental, regulatory, industrial, and social criteria into a coherent planning framework.

To synthesize the elements discussed above, Figure 7 presents the integrated technical pathway proposed in this research for the implementation of hydrogen technologies in small-scale maritime and inland waterway vessels. The framework illustrates how key decision stages—including energy selection, water resource assessment, safety and regulatory compliance, industrial capabilities, and sustainability verification—must be systematically evaluated to ensure a responsible and technically viable deployment of hydrogen systems. In particular, the pathway highlights the importance of incorporating sustainability verification criteria such as water footprint and carbon footprint assessments, operational safety standards, responsible resource management, lifecycle monitoring, maintenance planning, and timely decommissioning under circular economy principles.

Figures 6 and 7 have distinct roles. Figure 6 defines what must be verified for any hydrogen project throughout its life cycle (water and carbon footprint, safety and regulatory compliance, responsible resource management, circular economy and decommissioning). Figure 7 defines the order in which decisions must be taken for a small vessel, from energy selection to sustainability, so that each stage conditions the next. In the case of Section 4.7, for example, the energy-selection stage determines whether hydrogen or batteries should be used before water, safety and industrial requirements are evaluated.

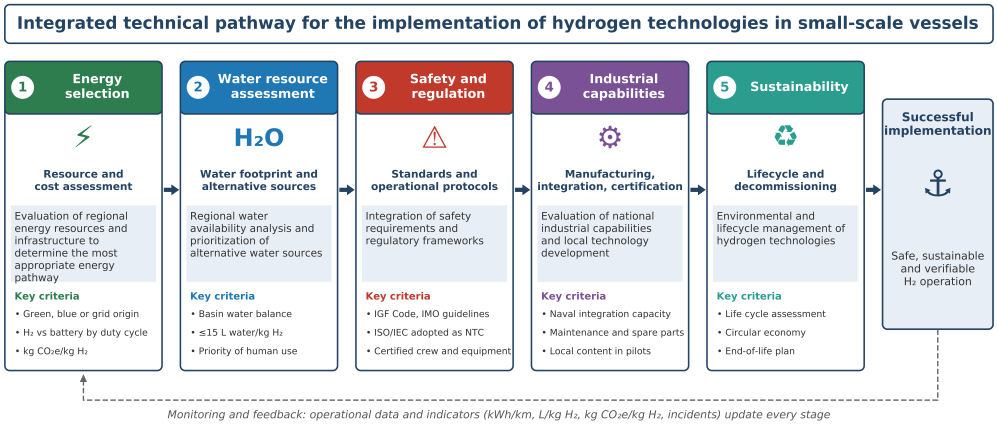


Figure 7. Integrated technical pathway for the implementation of hydrogen technologies in small-scale vessels. Source: authors' elaboration.

Beyond the specific case analyzed in this study, the proposed methodological framework presents broader applicability. The criteria developed for energy selection, water resource assessment, regulatory integration, technological safety, and territorial sustainability can be adapted or replicated in other industrial sectors evaluating hydrogen adoption, including heavy land transport, energy-intensive industries, and large-scale energy systems.

In this sense, the proposed pathway contributes not only to the development of hydrogen solutions for the maritime and inland waterway sector, but also provides a conceptual and methodological framework capable of supporting energy transition planning and governance in diverse productive contexts, facilitating informed decision-making in hydrogen technology deployment processes. In addition to the technical and environmental considerations discussed throughout this study, the implementation of hydrogen technologies within the energy transition also requires robust governance and public policy frameworks. The deployment of new energy systems is not only a technological challenge but also a regulatory, institutional, and strategic process that involves the coordination of multiple actors and policy instruments. In this context, the energy transition must be supported by coherent public policies, clear legal frameworks, regulatory standards, financial mechanisms, and effective institutional coordination that enable the safe and sustainable deployment of emerging energy technologies. Figure 8 summarizes the main governance dimensions that support the implementation of hydrogen technologies within the broader energy transition. These dimensions include national energy policy orientation, regulatory and legal frameworks, institutional coordination, financial mechanisms for clean energy investment, and monitoring and compliance systems that ensure the alignment of technological deployment with sustainability and climate objectives.

Although this study focuses on Colombia, the methodological framework proposed here may also be relevant for other emerging economies where energy transition strategies must be aligned with territorial resource availability, infrastructure limitations and industrial development constraints.

4.9. Institutional Responsibilities, Indicators and Prioritized Roadmap

To make the governance framework of Figure 8 operational, Table 7 assigns each gap identified in Section 4.1 to the institutions responsible according to their legal mandates and defines measurable indicators. The targets for vessel-level indicators are taken from the project's technical model and are proposed as initial references to be adjusted with pilot data. Table 8 and Figure 9 then classify the recommendations by priority, responsible institution, timeframe, resources and expected outcome.

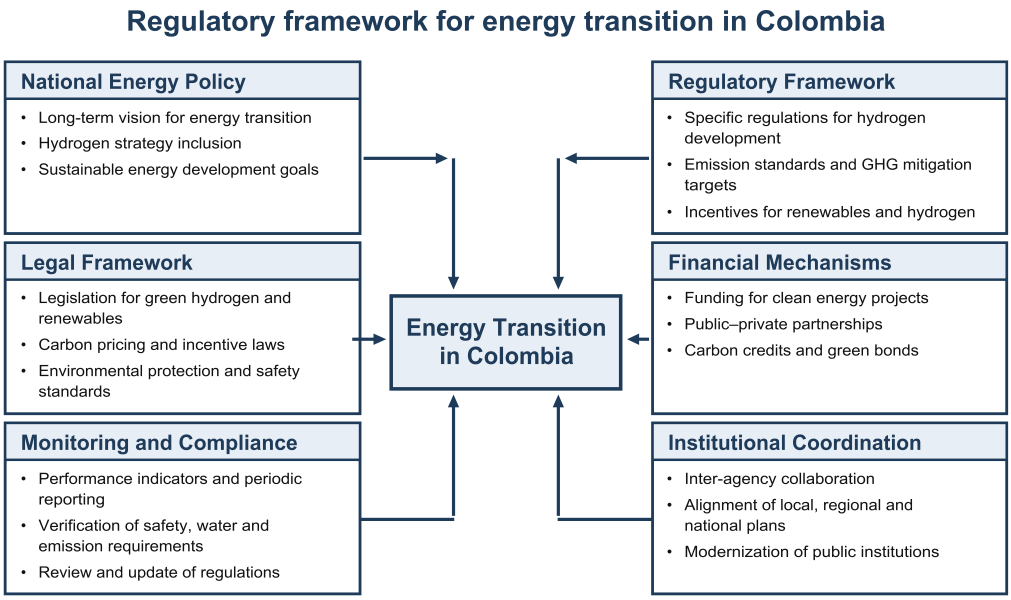


Figure 8. Governance and public policy framework for the implementation of energy transition strategies. Source: authors' elaboration.

Table 7. Institutional responsibilities and measurable indicators of the governance framework.

Gap	Lead (Support) Institutions	Responsibility	Indicator and Proposed Target
G1 Pathway and technology selection	MinEnergía, UPME (CREG, MinTransporte)	Criteria for green/blue H_2 and H_2 vs. battery by duty cycle; traceability of electricity	Criteria adopted (year 2); renewable electricity in H_2 $\geq$80%; carbon intensity of H_2 reported per project
G2 Vessel regulation outside SOLAS/IGF	DIMAR, MinTransporte (COTECMAR, class societies)	Interim technical guideline for H_2 systems on vessels $\leq$12 passengers and inland craft	Guideline issued (year 2–3); number of vessels approved under it
G3 Standards and conformity assessment	ICONTEC, MinCIT (ONAC, SIC)	Adopt priority ISO/IEC standards as NTC; technical regulation; accredited certification	$\geq$10 priority standards adopted as NTC by year 3; national missing cells in Figure 4 reduced from 71% to $<$30% by year 5
G4 Water security	MinAmbiente, IDEAM, ANLA (regional environmental authorities)	Basin water balance and water footprint (ISO 14046) as approval requirement	Water footprint $\leq$15 L/kg H_2; non-conventional water $\geq$50% in new projects
G5 Institutional coordination	MinEnergía, MinTransporte, DIMAR (DNP)	Inter-institutional working group on hydrogen in waterborne transport	Working group created (year 1); annual progress report
G6 Industry and human capital	MinCIT, Minciencias, SENA (COTECMAR, universities)	Integration and maintenance capabilities; certified competences	Certified technicians and crew (number); local content in pilots $\geq$30%
G7 Monitoring and decision gates	DNP, MinEnergía (operators)	Condition public support on verified indicators	CO_2e reduction vs. diesel $\geq$50%; kWh/km and kg H_2/km reported; safety incidents = 0

Institutional mandates as described in the technical comments submitted to the draft CONPES (Section 3.5); targets are proposals of this study.

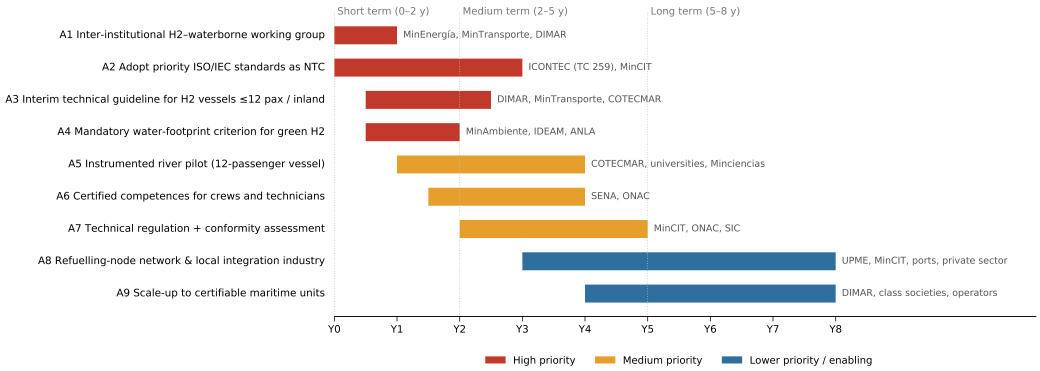


Figure 9. Prioritized implementation roadmap (Y = years from adoption of the framework). Source: authors' elaboration.

Table 8. Prioritized implementation roadmap.

Action	Priority	Responsible	Timeframe	Resources	Expected Outcome
A1 Inter-institutional working group on H_2 in waterborne transport	High	MinEnergía, MinTransporte, DIMAR	0–1 y	Staff time	Mandates agreed; work plan
A2 Adoption of priority ISO/IEC standards as NTC	High	ICONTEC (TC 259), MinCIT	0–3 y	Technical committee	≥10 NTC adopted
A3 Interim guideline for H_2 vessels ≤12 passengers and inland craft	High	DIMAR, MinTransporte, COTECMAR	0.5–2.5 y	Expert group: IGF Code and IMO guidelines as basis	Approval route for pilots
A4 Mandatory water-footprint criterion for green H_2	High	MinAmbiente, IDEAM, ANLA	0.5–2 y	Methodological guide	Criterion in licensing and incentives
A5 Instrumented river pilot (12-passenger vessel)	Medium	COTECMAR, universities, Minciencias	1–4 y	Pilot vessel and node; R&D funding	Operational data; TRL 6–7
A6 Certified competences for crews and technicians	Medium	SENA, ONAC	1.5–4 y	Training programmes	Certified personnel
A7 Technical regulation and conformity assessment	Medium	MinCIT, ONAC, SIC	2–5 y	Regulatory impact analysis	Binding requirements
A8 Refuelling-node network and local integration industry	Lower	UPME, MinCIT, ports, private sector	3–8 y	Public–private investment	Replicable nodes
A9 Scale-up to certifiable maritime units	Lower	DIMAR, class societies, operators	4–8 y	Private investment; classification	TRL 7–8; commercial units

Institutional mandates as described in the technical comments submitted to the draft CONPES (Section 3.5); targets are proposals of this study.

5. Discussion

5.1. Interpretation and Comparison with the Literature

The results support the view that the main obstacle to hydrogen deployment in emerging economies is not the absence of strategic ambition but the absence of the intermediate layer that turns ambition into technical criteria and enforceable, verifiable decisions, as anticipated by implementation research [28] and by recent analyses of hydrogen governance [3,29]. The contrast between international and national regulatory coverage (20% versus 71% missing cells) shows that the gap is not a lack of knowledge—international standards and guidelines exist—but a lack of national adoption, adaptation and institutional assignment. The SOLAS/IGF scope boundary adds a gap for small craft that is not discussed in the maritime hydrogen literature, which focuses on large ships [19,20,22]. The case results are consistent with studies indicating that battery–electric propulsion is preferable for short routes with access to low-carbon electricity, while hydrogen is more competitive for longer

autonomy [25,27], and they reinforce the argument that hydrogen should be applied where it adds value rather than as a universal replacement [5,24].

5.2. Hydrogen in a Renewable-Dominated Electricity System: Where Is It Needed?

The electricity data in Figure 2 could be read as suggesting that Colombia does not need hydrogen, since 70.64–87.29% of its electricity is already renewable [18]. The results of this study point to a different conclusion. Hydrogen is not needed in Colombia to decarbonize the power system, as it is in economies that depend on coal or natural gas, but to decarbonize specific end uses that the grid does not reach or that cannot be electrified directly: waterborne transport on rivers and coasts, long routes without charging infrastructure, the non-interconnected zones that still depend on diesel generation, and some industrial processes. Moreover, the dependence of the system on hydrology—thermal generation rose to 29.36% in the dry year 2024—means that the diversification of energy vectors and storage contributes to energy security, in line with the principle of resource complementarity discussed in Section 5.3. The case study also shows that, even within the waterborne sector, hydrogen competes with battery–electric propulsion, which is more efficient for short routes with grid access; hydrogen should therefore be prioritized for long missions, fast refuelling and nodes without sufficient grid capacity. Finally, because the carbon intensity of grid electricity varies with hydrology, the climate benefit of hydrogen produced from the grid depends on the year and on the source of electricity, which makes electricity traceability and water-footprint criteria essential. Colombia therefore needs hydrogen selectively and under explicit technical and territorial criteria, rather than by replicating transition pathways designed for fossil-based power systems.

5.3. Energy Security, Resource Complementarity and Territorial Implementation

The discussion presented in the forum "Seguridad energética y competitividad: el desafío de Colombia hacia 2030", organized by La República, reinforces a central reflection of this article: the energy transition should not be understood as an abrupt substitution of energy sources or as the adoption of a technological trend driven by short-term narratives, but rather as a progressive, planned and territorially coherent reconfiguration of the energy system. In this sense, it is limiting to frame the transition as simply "turning off" fossil sources and "turning on" renewable sources without considering the real conditions of infrastructure, reliability, costs, available resources, industrial capacities and national energy demand. Energy security must therefore be understood as an enabling condition for the energy transition, since without sufficient, stable and competitive energy, it is not possible to sustain productivity, attract investment, guarantee social welfare or advance in an orderly process of decarbonization [54].

From this perspective, the energy transition must begin with the recognition of the energy resources available in the country, rather than their premature exclusion or disregard. Colombia has a particular energy matrix in which hydropower resources, natural gas, coal, thermal backup generation, solar and wind potential, existing infrastructure and emerging opportunities associated with hydrogen coexist. Therefore, energy sources should not be understood as opposing alternatives, but as complementary components of a changing energy matrix. Renewable energy sources are essential for reducing emissions and diversifying the matrix, but their effective integration requires transmission infrastructure, storage systems, operational backup, clear regulation, energy efficiency and demand-side management. Likewise, natural gas, thermal generation, hydropower and coal under environmental mitigation criteria must be assessed according to their role in system reliability, avoiding decisions based only on simplified narratives or on the idea of

replacing one source with another before alternative solutions are fully available, financed, connected and operational.

This reflection does not imply ignoring climate commitments or the need to reduce carbon emissions. On the contrary, it makes it possible to understand that decarbonization must be progressive, verifiable and compatible with energy security, competitiveness and the territorial conditions of the country. Within this framework, thermal generation and natural gas may play a backup role during the transition process, while renewable energy sources, transmission infrastructure, storage systems, energy efficiency and emerging technologies are strengthened. The challenge is not to maintain a carbon-intensive matrix indefinitely, but to define orderly pathways for emission reduction without compromising system reliability or the competitiveness of productive sectors. Therefore, the energy transition should be oriented toward technological complementarity, allowing a gradual reduction in the carbon footprint without creating new vulnerabilities associated with energy shortages, cost increases, technological dependency or loss of industrial capacity.

The analysis also shows that the energy transition is a social, institutional and communicative process. Poor communication, the politicization of the mining-energy sector and narratives that demonize certain energy sources can affect social acceptance, weaken investor confidence and delay critical projects for the country. Consequently, energy security should become a national purpose, not only a business concern. This requires public education, inter-institutional coordination, regulatory stability, territorial management and informed participation from communities, users, industry and the state. It is not enough to formulate transition targets or announce new projects; institutional capacity is required to manage infrastructure, licensing, prior consultation, transmission, financing, operation and monitoring. Otherwise, technologies may remain as objectives in policy documents without becoming effective territorial solutions.

In the case of hydrogen, this vision is particularly relevant. Green hydrogen should not be presented as a universal solution or as an immediate replacement for all existing energy infrastructure, but as a complementary energy vector for specific applications where it provides technical, environmental and territorial value. Its implementation depends on the availability of renewable electricity, sustainable access to water, production and storage infrastructure, safety regulation, supply logistics, real demand and industrial capabilities. Therefore, hydrogen deployment must be analyzed within the national energy system and not as an isolated technology. A responsible energy transition for Colombia must integrate progressive decarbonization, energy security, responsible use of available resources, critical infrastructure, socio-environmental management and institutional strengthening. Only in this way will it be possible to advance toward a transition that reduces emissions, preserves competitiveness, strengthens energy resilience and responds to the real conditions of the country.

5.4. Policy Implications

The findings of this study provide several implications for energy policy and governance related to the deployment of hydrogen technologies within national energy transition strategies, while hydrogen has increasingly been recognized as a strategic energy vector for decarbonizing hard-to-abate sectors, the results indicate that the successful implementation of hydrogen technologies requires policy frameworks that go beyond technological promotion and address the broader conditions necessary for responsible deployment.

First, energy transition policies should incorporate methodological criteria for selecting energy technologies according to territorial conditions. Current policy instruments often promote hydrogen development in general terms without establishing clear procedures for determining where and under what conditions hydrogen technologies are technically and

environmentally viable. The results of this study suggest that the selection of hydrogen pathways should consider regional energy resource availability, existing infrastructure, operational conditions of specific sectors, and long-term sustainability considerations.

Second, public policy should integrate water resource management as a central criterion in hydrogen deployment planning. Although green hydrogen is widely promoted as a low-emission energy pathway, its production through electrolysis requires significant quantities of water. Therefore, hydrogen planning frameworks should incorporate systematic water footprint assessments and regional water availability analyses. In contexts such as Colombia, where some regions still face limitations in access to safe drinking water, hydrogen production strategies must ensure that energy development does not compromise water resources essential for human consumption, ecosystem preservation, and food production.

Third, the results highlight the need to strengthen regulatory frameworks and technical safety standards for hydrogen technologies. Although international technical standards exist for hydrogen production, storage, and use, their adoption and integration into national regulatory frameworks remain incomplete. In sectors such as maritime transport, these standards must also be aligned with international maritime regulations developed by the International Maritime Organization (IMO). In particular, the IMO has established regulatory frameworks aimed at reducing greenhouse gas emissions from shipping, including the Initial IMO Strategy on Reduction of GHG Emissions from Ships and the development of alternative fuels and propulsion systems for maritime decarbonization [6,19,23]. The integration of hydrogen technologies within maritime applications therefore requires coordination between energy policy, safety regulations, and international maritime conventions. Because vessels carrying up to 12 passengers and inland craft fall outside the mandatory scope of SOLAS and the IGF Code, national authorities (DIMAR and the Ministry of Transport) should establish a specific regulatory pathway for these vessels, using the IGF Code and the IMO interim guidelines as technical references [31–33].

Fourth, hydrogen deployment policies should be accompanied by industrial development strategies aimed at reducing technological dependency. In many emerging economies, hydrogen technologies rely heavily on imported components such as electrolyzers, fuel cells, and high-pressure storage systems. Strengthening domestic research, innovation ecosystems, and local manufacturing capabilities can contribute to building technological autonomy while supporting long-term energy transition objectives. Finally, energy transition policies should adopt a systemic and lifecycle-oriented approach to hydrogen deployment, incorporating sustainability verification criteria related to carbon footprint, water footprint, operational safety, resource responsibility, and infrastructure decommissioning. Such an approach would allow hydrogen projects to be evaluated not only in terms of emission reductions but also in relation to their broader environmental and social impacts.

In addition, the choice between hydrogen and battery–electric solutions should be explicitly included in technology-selection criteria, and public support and incentives should be conditioned on verified performance and on the source of electricity used for electrolysis. This is particularly important because, as the case study shows, hydrogen only reduces emissions relative to diesel if the electricity used is below a certain carbon intensity, which in Colombia varies with hydrology and with the share of thermal backup.

A central principle should guide all these instruments: the energy transition must not transgress other resources that are essential for the populations, especially water. In Colombia, the Constitutional Court has recognized access to drinking water as a fundamental right with priority over other uses [55], and it has recognized the Atrato River as a subject of rights, ordering the protection of the communities that depend on it [56]. This is directly relevant to hydrogen. La Guajira, the region with the greatest wind and solar potential and

where renewable energy and hydrogen projects are being planned, is also one of the regions with the most severe limitations in access to drinking water, a situation that led the Court to order measures to guarantee the rights of Wayuu children to water, food and health [57]. Hydrogen policies and regulations should therefore (i) establish explicitly that water for human consumption, food production and ecosystems has priority over water for hydrogen production; (ii) require the basin water balance and the water footprint before granting water concessions or environmental licences [43,46,47]; (iii) require non-conventional water sources, such as treated wastewater or desalinated seawater, in water-stressed basins; (iv) guarantee the prior consultation and participation of local and ethnic communities; and (v) ensure that projects leave tangible benefits in the territory, for example by sharing water-treatment infrastructure with the communities. In this way, hydrogen can contribute to decarbonization without creating new socio-environmental conflicts or deepening existing inequalities.

Taken together, these policy implications highlight that the energy transition cannot be addressed solely as a process of technological substitution. Instead, it requires coordinated governance frameworks capable of integrating energy planning, environmental sustainability, industrial development, and territorial considerations into the implementation of emerging energy technologies such as hydrogen.

6. Conclusions

The importance of this study lies in showing, with a coded regulatory matrix and a concrete vessel case, that the main barrier to responsible hydrogen deployment in emerging economies is the absence of the national implementation layer that connects strategic policy with territorial and sectoral reality.

The transition toward low-emission energy systems represents one of the most significant transformation processes of recent decades and offers an important opportunity to move toward more sustainable development models. However, the results of this research show that one of the main risks associated with the energy transition lies in the lack of methodological planning and clearly defined technical frameworks for the implementation of emerging energy technologies. In many cases, energy transition policies have focused primarily on promoting new technologies or energy vectors without simultaneously developing technical methodologies capable of guiding their implementation according to the territorial, industrial, and environmental conditions of each country or productive sector. This situation can lead to fragmented technological adoption processes in which new technologies are introduced without a comprehensive evaluation of their systemic implications.

One of the most relevant findings of this study is that the energy transition should not be interpreted solely as a process of technological substitution, but rather as a progressive reconfiguration of existing energy systems. In this context, some technologies currently in operation may require decarbonization, modernization, or energy reconversion processes rather than immediate replacement by new technological solutions. The premature elimination of infrastructures or technologies that can still be adapted to decarbonization pathways may generate significant economic, social, and technological impacts, while also slowing the development of national industrial capabilities.

The research also highlights that the accelerated implementation of emerging technologies without clear regulatory frameworks, defined technical standards, or sufficient industrial capabilities may generate unforeseen operational, environmental, and social risks. In the case of hydrogen-based technologies, aspects such as system safety, water resource availability, infrastructure requirements, and industrial capacity to manufacture or maintain equipment constitute critical variables that must be considered from the earliest planning stages.

Another relevant aspect identified in this study concerns the way global energy transition strategies are translated into national contexts. Although international policies and decarbonization strategies play a fundamental role in guiding global climate action, their direct adoption without proper adaptation to local energy systems, territorial conditions, and industrial structures may generate tensions and unintended consequences. In some cases, the adoption of global transition narratives without a contextualized technical assessment may result in policy decisions that weaken domestic technological development, increase technological dependency, or generate socio-economic impacts that differ from the expected sustainability outcomes.

A critical finding of this research relates to the need to incorporate water resources as a central criterion in hydrogen deployment planning, while green hydrogen is widely promoted as a key decarbonization pathway, its production through electrolysis requires significant amounts of high-purity water. In the Colombian context, this consideration is particularly important because, despite the country's overall water availability, there are regions where access to safe drinking water remains limited. Therefore, hydrogen deployment strategies should incorporate regional water availability assessments and water footprint evaluations, ensuring that water used for energy production does not compromise access to water for human consumption, food production, or ecosystem preservation. Furthermore, hydrogen projects should prioritize the use of alternative water sources, such as treated wastewater or desalinated seawater, reducing pressure on freshwater resources essential for sustaining life.

In this context, the findings suggest that water resource management in hydrogen deployment should not be addressed solely through national regulatory frameworks. Given the global expansion of hydrogen strategies and the diversity of hydrological conditions across territories, regulatory approaches should also evolve toward globally coordinated but regionally adaptable governance frameworks, ensuring that hydrogen implementation considers local water availability and environmental sustainability conditions in each region.

Within this broader context, the results of this study highlight the importance of developing methodological frameworks for energy transition planning that can guide the implementation of emerging technologies under clearly defined technical, territorial, environmental, and industrial criteria. The technical pathway proposed in this research contributes to this objective by providing a structured framework for evaluating the feasibility of hydrogen technologies in small-scale maritime and inland waterway applications.

Beyond the specific case analyzed in this study, the methodological approach developed here provides a conceptual basis that can support energy transition planning processes in other industrial sectors. By integrating criteria related to energy selection, natural resource availability, technological safety, industrial capabilities, and territorial sustainability, the proposed framework contributes to more balanced energy transition strategies capable of reducing emissions without generating unintended economic, environmental, or social impacts. Energy transition policies should therefore consider not only emission reduction targets but also principles of equitable and sustainable resource governance.

In this sense, the study suggests that the energy transition should not be approached solely as a process of accelerated technological adoption, but rather as a strategic transformation of energy systems, supported by rigorous technical planning, institutional governance, and coordination between public policy, industrial development, and territorial sustainability.

The specific findings of this research are as follows:

1. Colombia's hydrogen policy defines categories, incentives and targets, but seven implementation gaps remain (G1–G7), of which three are specific to the waterborne sector: the lack of a regulatory pathway for non-SOLAS vessels, of binding water-security criteria and of defined institutional responsibilities.

2. Regulatory coverage of the hydrogen value chain for small vessels is far lower at the national level (71% of applicable cells missing) than at the international level (20%); vessels carrying up to 12 passengers and inland craft currently have no regulatory pathway in Colombia.
3. Green and blue hydrogen differ in cost, emissions, efficiency and water use in ways that depend on the territory: grid-connected electrolysis adds about 5.5–5.9 kg CO_2/kg H_2 for each 0.1 kg CO_2/kWh of grid intensity, so traceability of electricity is essential.
4. For the 12-passenger case vessel, hydrogen requires 119–198 L of water per mission and about 3.6 times more electricity than a battery–electric alternative, but saves about 850 kg and refuels in minutes; technology selection must therefore be based on duty cycle, territory and electricity source.
5. Colombia does not need hydrogen to decarbonize its electricity system, which is already 70.64–87.29% renewable, but to decarbonize specific end uses that direct electrification does not reach, such as long-distance waterborne transport, non-interconnected zones and some industrial processes. Hydrogen should therefore be deployed selectively and under explicit technical and territorial criteria, rather than by replicating transition pathways designed for fossil-based power systems.

Above all, the results indicate that hydrogen policies and regulations must ensure that the energy transition does not transgress other resources that are essential for the populations. Water for human consumption, food production and ecosystems must have priority over water for hydrogen production, particularly in regions such as La Guajira, where the greatest renewable potential coincides with severe limitations in access to drinking water. A transition that reduces emissions while compromising water or the rights of local communities would not be sustainable.

Practical recommendations are as follows: (i) create an inter-institutional working group (MinEnergía, MinTransporte, DIMAR) within one year; (ii) issue an interim technical guideline for hydrogen in small and inland vessels; (iii) adopt priority ISO/IEC standards as NTC through ICONTEC; (iv) make water footprint and electricity traceability conditions for incentives; and (v) develop an instrumented river pilot to generate operational data.

Some limitations of this study should be acknowledged. The analysis focuses primarily on policy frameworks and technological planning criteria rather than on detailed techno-economic modeling of hydrogen systems. Future research could complement this approach through quantitative energy system modeling and lifecycle cost assessments for hydrogen deployment in maritime transport systems.

In addition, the regulatory-coverage coding involves expert judgement despite cross-checking; stakeholder validation was informal and did not include a structured survey; the case comparison uses design values and literature efficiencies rather than operational data, and cost figures are indicative; and the regulatory landscape is evolving rapidly, so the matrix reflects the situation in 2026. Future research should include a structured stakeholder consultation (e.g., Delphi) and validation of the framework with data from the river pilot.

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Conflicts of Interest: The authors declare no conflicts of interest.

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