Federal Centre for Technological Education Celso Suckow da Fonseca – CEFET/RJ
Postgraduate Programme in Production and Systems Engineering – PPPRO

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TECHNOLOGY ROADMAP OF LOW-CARBON HYDROGEN: TRENDS FOR RISK MANAGEMENT STRATEGIES

Rio de Janeiro
Novembro de 2025

CEFET/RJ
DIRETORIA DE PESQUISA E PÓS-GRADUAÇÃO

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Dissertação apresentada ao Programa de Pós-Graduação em Engenharia de Produção e Sistemas – PPPRO, do Centro Federal de Educação Tecnológica Celso Suckow da Fonseca, CEFET/RJ, como parte dos requisitos necessários à obtenção do título em Mestre em Engenharia de Produção e Sistemas.

Orientador: Ronney Arismel Mancebo Boloy

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Rio de Janeiro
Novembro de 2025

Ficha catalográfica elaborada pela Biblioteca Central do CEFET/RJ

M828 Moraes, Danielle Rodrigues de
Technology roadmap of low-carbon hydrogen: trends for risk management strategies / Danielle Rodrigues de Moraes. — 2025.
88f. : il. color. , enc.

Dissertação (Mestrado) Centro Federal de Educação Tecnológica Celso Suckow da Fonseca, 2025.
Bibliografia : f. 78-88
Orientador: Ronney Arismel Mancebo Boloy

1. Hidrogênio. 2. Cadeia de logística integrada - Avaliação de riscos. 3. Transição energética. I. Boloy, Ronney Arismel Mancebo. (Orient.). II. Título.

CDD 546.2

Elaborada pela bibliotecária Tania Mello – CRB/7 nº 5507/04

DEDICATÓRIA

À minha família e amigos, pelo constante apoio ao longo desta jornada. Agradeço, de forma especial, aos meus fiéis companheiros de quatro patas, Duke e Floki, pela cumplicidade e afeto silencioso nos momentos mais desafiadores.

RESUMO

Roadmap Tecnológico do Hidrogênio de Baixo Carbono: Tendências para Estratégias de Gestão de Risco

O presente estudo emprega a abordagem de roadmap tecnológico para caracterizar a cadeia de suprimentos do hidrogênio de baixo carbono e identificar tendências em gestão de riscos na cadeia de suprimentos (SCRM, do inglês *Supply Chain Risk Management*), principais atores e fatores essenciais para a expansão da economia do hidrogênio. Os dados analisados incluíram 22 patentes concedidas, 77 patentes pendentes e 50 artigos científicos correlacionados a diferentes períodos, delineando tendências e lacunas ao longo do tempo. A gestão de riscos operacionais e a eletrólise alcalina demonstraram alto interesse em propriedade intelectual, sendo identificadas como tendências de curto prazo. O médio prazo apresentou aspectos mais diversos de SCRM (como garantia de qualidade, prevenção de falhas e equipamentos de monitoramento), além de maior adesão à economia circular em comparação com os horizontes de curto e longo prazo. Os resultados para longo prazo revelaram colaborações internacionais voltadas à ampliação de projetos de hidrogênio, priorizando cadeias de suprimentos custo-efetivas e com alta eficiência exergética em múltiplos setores. As principais estratégias de gestão identificadas incluem: enfrentamento de falhas humanas, aprimoramento do monitoramento em tempo real, produção descentralizada com base em fatores regionais (resolução espacial), ativos flexíveis e integração de aplicações de aproveitamento energético de resíduos (*waste-to-energy*). Novas políticas públicas devem priorizar a eficiência da eletrólise, armazenamento avançado, controle de segurança e integração com biocombustíveis, além de soluções em larga escala para mitigar os efeitos da intermitência das fontes renováveis. Pesquisas futuras devem focar na otimização da prevenção de falhas, manutenção preditiva e sistemas de resposta a emergências, incorporando ventilação, design de barreiras e capacitação operacional adequada. O potencial de biocombustíveis alternativos (como etanol, glicerina e biogás) como insumos escaláveis, bem como a reciclabilidade dos equipamentos, permanece pouco explorado. Espera-se que este estudo ofereça subsídios para a gestão de P&D e o planejamento de estratégias de SCRM voltadas à transição energética.

Palavras-chave: Roadmap tecnológico; Hidrogênio de baixo carbono; Gestão de riscos na cadeia de suprimentos; Transição energética.

ABSTRACT

Technology Roadmap of Low-Carbon Hydrogen: Trends for Risk Management Strategies

This study employs a technology roadmap approach to characterise the low-carbon hydrogen supply chain and identify supply chain risk management (SCRM) trends, key players and essential factors to broader the hydrogen economy. Data included 22 granted patents, 77 pending patents and 50 articles correlated to different timeframes, outlining trends and gaps over time. Operational risk management and alkaline electrolysis had great intellectual property interest and are short-term trends. Medium-term included more diverse SCRM aspects (e.g., quality assurance, failure prevention and monitoring equipment) and circular economy adherence than short- and long-term results. Long-term roadmap revealed international collaborations to scale hydrogen projects, prioritising cost-effective and exergetic-efficient supply chains across multiple sectors. Key management strategies include addressing human error, improving real-time monitoring, decentralised production based on regional factors (spatial resolution), flexible assets, and integrating waste-to-energy applications. Policies should target electrolysis efficiency, advanced storage, safety control, and biofuels integration, alongside large-scale solutions to mitigate renewables intermittency effect. Future research should focus on optimising failure prevention, predictive maintenance and emergency response systems, integrating ventilation and obstacle design, and proper operational training. The potential of alternative biofuels (e.g., ethanol, glycerine, biogas) as scalable inputs and equipment recyclability remain underexplored. It is expected to provide insights to strengthen R&D management and SCRM strategies planning on energy transition.

Keywords: Technology roadmap; Low-carbon hydrogen; Supply chain risk management; Energy transition.

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LIST OF ABBREVIATIONS AND ACRONYMS

ANEEL	Brazilian Electricity Regulatory Agency
ANP	Brazilian National Agency of Petroleum, Natural Gas and Biofuels
CCUS	Carbon Capture, Utilisation and Storage
CO_2	Carbon Dioxide
CH_4	Methane
DBT-PDBT	Dibenzyl toluene-perhydro-dibenzyltoluene
EPE	Brazilian Energy Research Office
FCEV	Fuel Cell Electric Vehicle
GHG	Greenhouse Gas
GDP	Gross Domestic Product
GWP	Global Warming Potential
H_2	Hydrogen
IBGE	Brazilian Institute of Geography and Statistics
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IPC	International Patent Classification
IPVA	Motor Vehicle Property Tax
IRENA	International Renewable Energy Agency
ISO	International Organization for Standardization
LCA	Life Cycle Analysis
LCOD	Levelised Cost of Driving
LOHC	Liquid Organic Hydrogen Carries
MILP	Mixed Integer Linear Programming
NDC	Nationally Determined Contribution
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
PEM	Proton Exchange Membrane
R&D	Research and Development
SCRM	Supply Chain Risk Management
SMR	Steam Methane Reforming
SOEC	Solid Oxide Electrolyser Cell
SOFC	Solid Oxide Fuel Cell

STPA	System Theoretic Process Analysis
TOL-MCH	Toluene-methylcy-clohexane
TRL	Technology Readiness Level
TRM	Technology Roadmapping
UNFCCC	United Nations Framework Convention on Climate Change
WIPO	World Intellectual Property Organization

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Introduction

The hydrogen economy holds potential for global decarbonisation, energy security and economic growth. Low-carbon hydrogen can be produced via pathways that integrate zero-emission energy (e.g., biomass, wind, solar and hydraulic) or combined with carbon capture, utilisation and storage (CCUS). As a versatile fossil fuel alternative, it is essential for sectors with hard-to-abate emissions, like heavy industry, transport and power generation.

CCUS reduces carbon dioxide (CO_2) emissions from industrial and energy assets. Capture process separates CO_2 from flue gas or industrial streams, typically via post-combustion, for geological storage or utilisation in synthetic fuels, chemicals and construction materials (Kouri *et al.*, 2017). Industrial methods include absorption, adsorption, membrane separation, and cryogenics at emission points, while natural/semi-natural methods remove atmospheric CO_2 through direct air capture, reforestation, biochar, ocean fertilisation, and enhanced weathering (Kumar *et al.*, 2024).

Low-carbon hydrogen is a promising alternative fuel with notable progress in the production chain, yet key challenges must be addressed for developed technologies to achieve widespread CO_2 emissions abatement.

Sector-specific decarbonisation strategies are needed as CO_2 sources vary across heavy industries. For instance, calcination emissions in cement sector favour oxy-fuel combustion and calcium looping, whereas low-carbon hydrogen is recommended to replace conventional methods in specific chemical synthesis processes (Kumar *et al.*, 2024). Though post-combustion is the most viable method and traditional sorbents are currently unfeasible at scale due to raw material cost, low-cost and renewable biomass, petroleum and coal waste material-based sorbents demonstrated outstanding performance (Ochedi *et al.*, 2025).

Regions lacking suitable domestic formation for carbon storage rely on resilient CO_2 utilisation for long-term decarbonisation, while CCUS may delay diversification by preserving fossil employment and hindering environomic shifts (Carlson; Trencher, 2024; Kouri *et al.*, 2017).

Carbon intensity remains a key market uncertainty. The European Union sets a limit of 3.4 kg CO_2 eq. per kg of hydrogen (H_2) with a well-to-wheel boundary, the United States applies 4.0 kg CO_2 eq./kg H_2 from well to production gate, while Brazil allows up to 7.0 kg CO_2 eq./kg H_2 based on Life Cycle Analysis (LCA), with stricter limits from 2031 (Oxford Institute for Energy Studies, 2024; ANP, 2024).

In renewable-rich countries like Brazil, hydrogen integration could address water scarcity, energy shortages and renewable intermittence, particularly in hydropower-dependent regions (Tolmasquim, 2016). At scarcity periods, non-electrolysis hydrogen routes (i.e., biolysis and thermal processes with CCUS) may optimise water consumption, as they rely mainly on cooling and steam generation, which require lower water quality than electrolysis.

Desalination can ensure water supply at minimal energy cost for electrolysis, indicating water is not a limiting factor. Reverse osmosis adds only 0.26–0.37 EJ/year for 2.3 Gt global hydrogen demand (0.06–0.13% of electrolysis energy), with costs rising to 0.01–0.02 USD/kg H_2 (Beswick *et al.*, 2021). Desalinated water remains negligible in global energy and cost terms, supporting large-scale low-carbon solutions.

Between 2022 and 2023, solar and wind energy grew 54.8% and 20.7%, respectively, yet coal and gas plants remain essential during low hydropower availability (EPE, 2024). A sustainable complementary source is needed to offset these fluctuations, requiring controllable and flexible sources for stability (Tolmasquim, 2016). Hydrogen, with high energy density (120 MJ/kg), is a substantial energy storage solution (Brigljević *et al.*, 2020).

With low volumetric energy density at ambient conditions, high flammability and permeability, hydrogen storage and transport pose safety and logistical concerns as open problem of interest (Godinho *et al.*, 2023; Ocko; Hamburg, 2022). Conventional technologies for addressing these challenges often fail to comply with environmental standards, while non-traditional solutions are costly or under development/testing.

Proton exchange membrane (PEM) electrolysis favours high-pressure operation, cutting compression energy and cost, but poses dynamic reliability issues, H_2 leakage, and unanticipated operational faults (Zhu *et al.*, 2023). Zhu *et al.* (2023) applied System Theoretic Process Analysis (STPA) method to outline safety guidelines addressing component failure, design, human, and organisational factors in PEM systems. As a non-

traditional risk assessment method, STPA is applied in complex human-machine systems and can be extended by integrating fuzzy bayesian networks. Due to short application history and the absence of operational data, PEM systems rely on fussy set theory and experts' judgement (Zhu *et al.*, 2025).

The work is structured as follows: Section 1 reviews the current stage of low-carbon hydrogen supply chain; Section 2 describes the synergistic role of electromobility and the hydrogen in the energy transition; Section 3 presents a statistical analysis of the electrified vehicle fleet in Brazil; and Section 4 outlines the TRM methodology and discusses key findings with insights for Brazilian low-carbon hydrogen policy.

1 Low-carbon hydrogen supply chain outlook

This research considers "low-carbon hydrogen" as both renewable and low-emission hydrogen, as defined in the 2022 G7 Leaders' Statement (G7, 2022). It includes all hydrogen production methods with low life-cycle emissions, including hydrogen from renewables, which, despite being emission-free during electrolysis, entails environmental impacts from transport and mining. **Table 1** summarises the main production processes and their Technology Readiness Level (TRL), a 1–10 rating scale, with level 1 representing basic technological research and level 10 a bankable asset class (Dawood *et al.*, 2020).

Carbon intensity of low-carbon hydrogen varies thresholds across jurisdictions, with 3.4 kg CO_2 eq./kg H_2 in the European Union, 4.0 kg CO_2 eq./kg H_2 in the United States, and 7.0 kg CO_2 eq./kg H_2 in Brazil for instance (Oxford Institute for Energy Studies, 2024; ANP, 2024). CertifHy™ project aim is to establish a harmonised European guarantees of origin of low-carbon hydrogen, with an overall carbon intensity no greater than 4.36 kg CO_2 eq./kg H_2 from well-to-gate, which is at least 60% below a defined fossil benchmark process (H2Uppp, 2024).

Electrolysis, biolysis, thermal and thermolysis are key low-carbon hydrogen production categories. Electrolysis is clean if powered by renewables and has been commercial since 1890 via alkaline electrolyser and splits water into H_2 and oxygen with direct current and a membrane, while thermolysis decomposes water at high temperatures (Nikolaidis; Poullikkas, 2017; Castro *et al.*, 2023). Thermal processes are mostly mature and support biomass and biofuel integration with life-cycle benefits, whereas biolysis still experimental and uses algae/bacteria in photo- and dark fermentation (Nikolaidis; Poullikkas, 2017; Castro *et al.*, 2023).

Electrolysis efficiency depends on cell type, temperature, and voltage (Nikolaidis; Poullikkas, 2017). Alkaline and PEM cells offer comparable efficiencies, though PEM is costlier (Dawood *et al.*, 2020). Solid Oxide Electrolyser Cell (SOEC) faces durability challenges due to high temperature for adequate ionic conductivity, leading to fast degradation, sealing difficulties, and poor thermal cycling performance (Wu *et al.*, 2018).

Direct hydrogen transport involves containers, pipelines, gas cylinders, vehicle tanks, and pressure or cryogenic vessels, requiring resistant materials to prevent diffusion

and embrittlement (Durbin; Malardier-Jugroot, 2013; IEA, 2022a). Pipeline enables continuous flow over long distances with lower energy loss (IEA, 2022a).

Table 1 – Summary of main low-carbon hydrogen production processes

Category	Technology	Efficiency	TRL (1-10)	Advantages	Disadvantages
Electrolysis	Alkaline	62-82	9-10	Long lifetime, no expensive/rare catalysts, no direct emissions.	Low current density, system complexity, corrosion.
	Proton Exchange Membrane	67-84	7-9	High current density, simple system, no direct emissions.	Expensive/rare platinum-based catalysts, low durability.
	Solid Oxide	75-90	3-5	High electrical efficiency, low electricity demand, no direct emission.	High-temperature (500–850°C) resistant materials requirement.
Biolysis	Photo-fermentation	1.6-5	1-3	Green algae convert organic matter with low environmental impacts.	Low production capacity.
	Dark fermentation	60-80	3-5	Anaerobic bacteria convert carbohydrates with low environmental impacts.	Low production capacity.
Thermolysis	Water thermolysis	20-55	1-3	No direct emission, compatible with renewable energy.	High-temperature (900-2000ºC) resistant materials requirement, chemical reactions to reduce temperature.
	Pyrolysis	35-50	8-10	Simple system, compatible with renewable energy.	High electricity demand, high-temperature (500-2000ºC) resistant materials requirement, CCUS costs.
	Biomass gasification	35-50	10	Waste-to-energy solution.	CCUS costs, input compositions variability affects yield.
	Biofuel steam reforming	60-85	10	Cost-efficient, easily scalable.	CCUS costs.

Source: Adapted from Dawood *et al.* (2020); Castro *et al.* (2023); Dermuhl; Riedel, (2023); El-Shafie *et al.* (2019).

Indirect transport utilises hydrogen carriers, including cycloalkanes, n-heterocycles, formic acid, ammonia, and their derivatives, but remains inefficient due to catalyst stability in dehydrogenation, financial infeasibility of CCUS after hydrogen recovery and notable cost variability (0.28-37.4 €/kg) (Mehr *et al.*, 2024; Clematis *et al.*,

2023). In this process, hydrogen reacts with an organic or synthetic material to form a new compound, which is subsequently dehydrated at the destination to release hydrogen (IEA, 2022a).

Mehr *et al.* (2024) and Ganter *et al.* (2024) assessed the technology maturity and trade-offs of hydrogen transport and storage processes, summarized in **Table 2**.

Table 2 – Comparative analysis of the main hydrogen transport and storage processes

Product	Advantages	Disadvantages
Liquid Organic Hydrogen Carries (LOHC) and ammonia	High volumetric capacity, safer handling, compatible with existing fuel infrastructure, mature ammonia-related processes, and emerging technologies for efficient ammonia production (e.g., plasma or microwave-assisted synthesis, and chemical looping).	Nitrogen oxides emissions during ammonia synthesis, dependence on resistant materials and catalysts, high energy demand with CO_2 emissions during dehydrogenation; LOHC still emerging.
Compressed (Type I-IV) and cryogenic hydrogen	High-pressure tanks with composite/metal materials, reliable for mobile and stationary applications (up to 9.5×10^7 Pa), and large capacity applications.	Heavy tank weight, cost and safety concerns with high-pressure systems, liquefaction consumes 40% of H_2 energy content, with boil-off losses and insulation requirements.
Solid-state storage	Safe and stable, viable for long-term storage, and several materials suitable for physical hydrogen storage through van der Waals interactions or dispersive forces.	Limited large-scale application, hydrides are heavy, slow sorption and desorption kinetics.
Geological storage	Salt caverns offer low-cost, high purity, with moderate to mature technology status; natural formations (gas reservoirs, mines, salt domes) and Permian Basin well suited.	Moisture in brine at salt caverns requires drying, brine disposal, and risk of contamination in depleted fields.
Cryo-compressed hydrogen	Combines cryogenic cooling and compression for higher-density storage, with moderate maturity, and suitable for mobile applications and flexible refuelling options.	Requires extreme cooling (20 K), high energy cost for liquefaction.
Ammonia-Borane	Solid-state storage with high gravimetric and volumetric capacities for medium-scale, stable under ambient conditions.	Energy-intensive hydrogen recovery, potential for toxic by-products, still emerging.
Metal-Organic Frameworks	Porous crystalline materials for hydrogen adsorption, with high surface area and customisable pore structures.	High cost, limited gravimetric capacity, energy-intensive regeneration, still in research stage.

Source: Adapted from Mehr *et al.*, 2024; Ganter *et al.*, 2024.

Storage options include pressure and cryogenic tanks or solid-state storage. Solid-state storage presents another promising alternative, securely encapsulating hydrogen in materials (e.g., metal hydrides and carbon nanotubes) with lower capacity and variable discharge rates (Durbin; Malardier-Jugroot, 2013; Lototskyy *et al.*, 2020; Mehr *et al.*,

2024). Porous rock formations are considered as geologically suitable for hydrogen containment, with depleted hydrocarbon reservoirs, deep aquifers, and empty salt caverns identified as promising candidates for underground storage (Mehr *et al.*, 2024).

Ageing of oil and gas assets raise maintenance demands, well interventions, and fugitive emissions, raising annual greenhouse gas (GHG) emissions (Davies; Hastings, 2023). Methane operations pose GHG leakage risks pre- and post-abandonment, requiring inclusion in emissions assessments. CO_2 transport is central to CCUS. In China, CCUS network design primarily employs source-sink matching to plan pipelines, yet struggles with large CO_2 volumes and numerous, dispersed sources and storage sites (Wang *et al.*, 2024).

2 Electromobility and hydrogen economy synergies

Electromobility and the hydrogen economy are increasingly seen as complementary pillars of transport decarbonisation, each offering distinct advantages and facing specific constraints. Electrified vehicles provide a highly energy-efficient pathway and lower investment costs for infrastructure deployment. As noted by Rozzi *et al.* (2024), however, their levelised cost of driving (LCOD) may be higher than that of hydrogen mobility, reaching €0.50/km compared with €0.40/km for hydrogen systems. Hydrogen mobility benefits from a lower LCOD partly because oversizing renewable generation allows surplus electricity to be exported to the grid, offsetting operational costs (Rozzi et al., 2024).

Fuel Cell Electric Vehicles (FCEV), by contrast, rely on hydrogen stored on board and use fuel cell stacks requiring platinum-based catalysts. FCEV can offer greater driving ranges than electric vehicles while using batteries at least ten times smaller (IEA, 2025b). Yet their deployment faces barriers relating to high system costs, onboard storage and safety considerations.

Significant cost reductions in low-carbon hydrogen production, transmission and refuelling infrastructure are still required for FCEV to achieve cost parity with electrified vehicles or internal-combustion alternatives (IEA, 2025b). Overall, electromobility excels in maturity and efficiency, while hydrogen mobility offers strategic advantages for long-range transport and deeper decarbonisation, making both essential and synergistic components of a net-zero transport system.

3 Evolution of electromobility in Brazil (2019–2023): Statistical analysis of the electrified fleet and a roadmap for public incentive policies

The transport sector is central to the global economy, supporting commercial interactions, tourism and national and international mobility. However, it is also a major source of GHG, largely due to the widespread use of fossil fuels across road, rail, air and maritime modes, representing around 20% of global carbon dioxide (CO_2) emissions. In Brazil, the sector accounts for approximately 14% of national emissions (MCTI, 2021).

Brazil expected economic and population growth reinforces the need for government action to mitigate transport-related GHG emissions. In this context, and in line with global climate commitments, it is essential to discuss the role o

f electrified vehicles – both electric and hybrid – in reducing CO_2 emissions from the Brazilian transport sector.

Brazil has adopted commitments consistent with the Paris Agreement, signed in 2015 by 195 countries. At COP27, held in Sharm el-Sheikhto (Egypt), the country reaffirmed and expanded previously established targets (UNFCCC, 2022). Through its Nationally Determined Contribution (NDC), Brazil committed to reducing GHG emissions by 37% below 2005 levels by 2025, and by 43% by 2030 (Brazil, [n.d.]). Additional commitments include restore and reforest 12 million hectares of forests and ensuring that renewable sources reach 45% of the national energy matrix by 2030. A revised NDC later increased the ambition: a 50% reduction in emissions by 2030 and climate neutrality by 2050 (Brazil, 2016).

This work focuses on the statistical analysis of Brazil's electrified vehicle fleet, together with a roadmap of public policies and governmental actions implemented up to 2023, to assess current impacts and challenges.

3.1 Literature review

Recent studies have evaluated electromobility in Brazil and Latin America. Correa *et al.* (2023) assessing the well-to-wheel energy and environmental performance of urban buses in Brazil, Argentina and Chile, project that by 2030 electric vehicles will offer

superior performance despite higher costs, while fuel-cell hybrid vehicles may become competitive alternatives with improved emissions and cost indicators.

Gauto *et al.* (2023) applied LCA to compare GHG emissions from conventional internal combustion engine, hybrid and electric vehicles in Brazil and Europe. The authors observed that combining Brazilian biofuels with hybrid vehicles yields greater efficiency, in terms of distance travelled per unit of GHG emitted, when compared to electric vehicles. Mena *et al.* (2021) reinforce this conclusion, noting that electromobility in Brazil benefits from low operation cost and quiet performance, while still facing challenges including high purchase prices and limited charging infrastructure.

According to Soares *et al.* (2022), Brazil's transition to electric mobility involves multiple variables. Plug-in electric vehicles benefit from the country's low-carbon electricity supply, while hybrid vehicles powered by bioethanol alone or by bioethanol and biogas in dual-fuel mode may be particularly suitable. Their results show that bioethanol has the lowest energy–ecological efficiency (27%), influenced by factors such as human toxicity and pollution, whereas biogas in single-fuel internal combustion engines reaches the highest efficiency (64%). These findings illustrate the complexity of decision-making in the Brazilian context, which combines a renewable electricity matrix with significant potential for biofuel production.

Glyniadakis and Balestieri (2023) assess the decarbonisation of Brazil's automotive fleet by 2050, emphasising structural challenges such as high EV costs, battery disposal and the need for supportive policies and infrastructure investment. They conclude that a 59% reduction in emissions by 2050 is feasible, exceeding the target set by the Ministry of Mines and Energy. Additionally, Gonçalves *et al.* (2021) identify a mitigation potential via solid oxide fuel cell (SOFC) technology, which could make eco-efficient use of existing ethanol and petrol refuelling infrastructure.

Battery lifespan is another recurring concern, whether fully electric or hybrid. Eckert *et al.* (2021) analysed a light hybrid electric vehicle with a single-shaft series hybrid propulsion system. By applying gear-shift control and energy management based on fuzzy logic optimised with an adaptive genetic algorithm, they achieved significant improvements in energy efficiency: a 15.18% reduction in travel cost, preserved battery life and notable emission reductions. The authors recommend short-term public policies

to promote light hybrid vehicles equipped with advanced control systems due to their capacity to improve environmental performance.

To stimulate domestic production, the Brazilian government has introduced fiscal incentives for electric vehicle manufacturers, including tax reductions or exemptions, R&D support, dedicated credit lines and participation in electromobility programmes. These measures aim to enhance industrial competitiveness, foster innovation and consolidate Brazil's role in the global electromobility landscape. Some municipalities also offer practical benefits, including discounted parking and dedicated traffic lanes, to encourage adoption, reduce emissions and promote more sustainable mobility patterns.

Although electric vehicles represent a transformative shift towards sustainable mobility, the transition involves significant challenges and opportunities. A major barrier in a country of continental scale is the limited charging infrastructure. The absence of an extensive national network restricts long-distance travel and reduces consumer confidence. Estimates suggest that approximately R$ 14 billion will be required to deploy around 150,000 public charging points, which would address range concerns and support wider market expansion.

Charging time remains another obstacle. A fully electric vehicle currently requires around eight hours to charge from a 220-volt outlet. Manufacturers are investing in three modes of charging: standard (8 hours), semi-fast (3.5 hours) and fast (15 minutes), with the latter requiring a more robust electrical infrastructure. This variety aims to make electric vehicles more practical and appealing to consumers.

Increasing environmental awareness and ongoing technological advances are also likely to accelerate electrified vehicles uptake. In Brazil, renewable sources account for an average of 85% of the electricity matrix, which further enhances the viability of electric mobility in the country (Sebrae, 2023). Investment in a reliable charging network by public and private actors would mitigate concerns related to vehicle range and infrastructure availability, strengthening the attractiveness of electric vehicles and supporting the transition to sustainable mobility.

3.2 Methodology

The study applied data on Brazil's national vehicle fleet by fuel type, published monthly by the National Traffic Secretariat – Senatran (Senatran, 2023). The period from January 2019 to December 2023 was selected to assess electromobility development in Brazil. The study focuses on both electric vehicle and hybrid vehicle fleets, the latter defined as using two distinct power sources – an internal combustion engine and an electric motor – for energy generation and propulsion (Brazil, 2018).

Data covering 60 months were examined. Records from August 2023 were excluded due to inconsistencies relative to earlier and later months. The hybrid category comprises vehicles whose fuel type indicated the combined use of electricity and fuels such as diesel, ethanol, petrol and others.

Additionally, the study developed a roadmap of public policies directly or indirectly related to the emergence of hybrid and electric vehicles in Brazil up to 2023. This involved a bibliographic and legislative review to assess the impacts of existing measures and identify gaps and opportunities for improvement.

3.3 Results and discussion

3.3.1 Temporal analysis

Over recent years, the Brazilian market for electrified vehicles has expanded rapidly. Regarding the uptake of hybrid vehicles, in the Central-West Region the Federal District stands out, having risen from 1,183 units in 2019 to 13,529 in 2023, followed by Goiás, which began the period with 605 units and reached 7,633 in 2023. In contrast, the Northern Region records the lowest number of electrified vehicles among all administrative regions: Acre registered its first electric vehicle only in 2020 and Roraima did so only in 2022.

The Southeast and South regions hold the largest electric and hybrid fleets. São Paulo leads national sales, with fully electric vehicles increasing from 1,133 to 15,387 between January 2019 and December 2023. Paraná ranks second nationally, recording 5,473 electric units by the end of 2023.

Although the South and Southeast regions stand out quantitatively, it is worth highlighting the recent growth of the electrified fleet in the Northeast Region, which surpassed the South in 2020 and 2021. One contributing factor may be the establishment of the Green Corridor, which links Salvador (Bahia) to Natal (Rio Grande do Norte), passing through Aracaju (Sergipe), Maceió (Alagoas), Recife (Pernambuco) and João Pessoa (Paraíba). Once fully completed, the Green Corridor will extend over 1,200 kilometres and will comprise 18 charging points along the routes connecting the six states (Neoenergia, 2023).

Most states have an average distribution of urbanised areas, with between 70% and 80% classified as densely populated urban zones and between 20 – 30% as less dense (IBGE, 2022). However, notable exceptions include Piauí, Amazonas, Pará, Acre and Roraima, where more than 30% of urbanised areas are classified as low density. Conversely, states such as Paraná, Rio de Janeiro, Espírito Santo and the Federal District record more than 85% of urbanised areas as dense, with the Federal District reaching 94.59%.

Taken together, the data reveal significant disparities in the growth rates of electric vehicle fleets across regions. Whilst urban areas have experienced consistent growth, rural regions have shown a more moderate increase. This discrepancy may be attributed to several factors, including rapid urbanisation, demand for public transport, and region-specific economic dynamics.

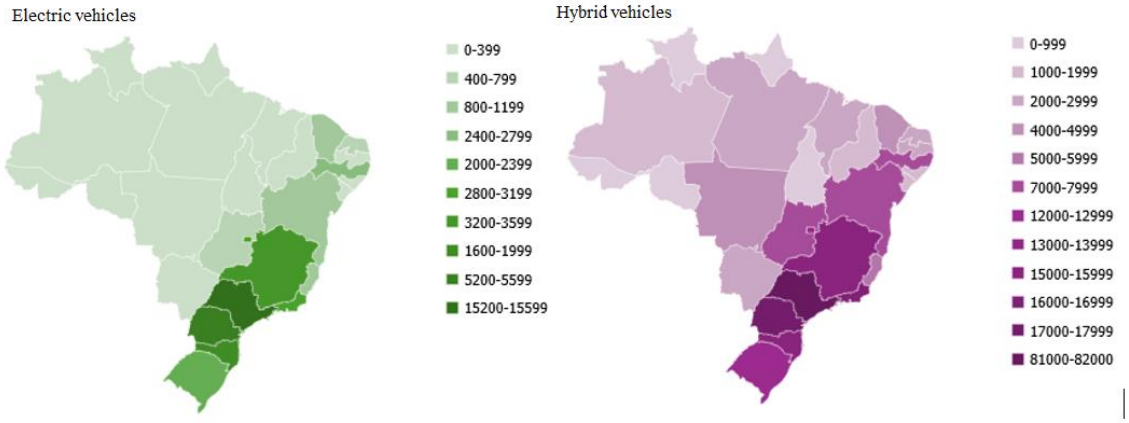
3.3.2 Current scenario

When examining the geographical distribution of electrified vehicle registrations in Brazil in 2023 (**Figure 1**), the Southeast region remains the leading area, headed by the state of São Paulo, which closed the year with 15,387 fully electric vehicles in circulation and 81,031 hybrid vehicles.

Flex-fuel hybrid vehicles represent Brazil's natural pathway for the energy transition. This assertion can be supported by four main factors: the country is the world's second-largest producer of biofuels; the production of electric vehicle batteries carries a high environmental impact; hybrid vehicles offer greater energy efficiency; and the energy supply infrastructure is already well established. Taken together, these factors

enable hybrid vehicles to achieve lower carbon emissions than fully electric vehicles of a similar size, even within a comparatively clean electricity matrix such as Brazil's.

Figure 1 – Number of electric and hybrid vehicles in Brazilian states in 2023



Source: Adapted from Senatran (2024).

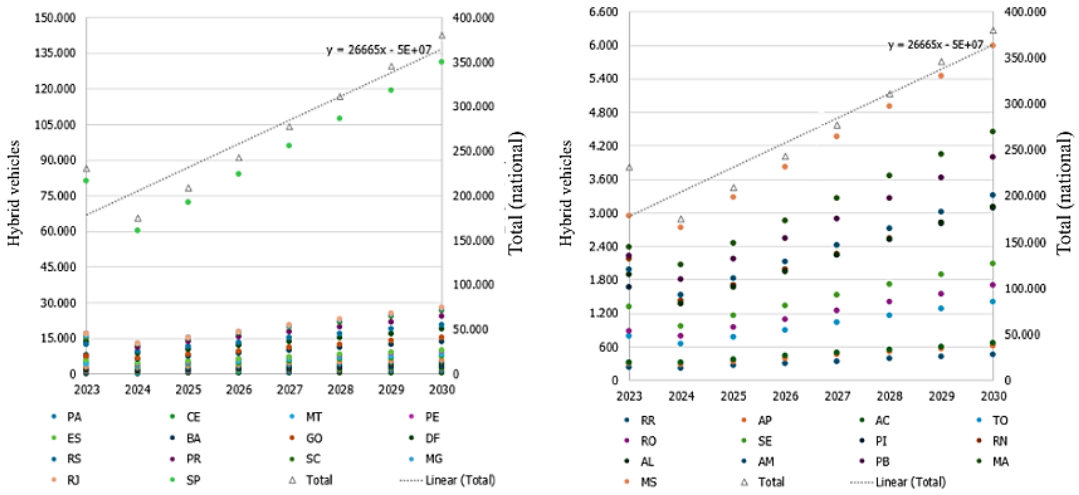
The rapid growth of electric vehicles indicates that peak fossil-fuel demand for road transport has already passed. Global oil demand for vehicles reached its peak in 2019 and is now stagnating due to combined gains in efficiency and the increasing adoption of electric vehicles.

Figure 2 presents the trend analysis, based on linear regression, for the hybrid vehicle fleet across Brazil's federal units up to 2030, using the 60-month historical series collected. In the Northern region (Amazonas, Pará, Acre, Rondônia, Tocantins, Amapá and Roraima), which records the lowest overall numbers, the states of Pará and Amazonas stand out, with petrol–ethanol hybrids predominating, followed by diesel hybrids.

A similar pattern is observed across the Northeast (Maranhão, Piauí, Ceará, Rio Grande do Norte, Paraíba, Pernambuco, Alagoas, Sergipe and Bahia) and Centre-West (Mato Grosso, Goiás, Mato Grosso do Sul and Federal District). It was not possible to determine the predominant hybrid category in the South and Southeast due to missing information on the non-electric power source in the dataset.

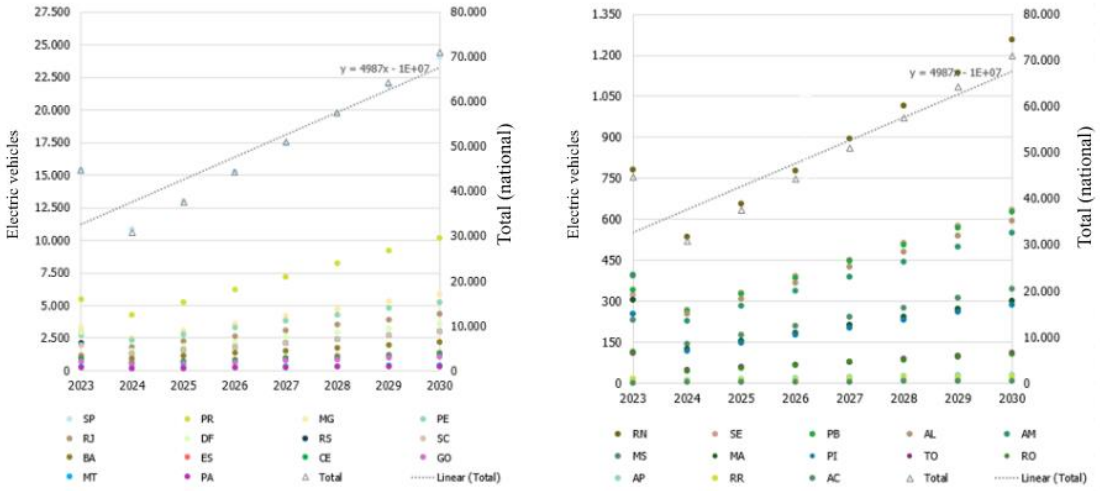
Projections indicate that Brazil's hybrid fleet may reach around 380,047 units by 2030, with the Southeast accounting for approximately 53.4%. However, it is not possible to estimate any reduction in greenhouse gas emissions, as tailpipe emissions vary according to the configuration of each hybrid powertrain.

Figure 2 – Linear regression trend analysis of hybrid vehicle data across Brazilian states, 2023–2030



Source: Elaborated by the author.

Figure 3 – Linear regression trend analysis of electric vehicle data across Brazilian states, 2023–2030



Source: Elaborated by the author.

Figure 3 illustrates the trend analysis, based on linear regression, of monthly electric vehicle data from 2019 to 2023 across Brazil's federal units. The findings indicate that the fully electric fleet in Brazil could reach 71,034 units by 2030, once again with the Southeast region standing out, potentially accounting for 50.3% of the total. All states in the Southeast show strong annual growth rates in the electric fleet, with particular emphasis on the consistent expansion observed in Minas Gerais, which was the only state in the region to maintain growth rates above 100% between 2020 and 2022.

The results presented in the graphs reveal a linear regression analysis with limited data dispersion, evidenced by a very low gradient coefficient. This limitation suggests a weak dependence of electric and hybrid vehicle sales on the variables considered, such as public incentive policies for their adoption. Consequently, it is possible that sales remain relatively stable or are influenced by other factors not captured by the regression model, including the maturity and convergence of the technology, as well as growing environmental awareness among consumers at both household and corporate levels. Furthermore, factors such as the increasing interest in obtaining international certifications attesting to carbon neutrality among companies in the energy, transport, and related service sectors should also be considered.

3.3.3 Overview of public incentive policies

The introduction of policy instruments aligned with the theme of electric mobility in Brazil began in 1986 with the launch of the Air Pollution Control Programme for Motor Vehicles (PROCONVE), which encouraged domestic production and prepared the transport sector for a sustainable transition focused on emission control and vehicle energy efficiency. However, until 2018 most policies in this field were indirectly related to the advancement of electromobility in the country. In 2012, the Inovar Auto programme was launched to foster innovation within the automotive industry. One of its objectives was to improve vehicle energy efficiency, with a target of 1.82 MJ/km for 2017. Regulated by Law nº 12,715/2012, it marked a regulatory cycle for energy efficiency in the Brazilian automotive sector until 2017. In 2013, the Inova Energia programme introduced financing for pilot projects involving charging systems for electric vehicles.

In 2018, the federal government launched the Rota 2030 programme, which provides tax incentives and obligations for the automotive sector with the aim of improving vehicle energy efficiency and promoting new technologies. Within the scope of Rota 2030, the GT7 Working Group on Electric and Hybrid Vehicles was established as a multilateral body involving government, industry, and scientific and technological institutions. This group contributes recommendations to the National Electromobility Plan, complementing the Rota 2030 framework.

The National Biofuels Policy (RenovaBio) emerged indirectly from Brazil's ratification of the Paris Agreement in 2016, through which the country committed to increasing the share of biofuels in its energy matrix and reducing carbon emissions by 37% by 2025. Instituted by Law nº 13,576/2017, RenovaBio seeks to expand the participation of sustainably produced biofuels in the national energy matrix. Biofuels demonstrating proven energy–environmental efficiency (lower GHG emissions per MJ over the life cycle) compared with their fossil equivalents may obtain decarbonisation credits, which are traded on the financial market and provide additional revenue to producers (MME, 2017). By promoting an increased share of sustainably produced biofuels in Brazil's energy matrix, RenovaBio supports the adoption of less polluting technologies, such as hybrid vehicles powered by renewable electricity and, for example, ethanol with verified energy–environmental efficiency.

Furthermore, according to D'Agosto *et al.* (2020), the states of Maranhão, Piauí, Ceará, Rio Grande do Norte, Pernambuco, Sergipe, Rio Grande do Sul, São Paulo, Rio de Janeiro and Mato Grosso do Sul have enacted incentive regulations offering full or reduced rates of the Motor Vehicle Property Tax (IPVA) for electric and hybrid vehicles.

At the federal level, the Brazilian Electricity Regulatory Agency (Aneel) issued Normative Resolution No. 1,000/2021, which consolidated 61 regulations related to the rights and obligations of electricity consumers. Among them was Normative Resolution nº 819/2018 (now revoked), which aimed to encourage the expansion of charging infrastructure across the country (Aneel, 2022). In 2022, the Brazilian government updated its commitments to the United Nations, pledging to reduce emissions by 37% by 2025 and by 50% by 2030, relative to 2005 levels. Although the revised NDC emphasises concerns regarding deforestation, it does not address in detail issues related to the transport sector or biofuels, suggesting a possible lack of prioritisation of these areas within sustainability policy.

In 2023, Law nº 710/2023 was proposed, seeking to establish mandatory charging points for electric and hybrid vehicles in private car parks for collective use, as well as in public car parks and public roads (Brazil, 2023). Additionally, COP 28, which concluded on 13 December 2023, placed strong emphasis on the use of fossil fuels, with 130 countries agreeing to reduce their carbon footprint over time, with a view to cutting GHG emissions in the transport sector. As a result, measures such as the expansion of

infrastructure for vehicles and bicycles and the broader adoption of clean vehicles are expected to receive increased attention and support in the coming years.

3.3.4 Correlation analysis with GDP

Based on the historical series of the national Gross Domestic Product (GDP) from 2019 to 2021, as well as the estimates for 2022 and 2023 published by the Brazilian Institute of Geography and Statistics (IBGE), it is important to note that the states in the Southeast have historically accounted for the three federative units with the highest share of Brazil's GDP. Accordingly, it becomes evident that the region currently showing the sharpest increase in the percentage of electric vehicles is also, historically, the one with the strongest GDP performance.

Maranhão shows a weaker performance compared with other Northeastern states regarding the ratio between population size and the number of electric vehicles in circulation. There are indications that this outcome is rooted in its low GDP per capita in comparison with other regions, which suggests a slower implementation of public policies that should, in the future, focus on the development of charging infrastructure through fiscal incentives and programmes such as Rota 2030. Paraíba and Alagoas present similar scenarios, yet with higher rates of adoption, indicating a promising potential for integrating incentive policies for infrastructure, vehicle acquisition and ownership.

When comparing the technology adoption index and the charging infrastructure reported by the National Electric Mobility Platform (PNME) in 2023 for the states of Piauí, Ceará, Rio Grande do Norte, Sergipe, Bahia and Pernambuco, a moderate level of adoption and an adequate supply of chargers can be observed – an indication of positive impacts from incentive policies. However, Pernambuco's charging infrastructure requires improvement to keep pace with the growth in its electric fleet observed over recent years.

The Southeast region exhibits a generally high GDP per capita, particularly in São Paulo, Rio de Janeiro and Espírito Santo, all of which also present favourable electric vehicle adoption rates. Nonetheless, the charging infrastructure has not kept pace with fleet growth, especially in Espírito Santo, followed by Minas Gerais and São Paulo.

This demonstrates that policies such as tax exemption and differentiated tax rates have been effective and that their success does not depend exclusively on high GDP per capita – given the significant adoption rates observed in several Northeastern states that benefit from similar subsidies.

Considering the population data from the 2023 census for the North and Centre-West regions – both of which have similar population sizes – there is a marked disparity in GDP per capita across their federative units. These include two extremes: the Federal District, which has recorded the highest GDP per capita over the last five years, and Acre, which has remained among the three lowest in the country during the same period. A comparable pattern emerges when examining the number of electric vehicles: the total electric fleet of the seven Northern states (Amazonas, Pará, Rondônia, Amapá, Roraima and Acre) represents only 30% of the electric vehicle count in the Federal District alone. It is also worth noting that the Northern states, in addition to having low GDP per capita, did not benefit from public incentive policies in 2014.

Mato Grosso do Sul shows weaker performance than the other Centre-West states regarding technological adoption. This may be linked to its GDP per capita being lower than that of Goiás and Mato Grosso, despite being the only one of the three to benefit from tax exemption since 2014. This indicates that incentive policies for electric vehicle adoption must be strengthened in Mato Grosso do Sul. In contrast, Goiás and Mato Grosso show greater growth in adoption, suggesting strong potential for infrastructure-orientated policy measures.

Rio Grande do Sul performs less favourably than other Southern states in terms of technological adoption, despite having a GDP per capita higher than both Paraná and Santa Catarina. Although it has been the only Southern state to offer tax exemption since 2014, these incentives have not significantly expanded its electric fleet. Additional measures – such as policies aimed at raising awareness of the environmental benefits of electric mobility – are needed. Santa Catarina and Paraná, meanwhile, show higher adoption rates and will require continuous expansion of charging infrastructure to meet rising demand and increasing environmental awareness among consumers.

It is also important to highlight the substantial progress in electric-vehicle charging infrastructure across the country. Projects such as Copel's Eletrovia in Paraná, Celesc's Eletroposto in Santa Catarina, and Neoenergia's Green Corridor in the

Northeast illustrate a growing national commitment to electromobility (PNME, 2023). Copel's Eletrovia, inaugurated in 2018 with 12 charging stations along the BR-277 motorway, has since expanded its operations. In the South, the privately funded Rota Sul charging network connects Paraná, Santa Catarina and Rio Grande do Sul, facilitating long-distance travel for electric-vehicle users. These initiatives form part of a national trend towards expanding charging infrastructure, an essential factor for supporting the wider adoption of electric vehicles.

Another important observation concerns the strong performance of hybrid vehicles in states with GDP levels below the national average. This suggests that the existing fuel-station network and consolidated biofuel-distribution infrastructure already support part of the decarbonisation needs of the transport sector – and could contribute even more as biofuels increase their share in each state's energy matrix.

3.4 Key findings

The study offered a statistical analysis of the electrified vehicle fleet in Brazil for the period between January 2019 and December 2023, based on the collection and processing of data published by Senatran for the 60 months within the study's scope. In addition, a roadmap of public policies and governmental actions launched up to 2023 was outlined, in association with the topic, to identify potential impacts, gaps and areas for improvement to support the development of Brazilian electromobility.

In recent years, the Brazilian market for electrified vehicles has experienced substantial growth, with the Southeast and South regions standing out. The analysis reveals steady progress in the adoption of electrified vehicles in urban areas, while rural regions show more moderate expansion. The predominance of flex-fuel hybrid vehicles in Brazil is justified by factors such as enhanced energy efficiency and the country's well-established refuelling infrastructure. This trend indicates an ongoing energy transition, reflected in the decline in fossil fuel demand and positive projections for the future of the hybrid fleet.

The data analysis highlights a clear disparity among Brazilian states, both in terms of GDP and in the adoption of electric vehicles. States in the North and Centre-West, characterised by low GDP per capita and limited public incentive policies, exhibit a

marked delay in the uptake of electric technology. In contrast, states such as Goiás and Mato Grosso, with comparatively higher GDP per capita, demonstrate greater potential for implementing infrastructure policies and incentives. Nevertheless, nationwide progress in expanding the charging infrastructure is evident, illustrated by initiatives such as Copel's Eletrovia in Paraná and Neoenergia's Green Corridor in the Northeast, signalling a growing commitment to electromobility.

It is also important to note that the presence of hybrid vehicles in states with GDP levels below the national average suggests the potential effectiveness of the existing refuelling and biofuel distribution infrastructure. This may indicate that, with increased participation of biofuels in each state's energy matrix, this established infrastructure could play an even more significant role in the decarbonisation of the transport sector, complementing advances in the adoption of electric vehicles.

Estimates suggest that the electrified fleet in Brazil could reach approximately 451,081 units by 2030 if linear growth is maintained, underscoring the need for well-targeted governmental incentives and investment in fast and accessible charging infrastructure to accelerate the transition. Recent governmental proposals indicate a growing focus on decarbonising the transport sector; however, further discussion is needed regarding the main factors influencing the growth of Brazil's electrified fleet. Future research could address topics such as fiscal incentives, ongoing legislative proposals, state and federal regulations, consumer perceptions, and the geoeconomic disparities across the country's regions.

4 Technology roadmap of low-carbon hydrogen: Trends for risk management strategies

Efficiency and resilience necessary for a stable hydrogen economy. Despite increasing interest in SCRM of low-carbon hydrogen, barriers include electrolysis efficiency and storage materials, while the slow uptake of low-carbon hydrogen and the cost-effectiveness of hydrogen from natural gas with CCUS hinder investments (Bhuiyan; Siddique, 2025; Jumah, 2024; IRENA, 2022).

A recent study tracking 190 projects over 3 years identified a wide 2023 implementation gap with only 7% of global capacity announcements finished on schedule (Odenweller; Ueckerdt, 2025). Without carbon pricing, achieving all these projects may require USD 1.3 trillion in subsidies. Several projects faced delays and cancellations, threatening pipeline projects due to uncertain demand, financial barriers, delayed incentives, regulatory and licensing issues, and operational challenges (IEA, 2024a).

The current stage of low-carbon hydrogen supply chain is extensively studied in the literature. These investigations often analyse product, market, and technology in isolation, lacking integrated analyses to identify SCRM trends, key actors, and essential factors for advancing the hydrogen economy. Few studies investigate multidisciplinary trends in risk mitigation within this field (Bhuiyan; Siddique, 2025).

This research addresses an existing gap by applying a Technology Roadmap (TRM) approach to characterise the global low-carbon hydrogen supply chain across short-, medium-, and long-term horizons and to identify risk management trends to answer the following research question: “What technological trends and gaps identified in the global low-carbon hydrogen roadmap are most relevant for improving the resilience of supply chains to decarbonisation risks?”.

TRM is a structured framework for technology foresight and strategic alignment, highlighting gaps and emerging opportunities in research and intellectual property (Kostoff; Schaller, 2001; Borschiver; Silva, 2016). A key novelty of this study is applying TRM to assess technological trends through the lens of decarbonisation risks, defined as any adverse impact of a technology, resource, or end-use on national climate goals (Carlson; Trencher, 2024). This contrasts with the siloed assessment of environmental, technological, or financial risks common in logistics.

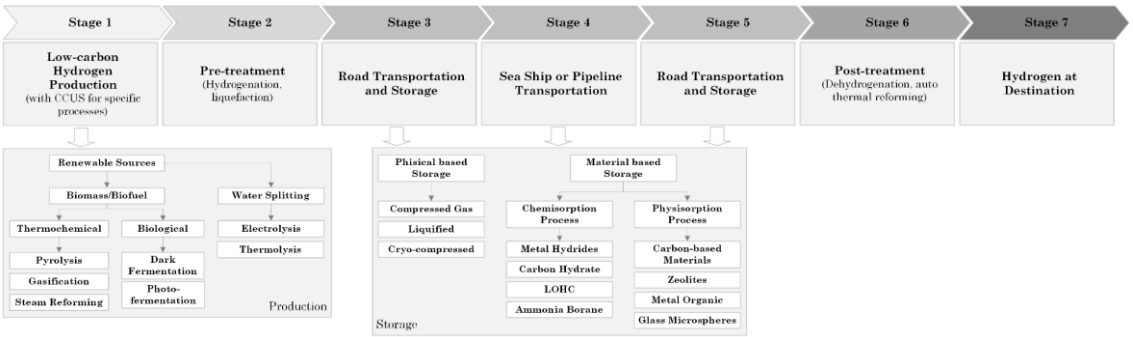
By focusing on transition-specific risks, TRM enables structured identification of technological vulnerabilities and supports strategic decisions on production, storage, transport, and investment under uncertainty. The method offers a technical basis for selecting the most appropriate logistical vector by assessing trade-offs and provides direction for future research in SCRM.

4.1 Methodology

TRM is a comprehensive and adaptable method for technology foresight, strategic planning, and innovation management, widely applied across industry, government, and academia to illustrate links between science, technology, and applications (Kostoff; Schaller, 2001). It facilitates communication among stakeholders while integrating technology and market information and identifying global gaps and opportunities in science and intellectual property (Borschiver; Silva, 2016).

This study applies TRM methodology developed by the Núcleo de Estudos Industriais e Tecnológicos (Neitec) at the Federal University of Rio de Janeiro, Brazil, to identify risk management trends in the low-carbon hydrogen supply chain (**Figure 4**). It comprises four steps: pre-prospective, technological prospection, post-prospective, and post-roadmap, as described in **Figure 5**.

Figure 4 – Low-carbon hydrogen supply chain stages

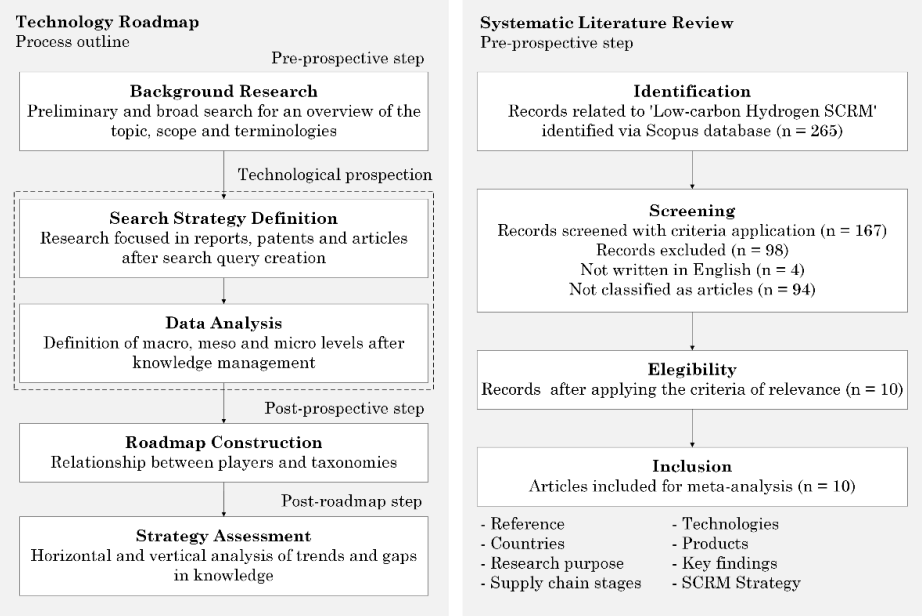


Source: Adapted from Bhuiyan and Siddique (2025).

This TRM method was chosen as the Neitec approach enables global rather than local analysis, instead of segregated assessments, integrating technology and market data on publicly available data from suppliers, patent documents, and scientific articles (Assunção *et al.*, 2021). Previous applications include TRM for production and

application of biomethane, hyaluronic acid, biopolymers, and the biotechnological production of 2,3-butanediol (Assunção *et al.*, 2021; Borschiver *et al.*, 2018; Jaconis *et al.*, 2019; Tinôco *et al.*, 2021).

Figure 5 – Methodological flowchart of the study



Source: Adapted from Bhuiyan and Siddique (2025).

4.1.1 Pre-prospective step

An initial exploratory search provided an overview of the topic and terminology in low-carbon hydrogen SCRM, guiding the scope for technological prospection. This background research was developed using the Scopus database advanced search and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), complemented by bibliometric analysis with OpenRefine (3.8.5) and VOSviewer (1.6.19). This approach is valuable in research fields with extensive publications and diverse perspectives (Mardani *et al.*, 2017).

Thus, bibliographic data was collected in December 2024, encompassing English articles in indexed journals. An initial list of terms was defined and iteratively tested to validate the most representative query. The following advanced search strategy was formulated and applied: TITLE-ABS-KEY (("green hydrogen" OR "low-carbon hydrogen" OR "sustainable hydrogen") AND ("supply chain risk management" OR

"SCRM" OR "supply chain" OR "risk management" OR "risk mitigation") AND ("storage" OR "transport*" OR "production" OR "generation" OR "recycl*" OR "compress*" OR "reform*" OR "electrolysis" OR "gasification" OR "pyrolysis" OR "water splitting" OR "photobiological decomposition" OR "photofermentation" OR "dark fermentation" OR "liquefaction" OR "carrier*" OR "liquid organic hydrogen carriers" OR "LOHC" OR "ammonia" OR "carbon capture" OR "CCS" OR “CCUS”)).

The rise in scientific output since 2020 resulted in 265 publications from 2020 to 2024 on this topic. After filtering for English articles, 167 remained. Data exported were cleaned and de-duplicated using OpenRefine. VOSviewer then quantitatively analysed the 167 articles through bibliometric maps to support the authors with a clear and detailed field interpretation.

4.1.2 Technological prospection

This step is divided into two parts: search strategy definition and data analysis, as described below.

4.1.2.1 Search strategy definition

The search strategy was focused on documents correlated to current, short-, medium-, and long-term roadmap stages (Borschiver; Silva, 2016). The current stage applied systematic review data and specialised media of relevant organisations. Short-term included granted patents, indicating commercial readiness. Medium-term included patent applications, demonstrating advanced technology development that is still under analysis for protection. Long-term included scientific articles reflecting early-stage academic research.

The advanced search query used in the pre-prospective step was reapplied in Scopus to select 50 English articles for the long-term section, sorted by date (newest first). Short- and medium-term information was collected from patent documents in Questel’s Orbit Intelligence (2.0.0) software database. This allowed searches of more than 100 million patent documents filed in patent offices from several countries, covering more than 99.7% of applications worldwide (Questel, 2025). The searches

were conducted in March 2025, using the same terms as the bibliographic search, without any time filter.

Data from 22 granted patents, 77 pending patents, and 50 articles outlined trends and gaps over time. While estimating time horizons in a technology roadmap is complex, particularly due to market vulnerability to fast and disruptive shifts, we follow the multiperiod categorisation replicated by Borschiver and Silva (2016): short-term (up to five years), medium-term (five to ten years), and long-term (beyond ten years).

Technological learning rates were indirectly assessed by structuring the roadmap by document types, i.e., scientific articles (long term), pending patents (medium term), and granted patents (short term), reflecting typical stages maturity and cumulative learning. National patent backlogs were also considered as potential delays to commercial impact. As most patents dated from 2018, we assumed substantial learning and cost reduction over the next two decades, with alive patents representing early stages of the learning curve. These assumptions informed the long-term analysis, supporting reasonable projections despite uncertainties associated with disruptive developments.

4.1.2.2 Data analysis

Data analysis was organised into three levels for technological prospection: (i) macro analysis, extracting immediate information from documents (e.g., publication year, country, affiliations); (ii) meso analysis, categorising and creating taxonomies based on market, product, and technology perspectives; and (iii) microanalysis, extracting detailed information to define sub-categories (terms), within each taxonomy, grouping them by similarity, quantifying frequencies, and identifying patterns (Borschiver; Silva, 2016). Term extraction focused on titles and abstracts, with full-text analysis applied when necessary for technological identification.

4.1.3 Post-prospective step

Information from previous steps was structured into roadmap sections using Microsoft Visio, with key actor's logos (i.e., companies, universities, and research institutes) linked to relevant terms in their researches via arrows. This approach visually

represents actor-taxonomy relationships and was applied to depict long-term results (Borschiver; Silva, 2016). Maps generated with Orbit Intelligence were also employed to illustrate actor-taxonomy relationships, protection countries and other patent-related indicators corresponding to short- and medium-term.

4.1.4 Post-roadmap step

Post-roadmap step was conducted to identify trends, knowledge gaps, and actor similarities within SCRM context. Horizontal analysis quantified taxonomy trends by terms occurrence within each document, indicating technology evolution (Borschiver; Silva, 2016). Vertical analysis examined key institutions, identifying partnerships and actors with similar technological focus and challenges.

4.2 Results and discussion

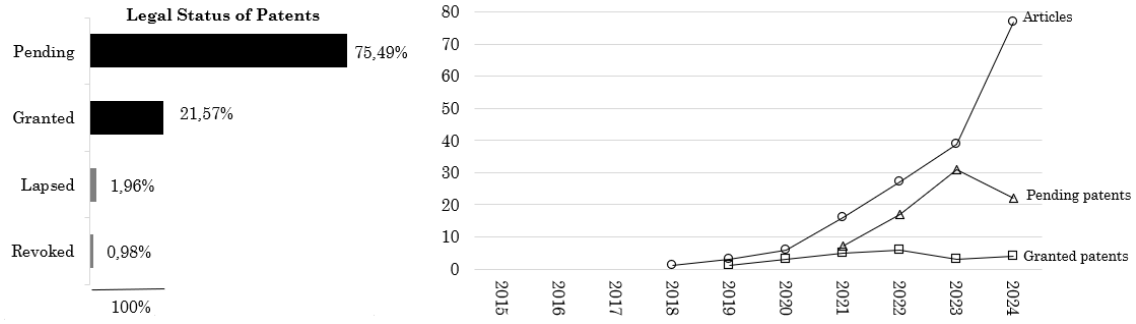
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4.2.1 Macro analysis

Despite the growing scientific output observed since 2018, patent filings related to the topic have shown steady yet less pronounced growth (**Figure 6**). It should be considered that patent documents take a period of up to 18 months to be published, leading to the inference that the number of patents in 2024 and, to a lesser extent, in 2023, should increase. Of the 102 patents analysed, only 2.94% are inactive (revoked or

lapsed), while 97.06% are alive (granted and pending), with notable predominance of applications under examination.

Figure 6 – Temporal analysis of patent legal status and scientific publication



Source: Elaborated by the author.

Of the 151 institutions contributing to scientific production in 2024 – based on English articles indexed in Scopus – 78% were universities and 16% were government actors. This emphasises the key role of academic institutions in advancing research. Research institutes and government entities provide specialised research capabilities and support collaborations with universities.

Private sector involvement in scientific production, comprising 6% of the institutions, included companies like Shell, Exxon Mobil, Protech Engineering Inc., Aramco and others. Protech itself has featured R&D collaboration with Korean universities, while others have mainly offered financial, instrumental and knowledge support. Though smaller, their role is relevant, driving applied research, pilot projects, and commercial applications. This aligns with global R&D trends where private sector innovation increasingly shapes progress. Companies in this sector are expected to address technical and logistical risks in hydrogen supply, which present safety, environmental, and cost challenges.

The increase in pending applications since 2021 may be linked to the trend of formulating or re-formulating national hydrogen strategies. It was first observed in Japan (December 2017), Republic of Korea (January 2019), New Zealand (September 2019), and Australia (November 2019), and intensified in 2020 with Norway (June 2020), European Union (July 2020), Portugal (August 2020), Spain (October 2020), Chile and Italy (November 2020), France and Canada (December 2020) (IRENA, 2024a).

Publications intensified with 12 national strategies launched in 2021 (Morocco, Paraguay, Slovak Republic, Hungary, Czech Republic, United Kingdom, Luxembourg, Colombia, Poland, South Africa, Sweden, and Denmark), 11 in 2022 (Croatia, China, Austria, Uruguay, Costa Rica, Belgium, Oman, Singapore, Namibia, Netherlands, and Trinidad and Tobago), and 17 in 2023 (India, Estonia, Finland, Panama, Türkiye, Bulgaria, United States, Ecuador, Germany, Ireland, United Arab Emirates, Sri Lanka, Algeria, Argentina, Kenya, Malaysia, and Indonesia) (IRENA, 2024a). Until September 2024, at least 58 governments approved strategies for hydrogen deployment, including Viet Nam, Tunisia and Brazil (Brazil, 2024a; IRENA, 2024a; IEA, 2025a).

Low-carbon hydrogen promotion through public policies positively impacts the patent horizons by means of financial incentives, innovation subsidies, and a shift in global perception, thereby encouraging private investment and market development. This policy scenario sets important regional target markets for hydrogen projects, some with more than half of their countries with initiated hydrogen strategies, such as Latin America (8 out of 12) and Europe (23 out of 44).

A review of the global political landscape revealed the following national technological priorities related to low-carbon hydrogen: France initially focused on industrial decarbonisation via electrolysis, direct use in heavy-duty vehicles, and pipeline infrastructure development; Germany aims to redesign and expand its pipeline infrastructure while diversifying end-users (e.g., industrial, vehicular, aviation, and maritime); Japan seeks to enhance industrial processes and promote broad vehicular applications; Republic of Korea, similarly, prioritises vehicular applications, with an emphasis on FCEV production and expansion of refuelling networks and bus fleets, although it faces regulatory hurdles related to safety that affect station supply; Australia concentrates on exports, particularly in connection with the decarbonisation of transport and chemical industry (ANP, 2024).

The legal status of the analysed patents suggests low technological maturity, positioning technological advancements in hydrogen-related SCRM at an early stage of development and innovation. Although the proportion of inactive patents is low, it is not possible to infer the quality of the patents analysed. The high proportion of pending patents (75.49%), the absence of expired patents and the low average age of granted

patents (3.13 years) indicate a technological field in the process of consolidation, where innovations are still under testing and market competition.

4.2.2 Meso and micro analyses

Categorised taxonomies and terms (**Table 3**), derived from technological prospection, were applied to construct the roadmap layers and are considered essential factors related to low-carbon hydrogen SCRM. Each information source could be classified under one or more taxonomies, and within each taxonomy, it may correspond to one or more terms. Some documents lacked sufficient detail for classification under specific taxonomies.

'Market' layer maps potential economic impacts of selected scientific studies. 'Focus' taxonomy reflects research purpose, including: 'Cost-effectiveness' (economic viability and cost reduction); 'process efficiency' (low energy consumption, heat recovery, energy savings); 'environmental-friendly' (low emissions, recycling/reuse; 'quality control' (hydrogen purity); 'operational safety' (accident and physical risks prevention); 'reliability' (consistent system performance); 'stability' (regular operations despite demand shifts); 'risk mitigation' (reducing vulnerabilities and uncertainties along the supply chain); 'equipment failure' (mechanical failures, deterioration); 'scalability' (expansion potential); and 'optimisation' playing a central role in maximising efficiency and minimizing resource use. 'Application' taxonomy highlights major hydrogen uses. 'Scalability' taxonomy categorises supply chain solutions as: 'Domestic' (local supply within one country); 'small to medium scale' (intra-continental trade); 'large scale' (mass production for intercontinental trade, above 10 t/day or equivalent); 'modular' (portable, off-grid uses); and 'flexible operations' (adaptive production and storage).

'Product' layer maps key inputs, outputs and auxiliary systems in the hydrogen supply chain, considered essential for efficient expansion. 'CCUS' is classified as an output for CO_2 disposal. Likewise, 'Technology' layer maps key production, transport, storage processes, and risk mitigation strategies. 'Risk mitigation strategy' taxonomy includes actions ensuring safety, reliability and efficiency, such as 'emergency response planning' for incidents and potential disruptions, 'continuous monitoring systems' for real-time tracking, and 'leak detection', 'predictive maintenance' and 'failure prevention

systems' to address risks before they occur, preventing costly breakdowns and production delays. 'Process safety control' protects personnel, while 'operational risk management' encompasses broader risk identification and mitigation across the supply chain, including equipment failure, financial losses, regulatory compliance and resource shortages. 'Quality assurance and regulation' ensure adherence to safety, quality standards and specific regulations.

Table 3 – Layers, taxonomies, and terms for the roadmap horizontal axis

Layers	Taxonomy (meso)	Terms (micro)
Market (know-why)	Focus	Cost-effectiveness, Process Efficiency, Environmental-friendly, Quality Control, Operational Safety, Reliability, Stability, Risk Mitigation, Equipment Failure, Scalability, Optimisation
	Application	Gas-to-grid, Vehicle fuel, Fuel cell, High-Purity Hydrogen Production, Renewable Energy Integration, Zero-Emission Production
	Scalability	Domestic, Small to Medium scale, Large scale, Modular, Flexible Operations
Product (know-what)	Outputs	Green and Low-Carbon Hydrogen, By-products, Green Ammonia, Hydrates, LOHC, CCUS
	Supports & Inputs	Electrolysers, Reformers, Storage Tanks, Safety Devices, Sensors and Monitoring Equipment, Offshore platform (supports); Wind Energy, Solar Energy, Biomass, Methane (inputs)
Technology (know-how)	Production process	Alkaline Electrolysis, Proton Exchange Membrane Electrolysis, Solid Oxide Electrolysis, Steam Methane Reforming, Steam Natural Gas Reforming, Biomass Gasification, Photofermentation, Dark Fermentation
	Transportation and storage process	Pipeline Transport, Road and Railway Transport, Maritime Transport, Carrier Transport and Storage, Cryogenic Storage, Compressed Gas Storage, Geological or Solid Storage
	Risk mitigation strategy	Emergency Response Planning, Continuous Monitoring Systems, Leak Detection, Quality Assurance and Regulation, Operational Risk Management (or Risk Mitigation), Process Safety Control, Failure Prevention Systems, Predictive Maintenance

Source: Elaborated by the author.

Beyond physical and financial risks, the transition to a low-carbon economy presents climate-related risks to be considered when planning decarbonisation strategies. **Table 4** summarises the risks identified by Carlson and Trencher (2024) for national decarbonisation goals, grouped into seven categories (geophysical, environmental-

ecological, technological, economic, socio-cultural, institutional, and geopolitical). This Kyoto University study, financed by Japan Society for the Promotion of Science, highlights that broader interdisciplinary perspectives on decarbonisation through hydrogen are often overlooked. "Decarbonisation risks" refers to any adverse consequence that a proposed technology, resource, or end-use might present to national-scale decarbonisation efforts (Carlson; Trencher, 2024).

Table 4 – Framework of decarbonisation risks for national hydrogen economy

Category	Risk	Description
Geophysical	Water availability	Significant water requirement for hydrogen production
	Fossil or renewable resource availability	All methods require sufficient energy input
	Critical minerals availability	Electrolysers and fuel cells require materials as nickel, zirconium, platinum, yttrium, and vanadium.
	Geological conditions suited to carbon storage	CCUS requires local or regional storage (with CO_2 transport)
	Land availability	Low-carbon hydrogen requires more space, especially in green sets, due to renewable electricity demand
Environmental-ecological	Lifecycle GHG emissions	GHG (e.g., CO_2 and NO_x) and other influencing gases emissions
	Non-GHG environmental impacts	Indirect harms may affect social and political acceptance
Technological	Carbon capture's scalability and deployment	Few projects have scaled, depending on large-scale deployment
	Fossil fuel lock-in	CCUS policies may prolong fossil dependence
	Physical safety	Hydrogen is explosive and corrosive, while carriers (e.g., ammonia, methanol) may pose toxicity and exposure issues
	Reliance on unproven technologies	Many supported technologies lack proven scalability
	Infrastructure build-out requirements	Massive infrastructure demands (e.g., pipelines) may delay or derail decarbonisation
	Recyclability of end-of-life materials	Efficient system design can reduce mineral use while maximizing recyclability
Economic	Exposure to volatile prices for & on fossil fuels/emissions	CCUS depends on volatile fossil markets and carbon pricing
	Misdirection of financial resources to stranded assets	“Galapagos syndrome”, investing in limited-use technologies may waste funds, especially with short-lived transition plans (e.g., coal-ammonia, natural gas-hydrogen cofiring plants)

	Effects on other hydrogen markets and sectors	Existing markets (e.g., chemicals, fertilizers) must decarbonise, as increased demand for low-carbon hydrogen may disrupt prices and efforts
	Supply and demand creation	"Chicken-egg paradox", both supply and demand must be created, considering no pre-exiting market
	Delayed diversification in fossil regions	CCUS systems sustain fossil employment, delaying environomic shifts
	Cost competitiveness	Hydrogen is often most expensive than direct electrification or demand reduction
	Resource efficiency	Hydrogen systems present high energy losses compared to direct fossil and renewable energy use, raising total energy demand
Socio-cultural	Public acceptance	Perception of safety, cost, and sustainability shape uptake
	Distributional income effects of technology choices	Who benefits from hydrogen may affect acceptance, with dominance by large corporations raising concerns
	Social disruption from economic changes	Changes to employment, infrastructure, energy stability, and lifestyles may influence public outlook
	Domestic equity and justice concerns	Affordability and sustainability will drive public support or opposition
Institutional	Industry capture	Fossil industries may steer hydrogen policy to their benefit
	Offshoring and carbon leakage	Imports must count embodied carbon to prevent false progress
	Regulatory capacity	Hydrogen requires strict safety, emissions, and transport standards, enforced by strong regulatory bodies.
	Dichotomous perceptions of need for government intervention	Politicising national decarbonisation efforts through "picking winners" may cause political backlash
Geopolitical	Trade disruptions	Global trade could rely on fragile supply chains, similarly to fossil fuels, risking disruptions during disasters or conflicts
	International cooperation for standardisation	International and shared standards are essential for trading and decarbonisation
	International equity and justice concerns	Equity concerns in resource extraction will persist, especially with cross-border carbon storage
	Geopolitical realignments	Hydrogen trade may shift countries' status as energy importers or exporters, increasing geopolitical competition

Source: Carlson; Trencher (2024).

4.2.3 Vertical analysis

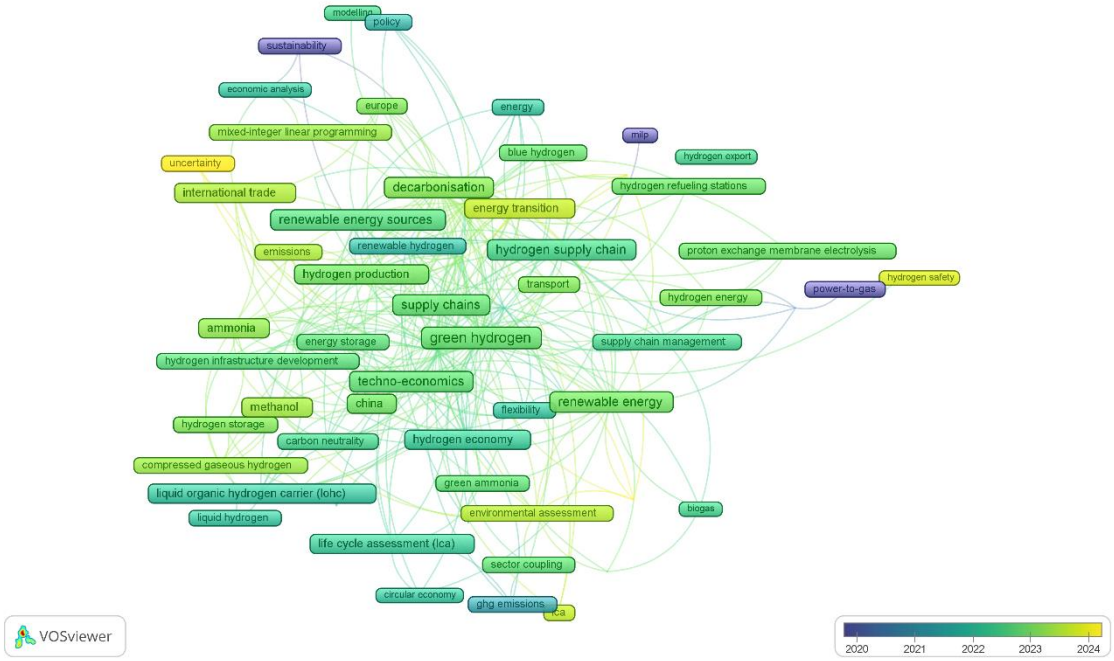
4.2.3.1 Current stage

From the 167 articles selected in the pre-prospective step, most were from the United States (15%), the United Kingdom (13%), Germany (13%), China (13%), South Korea (10%), Italy (9%), and the Netherlands (7%), considering all publication countries. United States presented more publications in partnership with Germany, United Kingdom, Netherlands, Canada, and China. Brazil presented six collaborations on three papers, partnering with Switzerland, Iran, Austria, South Korea, Saudi Arabia, and China. These studies focused on complete low-carbon hydrogen chain, green ammonia and hydrogen for mobility applications, and maritime transport of liquefied hydrogen for energy consumption reduction (Barros *et al.*, 2024; Hunt *et al.*, 2023; Moura *et al.*, 2024). Scientific output from Brazil is expected to grow with the launch of the National Low-Carbon Hydrogen Policy in August 2024 (Brazil, 2024a).

Author's keyword co-occurrence (**Figure 7**) provides precise and reflective insight into study content. A total of 568 keywords were found, of which 67 presented three or more occurrences. 'Optimisation' was mainly linked to cost-effectiveness, renewable energy integration, and CCUS. Recent partnerships between the United States and Republic of Korea, and Chinese research have focused on uncertainty in international trade and variable demand, including optimised supply chain planning and ammonia application (Kim *et al.*, 2024; Xu *et al.*, 2024).

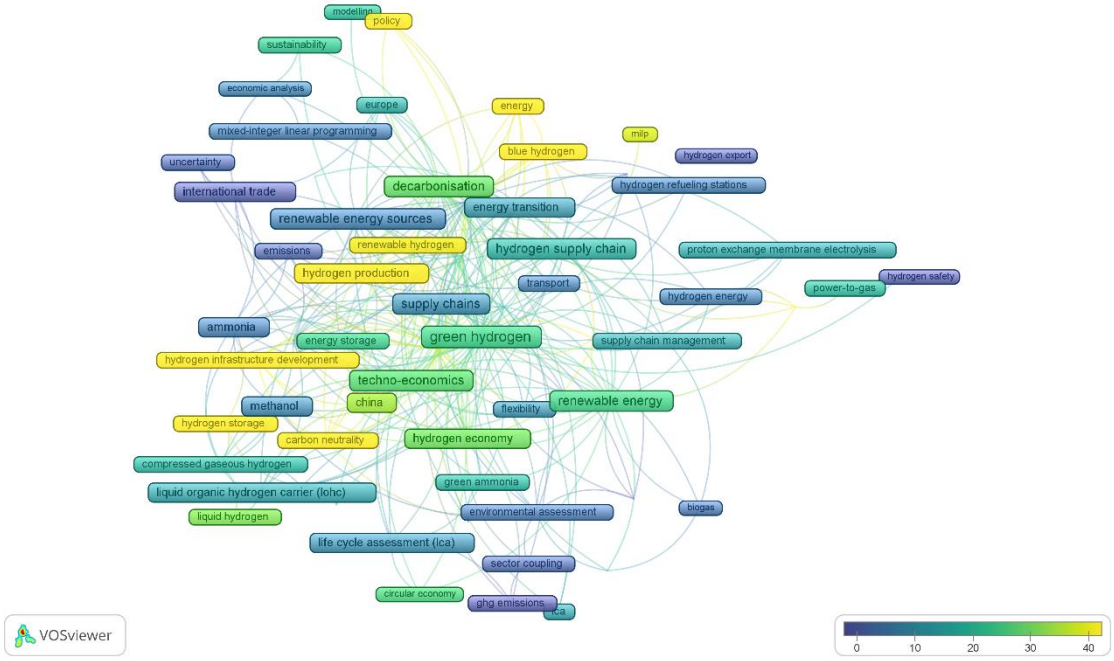
Figure 8 shows keyword co-occurrence in recent hydrogen SCRM research, emphasising average citations from 2020 to 2024. Keywords links indicate co-occurrence, while node colour reflects average citation of the keywords, with yellow meaning higher impact. 'Techno-economics', 'life cycle assessment', 'programming' and 'policy' reflect broad interdisciplinary approaches across economics, regulatory, and socio-environmental segments (Akhtar *et al.*, 2023; Alghool *et al.*, 2024). Besides terms with expected high frequency, 'circular economy', 'MILP' and 'flexibility' stand out, highlighting the importance of flexible logistics in managing demand fluctuations and the recyclability of components (Lahnaoui *et al.*, 2021; Wolf *et al.*, 2024; Clematis *et al.*, 2023).

Figure 7 – Author's keywords co-occurrence



Source: Compiled by the author with VOSViewer.

Figure 8 – Recent research interest by average citations of keywords co-occurrence



Source: Compiled by the author with VOSViewer.

Systematic literature review supported the technological prospection for low-carbon hydrogen SCRM. **Table 5** summarises the ten PRISMA-included articles, mostly

experimental (N=9) and one review (N=1), covering cross-disciplinary themes (N=10). Investigated supply chain stages included processing (N=10), production (N=9), storage (N=8), transport (N=7), fuel stations (N=1) and recycling (N=2). Main technologies addressed were LOHC dehydrogenation (N=9), hydrogen compression/liquefaction (N=8), hydrogenation (N=7), and electrolysis (N=6). 'Processing' covers compression, liquefaction, hydrogenation and dehydrogenation. Products analysed were compressed (N=9) and liquefied (N=8) hydrogen, LOHC (N=9), and ammonia (N=4), with one occurrence for methanol, metal hydrides, and CCUS.

Sustainability (N=10) was the focus, followed by cost-effectiveness (N=6) and optimisation (N=4). Minimising infrastructure costs requires selecting optimal logistics tailored to specific production and demand scenarios. Localised hydrogen production is preferred to reduce transport distances and costs, especially in low-demand scenarios (Lahnaoui *et al.*, 2021). Ideal transport and storage modes vary with distance and regional product and infrastructure availability. Strategic planning must account for local dependencies and cross-border exchanges, as flexible logistics mitigate demand fluctuations and distance variability (Wolf *et al.*, 2024; Lahnaoui *et al.*, 2021).

Compressed hydrogen presents lower energy demand (117-125 MJ/km) than liquefied hydrogen (133-139 MJ/km), but above 52,300 kg/day, 350-bar transport becomes less cost-effective due to low volumetric density, requiring more investments in vessels and control devices (Erazo-Cifuentes *et al.*, 2022; Reuß *et al.*, 2019). Liquefaction increases volumetric energy density despite cooling costs, offering advantages in safety, cost and scalability for large-scale applications (Erazo-Cifuentes *et al.*, 2022). Liquefied hydrogen is more favourable than LOHC for long-term storage, preferably when renewable energy is more abundant. Owing to major costs and energy losses concentrated during charging, cost-effectiveness of large-scale liquefied hydrogen systems depends on managing boil-off rates (Narayanan *et al.*, 2022).

LOHC is compatible with crude oil infrastructure and beneficial as seasonal energy storage, whereas compressed hydrogen suits short-term use (e.g., weekly cycling), with viability tied to energy consumption and capital costs (Zhang *et al.*, 2022; Narayanan *et al.*, 2022). Inflation management is recommended in LOHC-based chains to mitigate cost volatility effects (Godinho *et al.*, 2023). Hydrogen recirculation for dehydrogenation heat supports energy efficiency and global warming potential (GWP) reduction (Akhtar

et al., 2021). Ammonia requires smaller ships than liquefied hydrogen for equivalent hydrogen, with mandatory pre- and post-processing stages including purification (Seo *et al.*, 2023).

Diesel trucks exhibit superior performance in human toxicity and eutrophication impact categories over 100-400 km, in the proposed scenario compared to LOHC and compressed hydrogen pipelines (Wulf *et al.*, 2018). Pipelines demand high capital but offer efficient supply and the lowest GWP (1.57 kg CO_2-eq/kg H_2) for compressed hydrogen, plus the best results in acidification and particulate matter categories (Brigljević *et al.*, 2020; Wulf *et al.*, 2018). Urban pipeline networks benefit from scaling with fuelling stations, while trucks serve sparsely populated areas more cost-effectively (Reuß *et al.*, 2019). Logistic mode selection depends on spatial data on regional demand and resource availability.

Optimisation models are recommended for aligning risk strategies since they holistically address environmental and economic impacts throughout the supply chain (Ibrahim; Al-Mohannadi, 2023). A sustainable hydrogen supply chain relies on CCUS integration, carrier development, and improved recyclability of material-based storage solutions (Clematis *et al.*, 2023). Prioritising carbon reduction aligned with renewable directives can unlock investment subsidies and reinforce long-term sustainability goals (Godinho *et al.*, 2023).

Table 5 – Main characteristics and results of the ten selected articles

Source	Countries	Research purpose	Key findings
Brigljević *et al.* (2020)	Republic of Korea	Strategy evaluation for improved dehydrogenation and clean power generation via SOFC.	Temperature cascade dehydrogenation increased energy output per unit mass (kWh/kg LOHC) by 1.3–2 times in integrated system compared to stand-alone.
Akhtar *et al.* (2021)	South Korea, Pakistan	Cradle-to-gate LCA of seven hydrogen delivery pathways.	Pipeline-transported compressed hydrogen showed the lowest GWP. LOHC had the highest with 35% of GWP reduction potential (3.58 to 2.34 kg CO_2-eq/kg H_2) by partially utilizing the produced hydrogen for dehydrogenation heat.
Godinho *et al.* (2023)	Portugal, Netherlands	Cost and carbon footprint assessment of imported renewable	Under carbon tax and specific policy scenario, LOHC became viable, with logistic costs (2030 – 2050) reducing to 0.30-0.37 €/kg-

		hydrogen via LOHC maritime shipping.	H_2 for dibenzyl toluene-perhydro-dibenzyl-toluene (DBT-PDBT) and 0.28–0.34 €/kg-H_2 for toluene-methylcy-clohexane (TOL-MCH).
Wolf *et al.* (2024)	Germany	Techno-economic analysis of renewable hydrogen transport from Norway, Spain, and Morocco to Germany by 2050 via levelized cost evaluation.	Compressed hydrogen pipelines had lowest costs (0.08–1.34 €/kg), preferred over liquefied hydrogen (1.73–3.40 €/kg) and LOHC (2.33–7.29 €/kg).
Erazo-Cifuentes *et al.* (2022)	Colombia	Optimal renewable hydrogen supply chain design for Colombian transport sector, with economic analysis and 2030 projections.	Best alternative involved wind-powered alkaline electrolysis with compressed hydrogen at 350 bar. Compressed hydrogen and liquefied hydrogen required higher capital investment than LOHC, leading to greater total cost per kg H_2.
Lahnaoui *et al.* (2021)	Germany, France	Georeferenced optimal transport infrastructure for France and Germany, based on wind potential and mobility demand at 2030/2050 penetration levels.	At low demand, low- and medium-pressure hydrogen is preferred for lower energy requirements. High demand favours high-pressure compressed hydrogen and larger trucks, reducing transport distances. Distributed production lowers infrastructure costs, especially in low-demand cases, where total costs rise with flow and distance variability.
Seo *et al.* (2023)	Republic of Korea	Hydrogen supply chain design transporting offshore renewable hydrogen to onshore, with Busan port as consumption hub.	Compressed hydrogen chain faces challenges with high-pressure loading and unloading systems. liquefied hydrogen expansion depends on improving liquefaction efficiency and scaling cryogenic vessels.
Ibrahim *et al.* (2023)	Qatar	Optimisation model via Mixed Integer Linear Program (MILP) for hydrogen supply chain design under emissions mitigation policies, minimising network cost.	CCUS integration with renewables can reduce emissions by up to 90%, even under uncertain demand. Ammonia transport was 19% cheaper than other carriers.
Clematis *et al.* (2023)	Italy	Review on hydrogen carriers and the extreme operating conditions of pressure (300–700 bar) and temperature (T < −252 °C).	Carrier selection is a multiparametric function that depends on technological factors, policies and regulations.
Stöckl *et al.* (2021)	Germany, Australia	Energy efficiency and flexibility trade-off analysis for the German power sector and four options for filling hydrogen stations via open-source co-optimisation.	Liquefied hydrogen presented the best efficiency, flexibility, and investment cost, followed by LOHC and compressed hydrogen. Large-scale solutions reduce

	renewable intermittency effects, while small-scale electrolysis is recommended for lower demand and scarce renewable energy, offering efficiency gains but limited flexibility.

Information from specialised media on SCRM associations complemented the systematic review, comprising websites and reports. Media sources included International Organization for Standardization (ISO) and International Electrotechnical Commission (IEC), and intergovernmental organisations represented by the International Energy Agency (IEA) and International Renewable Energy Agency (IRENA). IEA Bioenergy Task 45 (Sustainability and Climate Impacts) evaluated the risk-based approach of Brazilian Biofuels policy 'RenovaBio' in reducing land-use change emissions (IEA, 2024b).

IEA Bioenergy Tasks 33 e 44 explore flexible and integrated bioenergy systems, including hydrogen from biomass gasification and e-methanol from captured CO_2 for carbon-neutral shipping (IEA, 2022b; IEA, 2025a). Other practices are fuel-flexible gas turbines developed by Siemens Energy in Sweden, hydrogen from ethanol reforming for buses in Brazil – by the University of São Paulo, Hytron, Shell, Raízen and Serviço Nacional de Aprendizagem Industrial (Senai) – and hydrogen-rich syngas produced from biomass gasification in Austria and Thailand (IEA, 2024c).

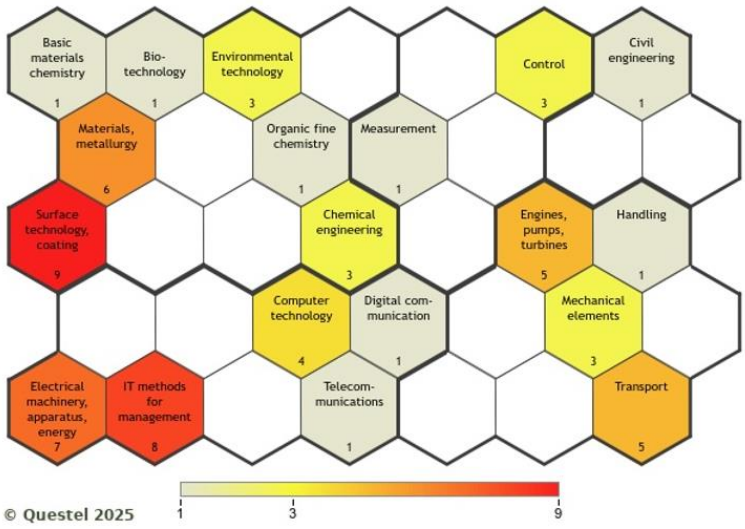
Adopting and adapting international standards ensures global compatibility, safety and efficiency. ISO and IEC have several SCRM-relevant committees: explosive atmospheres (IEC TC 31), control and protective devices for gaseous and liquid fuels (ISO/TC 161), high-pressure systems (ISO/TC 161/WG 5), gas cylinders (ISO/TC 58), energy (ISO/TC 301) and environmental (ISO/TC 207) management, hydrogen technologies (ISO/TC 197) and fuel cells (IEC/TC 105) (IRENA, 2024b). A participatory activity on these committees enables standard launch or revision, essential to energy transition resilience. Fuel quality (ISO 14687:2019), water electrolysis generation (ISO 22734:2019), fuel tanks (ISO 16111:2018), and fuel cells (IEC 62282 Series) are already standardised, while specific social/environmental standards and real-time sensor calibration are still under development (IRENA, 2024b). ISO/TC 197 published ISO 19880-9:2024 and ISO 19885-1:2024 on fuel quality and fuelling protocols for mobility (IEA, 2024a).

Current findings provide empirical evidence that optimising supply chains serves as a preventive strategy against economic and technological uncertainties, e.g. trade shifts and demand fluctuations. A parallel global regulatory convergence is observed towards strengthening supply chain resilience and reducing risks, reinforcing the need for integrated quantitative tools aligned with environmental and geopolitical variables.

4.2.3.2 Short-term

Considering that patents may involve one or more technological domains – based on International Patent Classification (IPC) codes (WIPO, 2009) – , the main domains addressed in granted patents were: surface technology and coating (14.3%), data processing systems or methods for management (12.7%), electrical machinery and energy apparatus (11.1%), transport (7.9%), metallurgy (7.9%), and non-electrical engines, pumps and turbines (7.9%) (**Figure 9**). This reflects a short-term focus on planning, managing and controlling risks from power availability in multi-source (e.g., solar, wind, hydropower) energy complexes, with machine learning and historical-data-based decision applications.

Figure 9 – Technology domain of granted patents



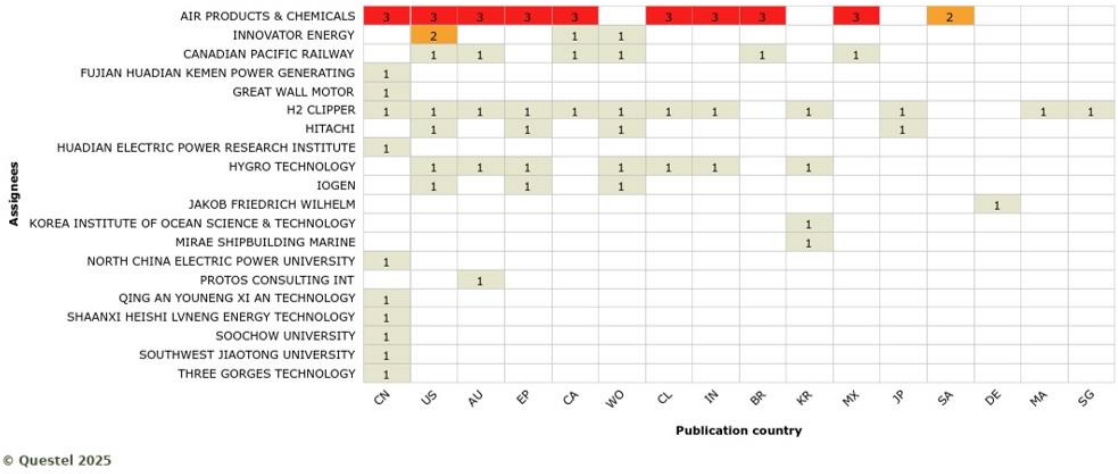
Source: Compiled by the author with Orbit Intelligence.

Patent coverage by protection country tends to be more comprehensive than that by publication country, since many countries (e.g., France, United Kingdom, Italy, Sweden, Belgium, Luxembourg, Netherlands and, recently, Germany) do not republish

patents originating from the European patent route (Questel, 2021). Patents by Air Products and Chemicals (protecting multiple target markets) and three Chinese companies (only national protection) (**Figure 10**) claimed systems (method and/or apparatus) capable of addressing renewable energy intermittency and enhancing plant efficiency through resource optimisation.

Another identified trend within analysed patents was electrolysis improvement via direct current converter for stability (Hygro) and 3D-printed electrodes (Soochow University) for better catalyst performance and durability (Hygro, 2025; Jiang *et al.*, 2023). Canadian Pacific Railway claimed a fuel-cell electric locomotive – with Brazil, Canada, Australia, Mexico and the United States as target markets – and H2 Clipper focused on pipeline retrofitting by inserting a monitored inner pipe into existing pipelines – protected in twelve countries, besides World Intellectual Property Organization (WIPO) and European offices (CPKC, 2023; H2 Clipper, 2022).

Figure 10 – Assignees of granted patents by publication country

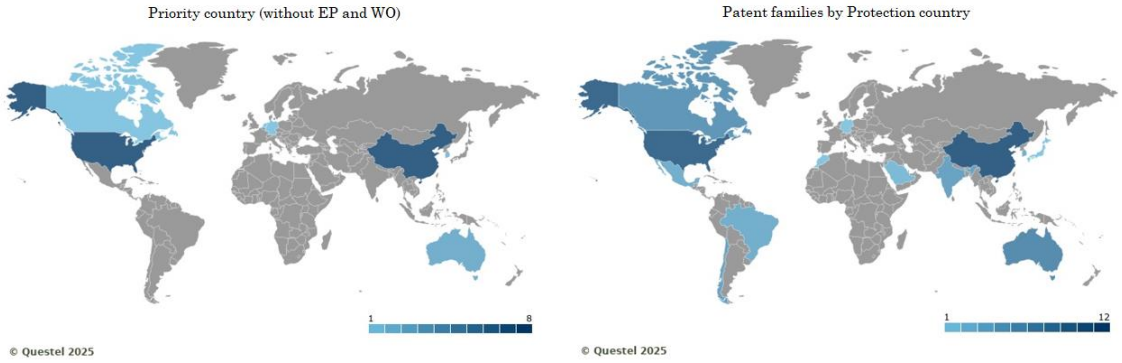


Source: Compiled by the author with Orbit Intelligence.

The distribution of protection countries (**Figure 11**) reveals the strategies of assignees in the sector analysed, as national filings indicate markets where intellectual property is needed for exploration, commercialisation and technology defence. Among active patents (granted), protection is concentrated in China (12), followed by the United States (10), Australia (7), European office (7), Canada (6), Chile (5), India (5), Brazil (4), Republic of Korea (4), Mexico (4), Saudi Arabia (3), WIPO (3), Japan (2), Germany (1), Hong Kong (1), Morocco (1) and Singapore (1). This distribution reflects a protective

focus on Asia, North America, and Oceanian markets, alongside emerging interest in Latin America and the Middle East.

Figure 11 – Geographical distribution of granted patents by priority and protection country



Source: Compiled by the author with Orbit Intelligence.

Priority countries (**Figure 11**) represent where patents were first filed, often reflecting the origin of the invention, as assignees typically prioritise R&D location – although this is not a strict rule. Among granted patents, 31 priority patents were identified, distributed as: China (8), followed by the United States (8), International Office (7), Australia (3), South Korea (2), Canada (1), Germany (1) and the Netherlands (1). This suggests countries like Brazil, Chile, India, the Republic of Korea, Mexico, Saudi Arabia, Japan, Morocco and Singapore have consolidated themselves as target markets for protection, without participation in technology development.

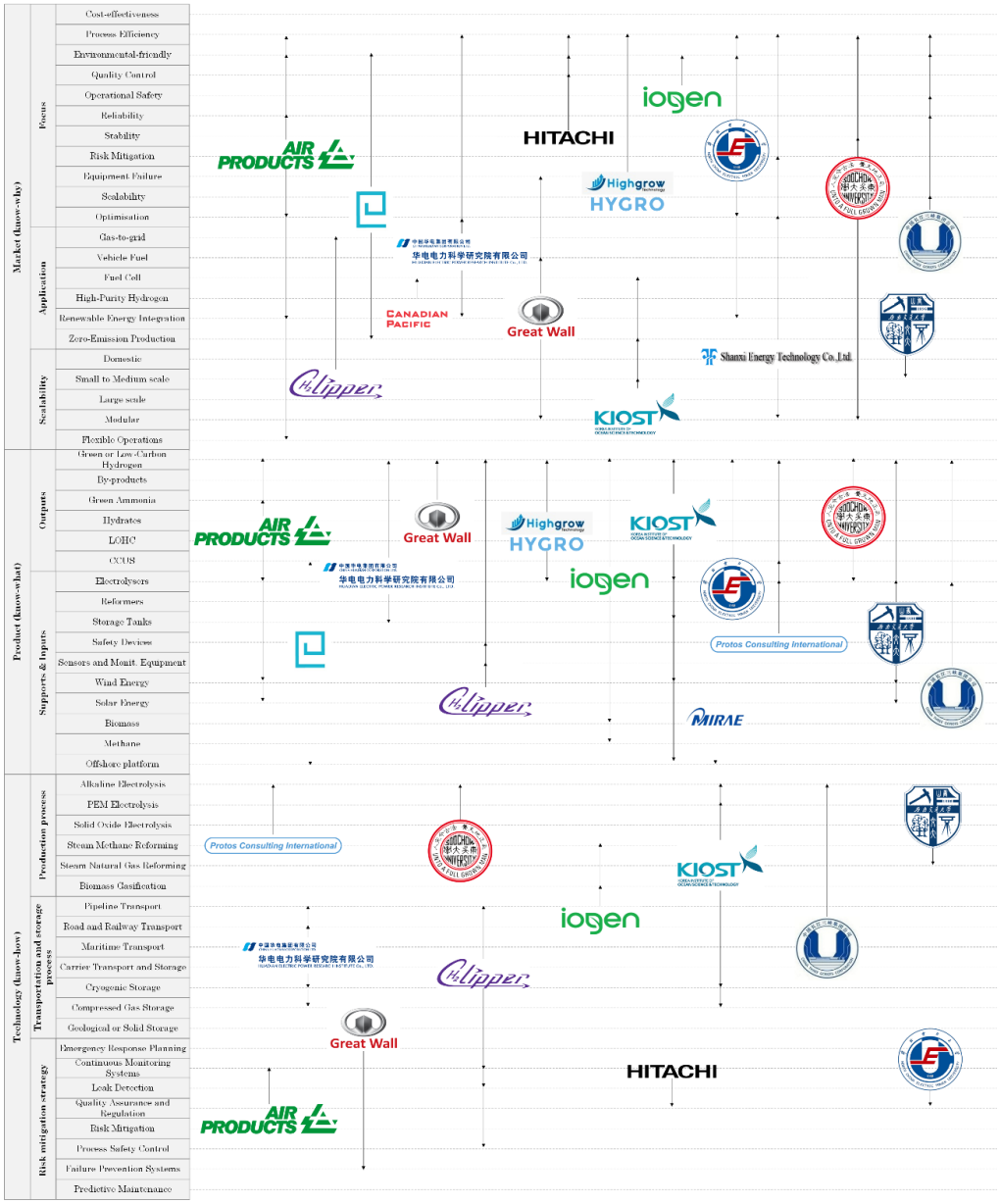
It is noted that the number of priorities is greater than the number of patent families granted. A simple patent family comprises a group of patent applications filed in multiple jurisdictions for the same invention, all claiming priority from one priority filing in other countries within twelve months of the first filing (Clarke, 2018). Priorities often exceed granted patent families as some offices – e.g., the United States Patent and Trademark Office – allow more than one provisional application per family, generating different numbers.

In the short term, few granted patents relate directly to biomass, leak detection, and operational quality. There is clear movement towards infrastructural resilience, with strong participation from energy and transport companies (**Figure 10**). Current and short-term stages reveal persisting gaps: (a) solutions for monitoring and mitigating specific

operational risks, such as leakage; (b) geopolitical impacts on global supply chains, requiring alignment between international policy and SCRM frameworks.

Figure 12 illustrates the market, product and technology sections of 20 granted patent families. Roadmap logos represent companies that assigned one or more patent families, linked to relevant terms with vertical arrows. The vertical axis shows the market, product and technology layers, with corresponding taxonomy terms. It should be noted that individual patent assignees were not illustrated, and that not all patent families contained term across every lawyer, owing to the limited scope of certain patents.

Figure 12 – Short-term roadmap



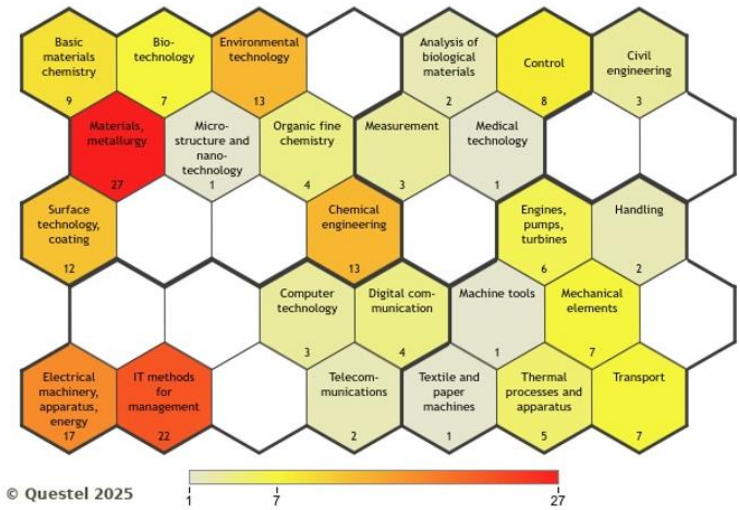
Source: Elaborated by the author.

4.2.3.3 Medium-term

A medium-term trend toward improved SCRM emerges, addressing safety, sensors, and circular economy challenges, despite limited short-term evidence. Growing interest in CCUS and electrolysis is observed. Industrial applications expand, particularly in iron, steel, batteries and recycling. Saft, a TotalEnergies' subsidiary and global battery supplier (Saft, 2025), filed a European patent for the simultaneous recycling of lithium-metal battery electrodes and clean dihydrogen production via hydrolysis. This technology may enable recycling of end-of-life lithium-ion batteries, as already practised by Saft for nickel batteries, yet hydrolysis is still considered immature (Saft, 2019; Chang; Rajuli, 2024). F3nice (Italy) supplies 100% recycled metal scrap for additive manufacturing and claimed a recycled metal alloy – including chromium, nickel and molybdenum – applied for hydrogen environments with improved mechanical properties (F3nice, 2023).

Considering that patents may involve one or more technological domains – based on IPC codes (WIPO, 2009) – , the main domains addressed in pending patents were metallurgy (20.0%), followed by data processing systems or methods for management (16.3%), electrical machinery and energy apparatus (12.6%), chemical engineering (9.6%), surface technology and coating (8.9%), basic material chemistry (6.7%), control and regulation of electrical and non-electrical systems (5.9%), biotechnology (5.2%), and mechanical elements – referring to fluid-circuit elements, couplings, valves, pipeline systems or mechanical control devices (5.2%) (**Figure 13**).

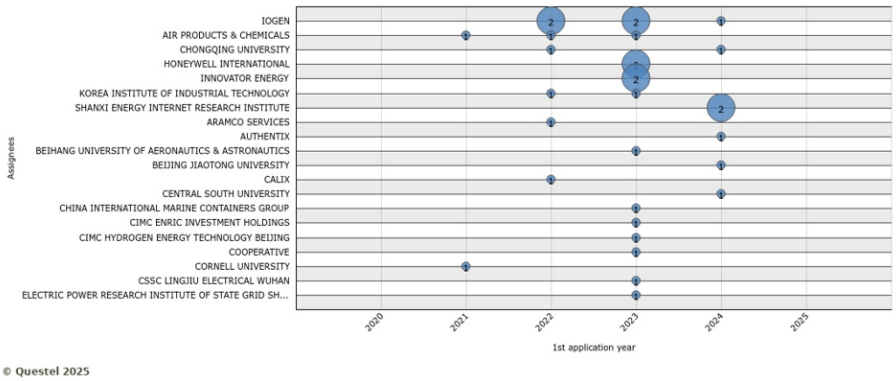
Figure 13 – Technology domain of pending patents



Source: Compiled by the author with Orbit Intelligence.

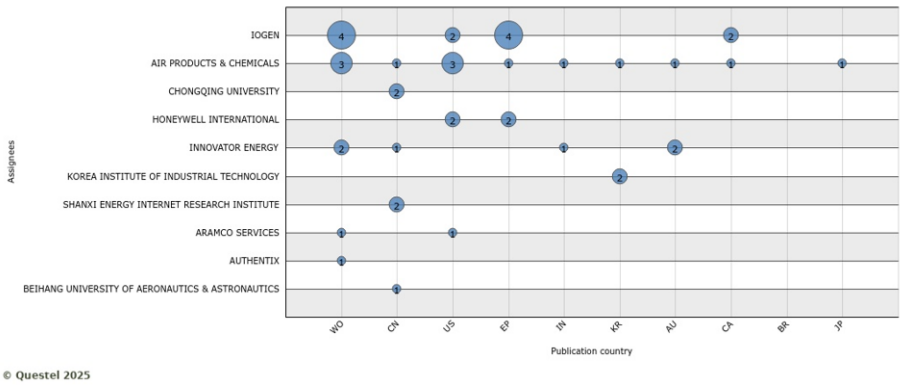
These technologies are undergoing patent examination in different target markets (**Figures 14, 15 and 16**). Iogen, a biofuel expert, is focusing on biomass- and biomethane-based hydrogen with reduced emissions, while Air Products & Chemicals has pending patents on ammonia cracking for hydrogen recovery and carbon intensity management (Iogen, 2025; Air Products and Chemicals, 2025).

Figure 14 – Assignees of pending patents by first application year



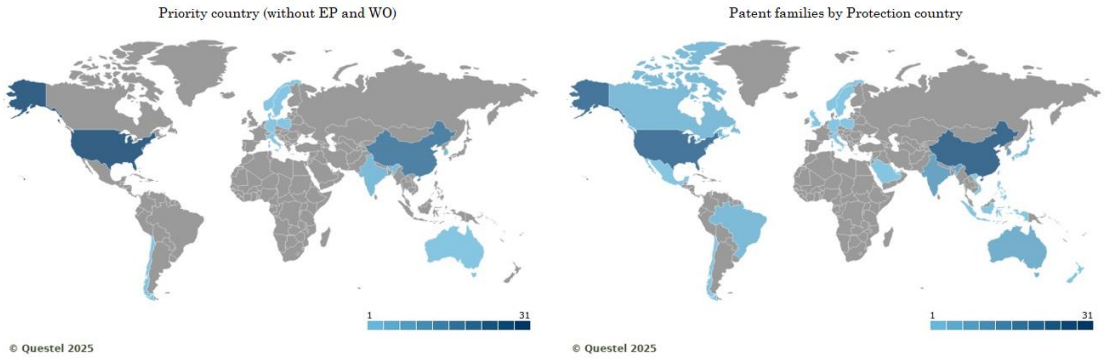
Source: Compiled by the author with Orbit Intelligence.

Figure 15 – Assignees of pending patents by publication country



Source: Compiled by the author with Orbit Intelligence.

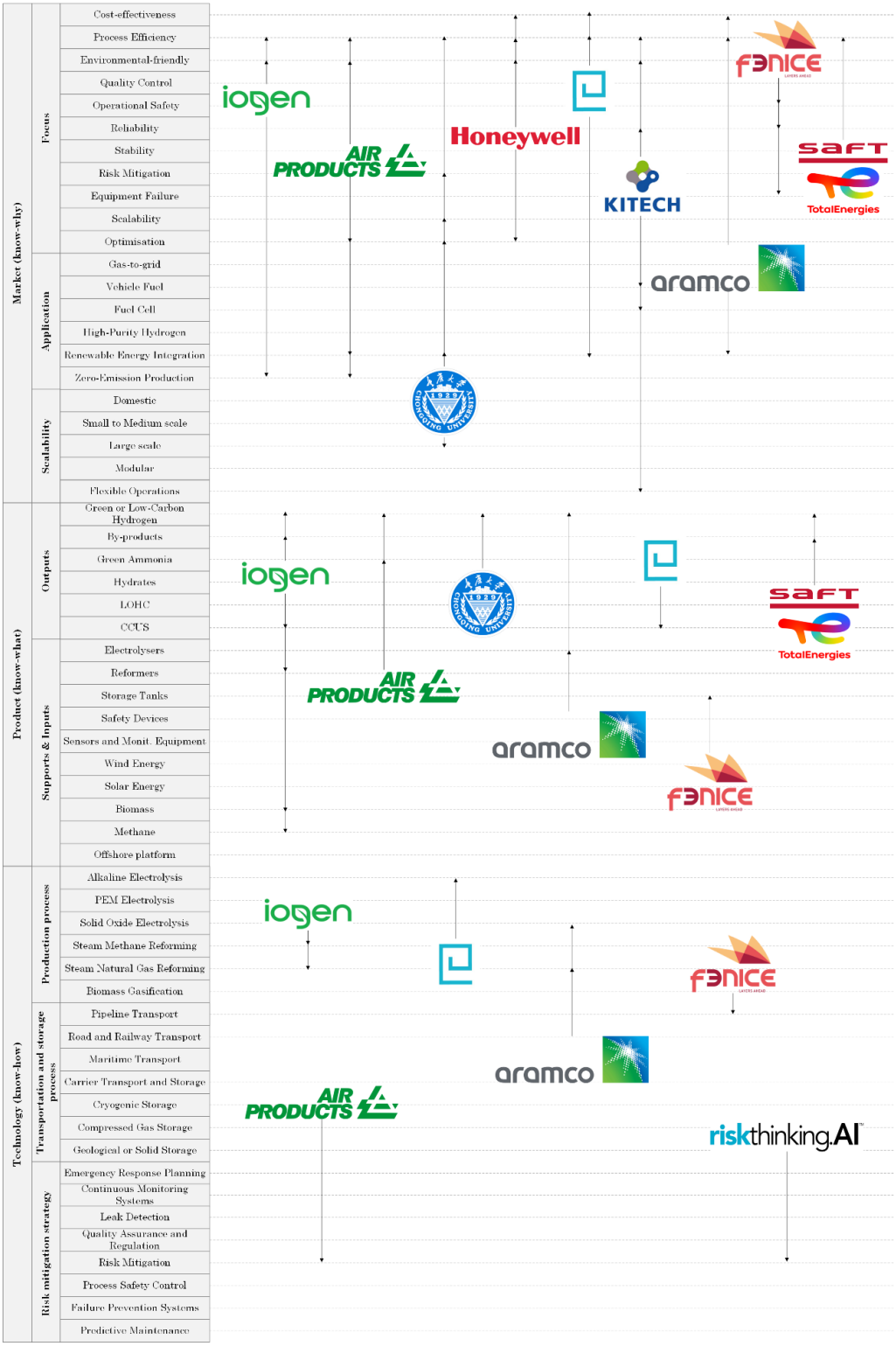
Figure 16 – Geographical distribution of pending patents by priority and protection country



Source: Compiled by the author with Orbit Intelligence.

Figure 17 illustrates the market, product and technology sections of 20 pending patent families. The vertical axis shows the market, product and technology layers, with corresponding taxonomy terms.

Figure 17 – Medium-term roadmap



Source: Elaborated by the author.

Air Products & Chemicals is investing in control systems for carbon intensity management, while RiskThinking AI claimed models for climate financial risk based on geographic and temporal data. No direct mention was found of safety control in geological reservoir operations, nor of methods to protect marine fauna in offshore setups (e.g., anchors and turbines).

The distribution of protection countries (**Figure 13**) was concentrated in the European (31) and international (30) offices, followed by China (26), United States (22), India (11), Republic of Korea (10), Australia (7), Canada (5), Japan (5), and Brazil (4). This distribution confirms the protective focus on Asia, North America, and Oceanian markets, with an evolution in European deposits. Priority patents were centred in the United States (31), China (21), international office (17), India (6), Republic of Korea (5), Australia (2), Germany (2), Denmark (2), Italia (1), Chile (1), Norway (1), Poland (1) and Sweden (1).

4.2.3.4 Long-term

Roadmap logos represent institutions, universities, research centres, government agencies, and companies that contributed to or financed the study, linked to relevant terms with vertical arrows. Logos grouped within the black line indicate that the study was funded by one or more stakeholders included in the representation. For example, in **Figure 18**, a University of Zaragoza study financed by the European Union, published in December 2024, investigated the cost, efficiency and sustainability of intra-continental hydrogen trade.

Figures 18, 19 and 20 present the market section, divided into three parts for better visualisation. The horizontal axis represents the timeline, while the vertical axis depicts market, product, and technology layers, with taxonomy terms. The 50 articles analysed were compiled into a long-term roadmap, aiding policymakers in understanding global efforts, collaborating on safety standards, and establishing incentives (Borschiver; Silva, 2016). ‘Focus’ taxonomy quantitative results are discussed later in the horizontal analysis, correlated to other taxonomies.

Companies like Shell, Aramco, WSP and ExxonMobil collaborate with academic and governmental partners. With the resources to deploy and scale hydrogen projects,

they rely on academic and policy support for effective implementation. Private-sector partnerships focus on cost-effective and efficient supply chains via multi-option levelized cost analysis – WSP with Swedish and Dutch institutions – and exergy-return on exergy-investment analysis – Shell with Delft and Stanford University (Kim *et al.*, 2024; Dogliani *et al.*, 2024).

South Korea and China are forming regional and intercontinental alliances to promote hydrogen technology, collaborating with universities, companies, and government agencies from August to December 2024 (**Figures 18** and **19**). Asia's long-term roadmap is heavily focused on transportation cost-effectiveness and sustainability, researching FCEV and battery vehicles for delivery and carriers (e.g., methanol, ammonia, methylcyclohexane) (Karthikeyan; Kumar, 2024; Kumaraswamy *et al.*, 2024; Wan *et al.*, 2024). A private-sector collaboration (ExxonMobil and University of Singapore) focuses on net-zero emission hydrogen network in Southeast Asia, addressing renewable energy intermittency and uneven spatiotemporal distribution (Kumaraswamy *et al.*, 2024).

European research centres focus on clean energy transitions, with institutions in Germany and Switzerland at the forefront in electrolysis, fuel cells, and decarbonising district heating (Ganter *et al.*, 2024). A collaboration (**Figure 19**) between universities from Thailand and Germany, financed by the Energy Sector Management Assistance Program (World Bank), evaluated renewable energy efficiency in Ubon Ratchathani based on geographical, climate, and economic factors (Ransikarbum *et al.*, 2024). The two-phase multi-criteria optimisation framework highlights the value of detailed spatial analysis in hydrogen production decisions.

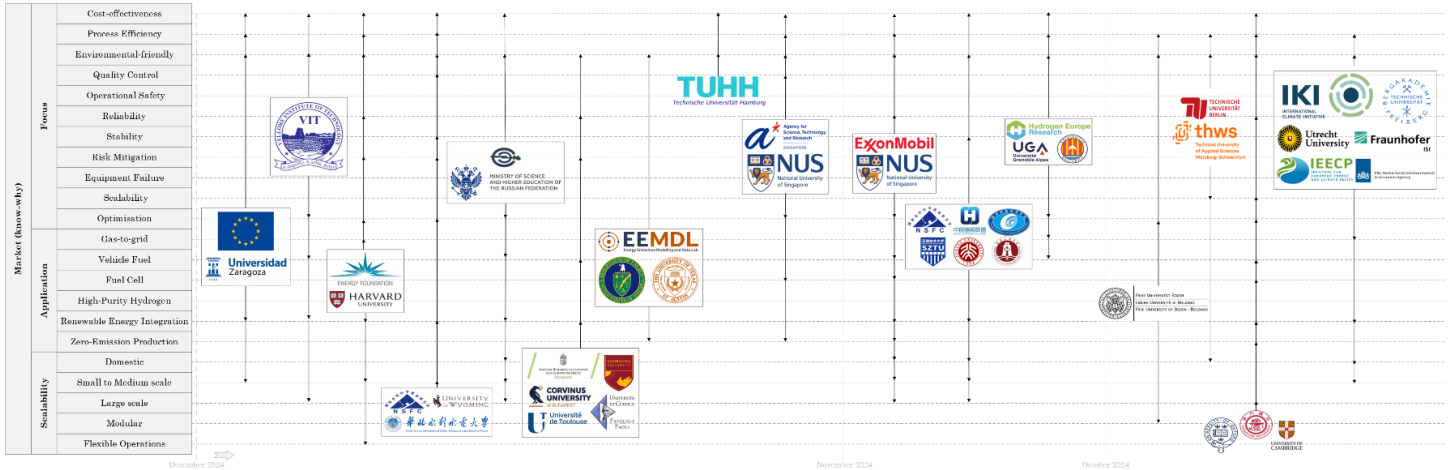
Figures 21, 22 and **23** present the product section, divided for clarity. Studies focused on green and low-carbon hydrogen (47), CO_2 management in CCUS (13), followed by green ammonia (8), diverse by-products management (5), LOHC (3) and hydrates (2), out of the 50 selected articles. Hydrogen produced from fossil fuels with CCUS is expected for medium-term use in energy transition, facing life-cycle efficiency challenges.

Ageing oil and gas assets increase maintenance, interventions, leaks, and fugitive emissions, raising carbon footprints over time (Davies; Hastings, 2023). Methane (CH_4) extraction and production also risk unintended GHG emissions, before and after well

plugging, which must be accounted for. Research on CCUS network design in China employed source-sink matching methods for pipeline development, though challenges arise from large captured CO_2 volumes and the numerous sources and storage sites (Wang *et al.*, 2024). Studies by Mehr *et al.* (2024) and Ganter *et al.* (2024) properly address the technology maturity, advantages and disadvantages of low-carbon hydrogen-associated products and processes.

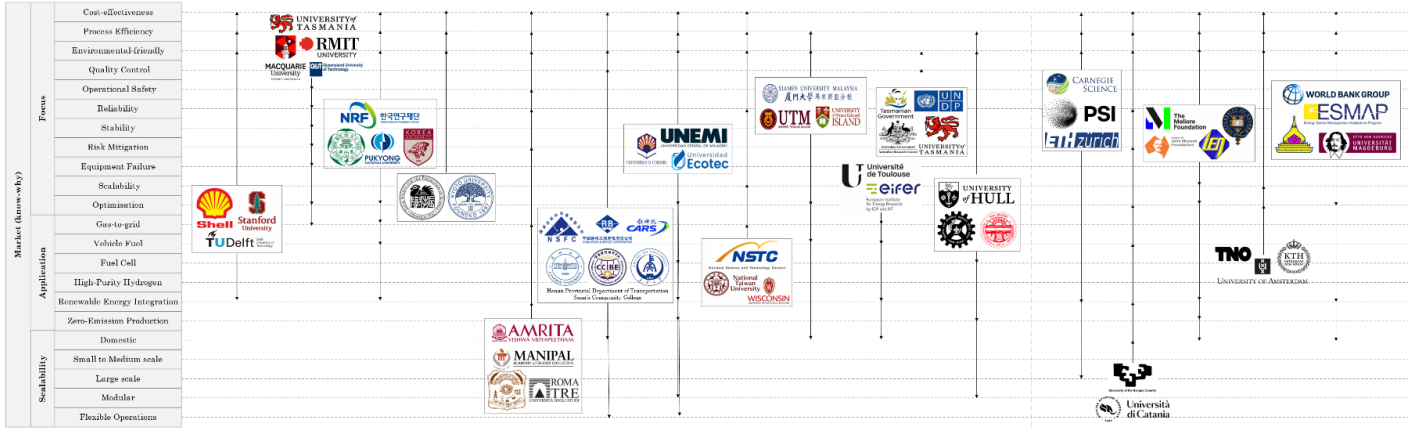
A collaboration from the Republic of Korea, financed by National Research Foundation of Korea (**Figure 19**) integrates artificial intelligence to enhance circularity and decision-making in hydrogen supply chain via hierarchical deep multi-agent reinforcement learning (Song *et al.*, 2024). Authors claim that it can replace mathematical programming with minimal computational demands, uncovering a new economic-environmental trade-off between profit and hydrogen refuelling station cost.

Figure 18 – Long-term roadmap by market section – Part I



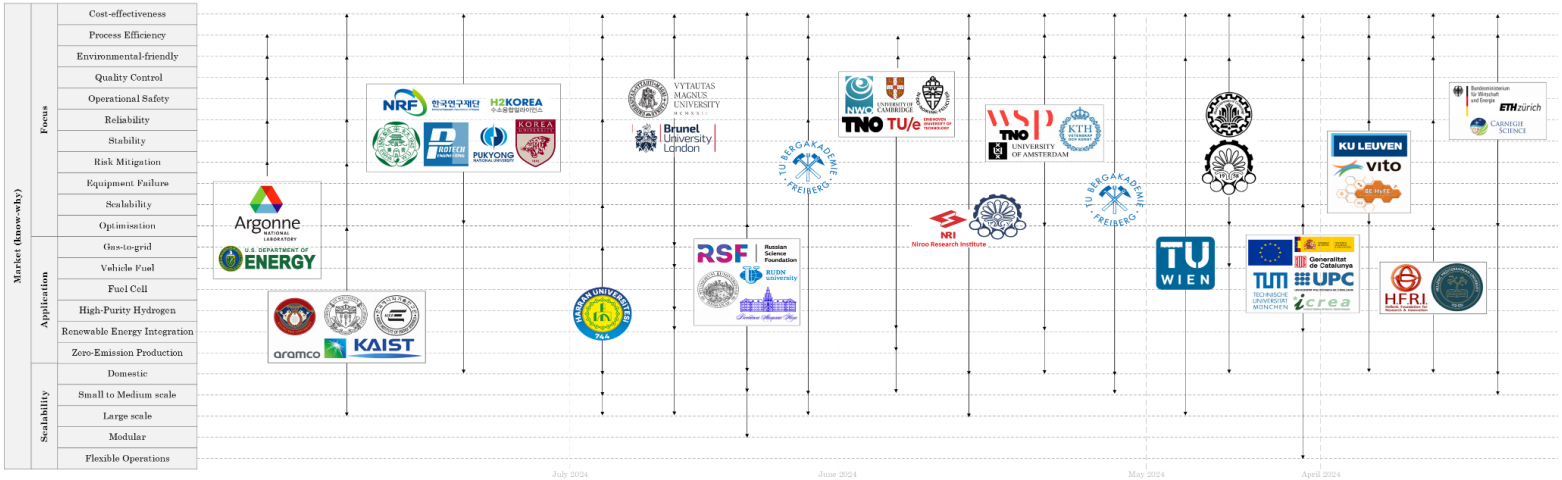
Source: Elaborated by the author.

Figure 19 – Long-term roadmap by market section – Part II



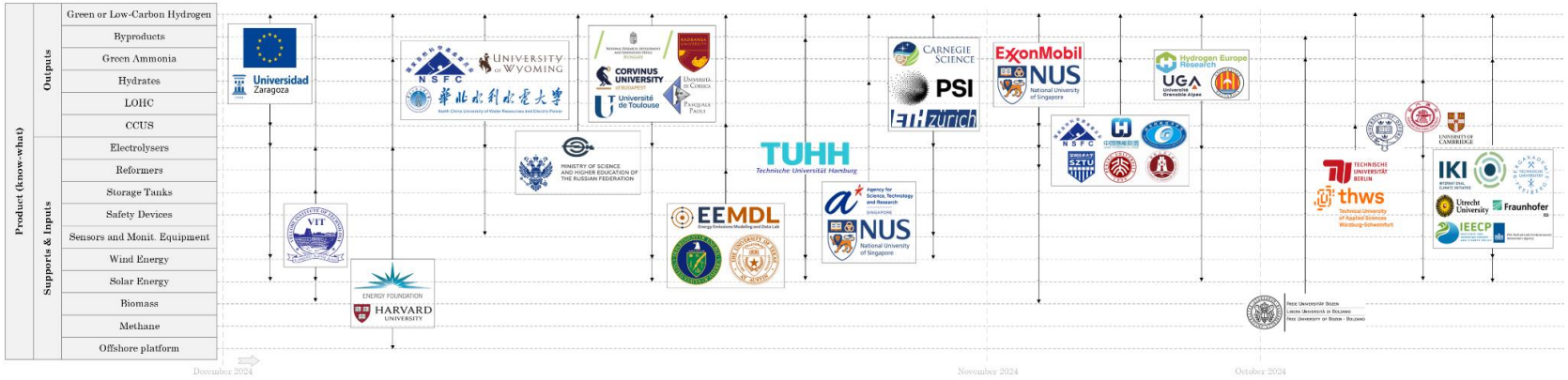
Source: Elaborated by the author.

Figure 20 – Long-term roadmap by market section – Part III



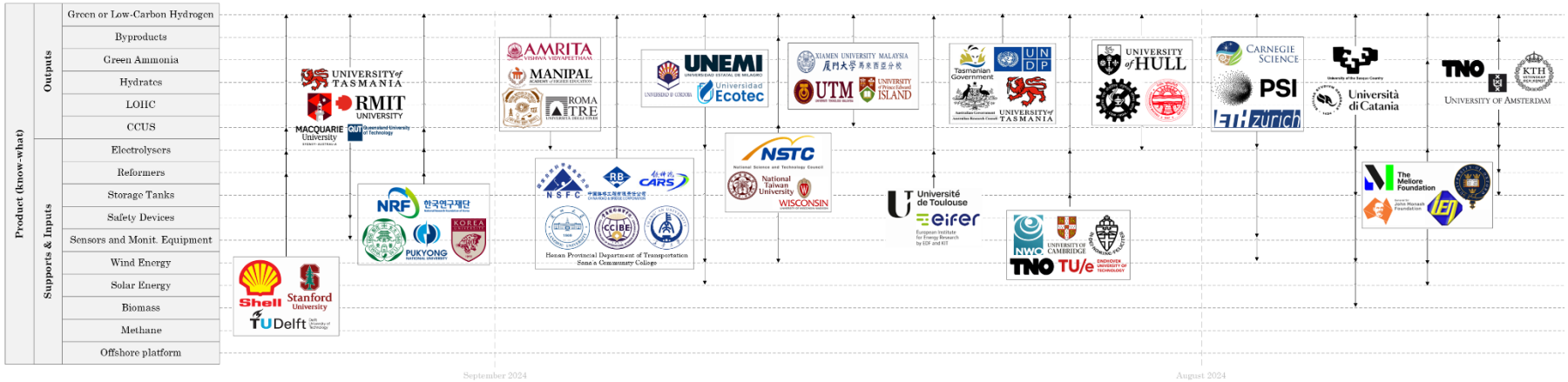
Source: Elaborated by the author.

Figure 21 – Long-term roadmap by product section – Part I



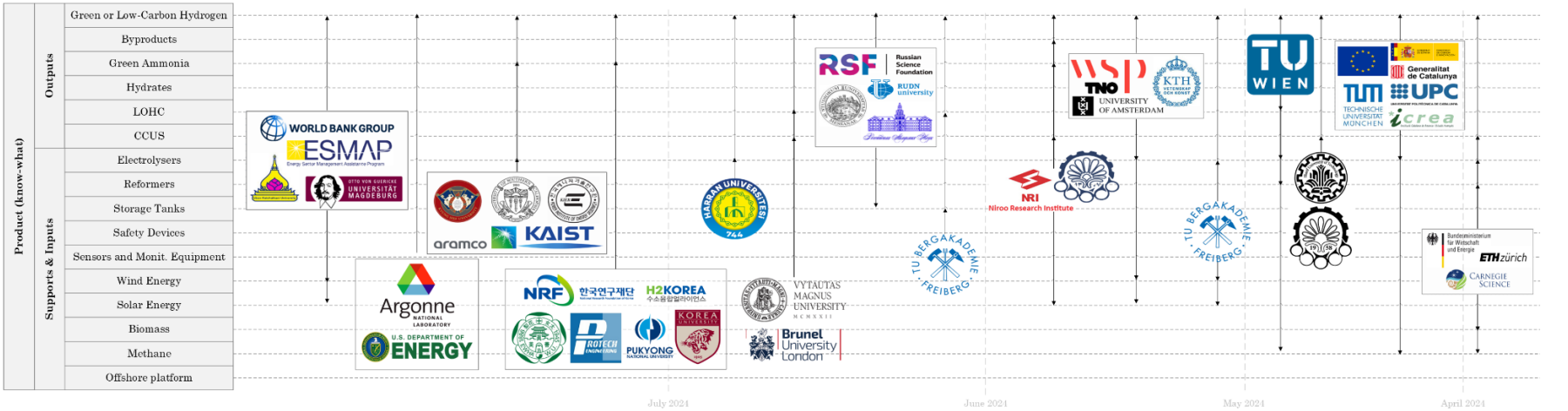
Source: Elaborated by the author.

Figure 22 – Long-term roadmap by product section – Part II



Source: Elaborated by the author.

Figure 23 – Long-term roadmap by product section – Part III



Source: Elaborated by the author.

Figures 24 and 25 illustrate the technology section, divided into two parts for better visualisation, including production, transport, storage and risk mitigation stages. PEM (12) and alkaline (11) electrolysis and steam natural gas reforming (7) with CCUS currently dominate, accounting for most research efforts in hydrogen production from renewables and fossil fuels, followed by steam CH_4 reforming (SMR) (3), SOEC electrolysis (3), and biomass gasification (3). High investment costs and uncertain cost reductions delay expansion (Ganter et al, 2024). Transitional approaches combining oil-based fuels with alternative fuels are anticipated, requiring minimal modifications to existing infrastructure and serving different economic sectors (e.g., food, transport, industrial and heating) (Gonzalez-Garay *et al.*, 2022). 'Photofermentation' and 'dark fermentation' were not depicted in **Figures 24 and 25** for a cleaner visualisation since none of the selected articles focused on these production technologies.

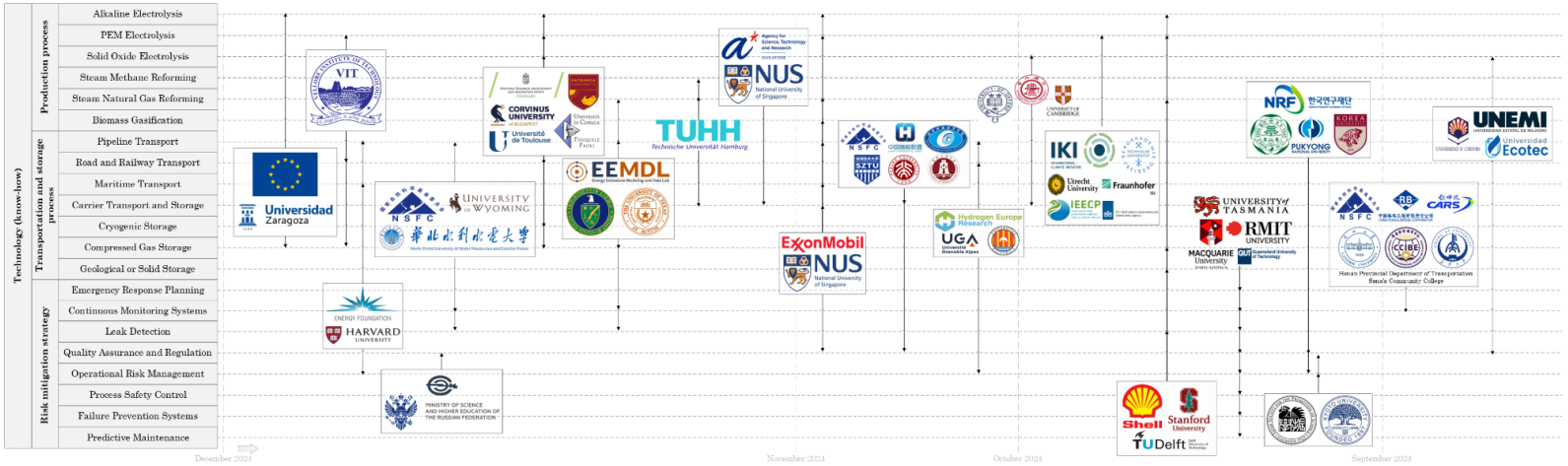
Electrolysis struggles to rival the cost-efficiency of other methods, such as biomass-based hydrogen production (Ganter *et al.*, 2024). In addition, LCA reveals that PEM technology has a higher environmental impact than alkaline type – which requires fewer and less impactful materials – due to reliance on platinum catalysts (Lotrič *et al.*, 2021). Davies and Hastings (2023) stress the importance of accurate monitoring and verification systems for carbon storage facilities to ensure that CO_2 remains securely stored and that all GHG emissions, particularly fugitive CH_4.

'Transportation and storage' taxonomy results revealed a growing interest in pipeline (11), maritime (7) and terrestrial (6) transportation, including road and railway routes. Regarding reliable technology for transportation, though generally more expensive than pipelines in high-demand scenario, trucks present a cost-efficient solution in the short-term while pipeline networks, expected to dominate in the future, are still under development. Ganter *et al.* (2024) have demonstrated that truck-based transport enables rapid scaling of hydrogen delivery capabilities using existing infrastructure.

Hydrogen storage technologies remain diversified, encompassing several hydrogen carriers (11) – including ammonia, methanol, TOL-MCH and DBT-PDBT –, followed by compressed (10), cryogenic (5) and solid-state or geological (2) storage. The United States deployment of 950-bar cylinders could accelerate Type V tank adoption (Mehr *et al.*, 2024). Hydrogen purification is a critical step to achieve the requisite purity of over 99.97% after dehydrogenation, necessary for many mobility applications. Widely

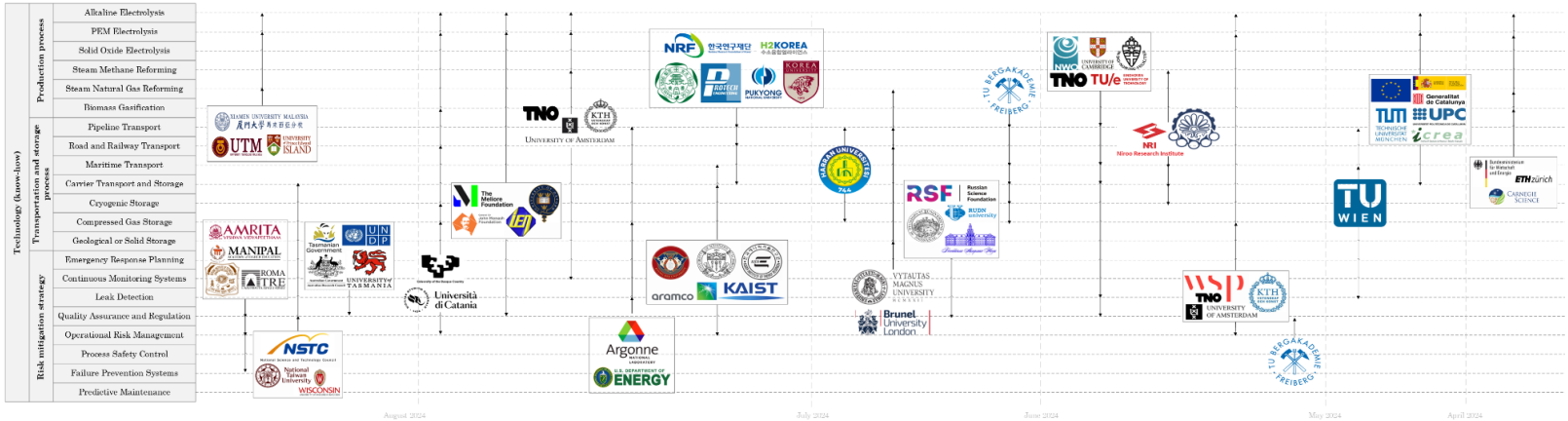
used methods include pressure swing adsorption, cryogenic separation, and membrane separations (Gonzalez-Garay *et al.*, 2022).

Figure 24 – Long-term roadmap by technology section – Part I



Source: Elaborated by the author.

Figure 25 – Long-term roadmap by technology section – Part II



Source: Elaborated by the author.

Karthikeyan and Kumar (2024) proposed a multi-objective supply chain optimisation including a polygeneration system using solar and biomass energy sources, with PEM hydrogen production unit for refrigerated trucks in India's fish supply chain. The system achieves 17.6% energy efficiency, 9.3% exergy efficiency, and reduces CO_2 emissions by 2 tonnes per day, with a payback period of 2.76 years. This solution requires 7,000–19,000 m² of solar panels and 0.08–0.21 kg/s of seaweed waste, highlighting the need for spatial resolution in diverse supply chains. Sufficient space and radiation for solar farms and a steady biomass supply are essential for effectiveness.

Spatial resolution in hydrogen development is gaining attention within decarbonisation efforts. It refers to the geographical detail in planning, influencing site selection (for production, infrastructure development, and resource allocation) by considering regional factors (e.g., renewable energy availability, transport distances and CO_2 storage locations), enhancing cost-effectiveness and decision-making. Wang *et al.* (2024) proposed an advanced CCUS-based supply chain framework integrating a source-sink model, meshing module, and transport optimisation to minimise costs in mega-scale networks. It uses a high-resolution database of carbon sources (power, steel, cement plants) and CO_2 storage sites (unminable oil fields, saline aquifers), enabling integrated CO_2 capture, compression, transport, utilisation, and storage management. Carlson and Trencher (2024) shift the focus from "how" hydrogen contributes to decarbonisation to "where" it can be utilised most effectively to minimise risks associated with emission reductions.

Ganter *et al.* (2024) investigate the cost-optimal planning of low-carbon hydrogen supply chains in Europe for the near-term period (2025–2035). The study evaluates multiple production technologies (e.g., SMR, biomass gasification and electrolysis), examining the effect of spatial resolution at regional and national levels. Incorporating additional regional data, such as hydrogen demand, resource availability, and transport distances, can lead to substantially different, more cost-effective hydrogen supply chain configurations (Ganter *et al.*, 2024). Integrating advanced optimisation frameworks and spatially aware models is essential to the efficient design and operation of low-carbon hydrogen supply chains, particularly through better planning and resource allocation at multiple scales, from plant-level decisions to regional and national infrastructure planning.

'Risk mitigation strategy' taxonomy results indicated that regulation and certification (14), reducing vulnerabilities and uncertainties along the supply chain (9) and leak detection (8) are the focus of the selected studies. It represents the impact of global mobilisation on climate policies formulation and expected progressive decarbonisation goals. Continuous monitoring systems (4), process safety control (2), emergency response planning (1), failure prevention systems (1) and predictive maintenance (1) received less academic attention. A collaboration among Australian universities in October 2024 (**Figure 16**) revealed the largest number of terms linked to risk mitigation strategies, outlining challenges and opportunities in developing safe and sustainable hydrogen supply chain (Patel *et al.*, 2024). After an evaluation of various types of failure related to poor management, human and technical error in hydrogen infrastructure, Patel *et al.* (2024) compiled thirty-four learned lessons and recommendations, highlighting the variability of facilities, summarised in **Table 6**.

Table 6 – Learned lessons, recommendations and major causes of hydrogen-related accidents from H2tool dataset

Failures	Accidents	Lessons (L1 to L34)
Poor management	11%	
Failure to manage the safety of operations adequately		• Avoid multitasking while filling hydrogen and follow strictly guidelines (L1).
		• Disconnect all lines (except inert gas) while compressing hydrogen (L2).
		• Conduct routine maintenance to avoid incidents (L3).
Failure to learn from accidents and near-misses		• Built protection wall around high-pressure storage to reduce fire/explosion impacts (L4).
		• Implement component Life-Cycle Management Plan (L5).
Failure to adequately respond to the accident		• Ensure competent staff present during hydrogen unloading (L6).
		• Ensure accurate communication for safe and efficient operation (L7).
Failure to be adequately prepared to respond to the accident		• Implement annual exercises to assess staff readiness (L8).
Failure to identify risks		• Label equipment with design parameters (material, pressure, temperature, etc.) (L9).
		• Define procedures and responsibilities for maintenance, construction, and operations (L10).
Post-accident emergency response program		• Evacuation procedures involving all working people before operation (L11).
		• Check emergency notification system regularly (L12).

		• Inspect fire suppression system before operation (L13).
Failure to provide adequate staff training		• Safety training to all members working on the site (L14). • Provide site-specific delivery procedures safety checklists (L15).
Human error	10%	
Failure to follow standards		• L1. • Apply hazard labels to samples and packages (L16). • Develop oversight processes to minimize construction errors (L17).
Failure to show competency during incidents		• L14 and L15. Provide manuals with correct steps of connecting or disconnecting (L18).
Failure to identify risks		• Avoid long-term storage of hydrides and promptly dispose after use (L19). • Trains operators to respond properly, i.e., contacting engineering support and evaluating risks (L20).
Failures to start a job with appropriate procedures		• Inspect high-pressure fuelling systems daily for external damage (L21). • Monitor pressure, temperature and vibration at startup to avoid thermal hazards (L22).
Failure to recognize and react to early warning		• Use gas analyser to detect gas purity/mixing (L23).
Technical error	31%	
Failure to calibrate equipment		• Calibrate all electrical devices (L24).
Failure to provide intrinsic safety of the infrastructure		• L14. • Obtain design safety approval before implementation (L25). • Check ventilation and gas detectors before operation (L26).
Failure to perform accurate investigations before implementing them into the real world		• Thoroughly simulate procedural changes (L27). • Identify inspection deficiencies and conduct second-part review (L28).
Failure to capture gas concentration		• Place gas detectors near any high-pressure components (L29).
Failure to open/close valves upon pressure and temperature variation		• L22. • Monitor hydrogen pressure visibly from a safe distance (L30). • Ensure balanced equipment capacity to avoid cascading failures (L31).
Failure to choose materials/facility according to design parameters		• Two ventilation fans in confined facilities, one continuous, one triggered when 1% H_2 concentration is reached (L32). • Verify software/hardware performance based on design parameters (L33).

		• Select materials per environmental and design parameters to avoid embrittlement (L34).
Multiple causes (human, management and technical)	48%	

Source: Adapted from Patel *et al.* (2024).

Long-term results highlight that regional detail enhances infrastructure planning and resource allocation, driven by the convergence of SCRM and geoprocessing, which enables new spatial optimisation methods for risk mitigation. Mitigation strategies should prioritise root causes (technical, human, and managerial) based on detailed diagnosis of hydrogen system vulnerabilities.

4.2.4 Horizontal analysis

Each granted patent was linked to one or more relevant terms from the meso analysis (**Table 3**), which term occurrences are quantitatively described here by technology and product taxonomies. Leading technologies in the granted patents included operational risk management systems (27.3%), alkaline electrolysis (18.2%), natural gas reforming (9.1%), followed by biomethane reforming, biomass gasification, pipeline retrofit, hydrogen-fuelled trains, continuous monitoring system, leak detection and quality assurance tied with 4.5%. Products included low-carbon hydrogen (40.9%), electrolysers (22.7%), solar/wind energy (18.2%), offshore platforms (9.1%), carbon capture (9.1%), followed by reformers, safety devices, monitoring sensors, biomass and biomethane tied with 4.5%.

Analysing the occurrence of terms defined in the meso analysis, leading technologies in pending patents were related to operational risk management (42.9%), monitoring (29.9%), quality assurance (24.7%) and failure prevention (15.6%), compression/liquefaction (11.7%), hydrogen carriers/SMR (10.4%), pipelines/natural gas reforming (9.1%), truck transport (7.8%), and biomass gasification (6.5%). PEM (3.9%) electrolysis drew slightly more attention than SOEC and alkaline, tied with 2.6%. Products included low-carbon hydrogen (62.3%), electrolysers (29.9%), storage tanks (26.0%), solar energy (24.7), carbon capture (22.1%), sensors and monitoring equipment (18.2%), wind energy (18.2%), methane (15.6%), biomass (14.3%), other by-products (13.0%), green ammonia (10.4%), and reformers (10.4%). Less focus on safety devices

(6.5%), LOHC (1.3%), desalination (2.6%), and offshore platforms (1.3%), and stable performance of natural gas compared to short-term were observed.

All selected articles presented terms from the 'focus' taxonomy, applied in this section to interpret recent scientific trends in low-carbon hydrogen SCRM. As expected, studies prioritised green and low-carbon hydrogen production, focusing on cost-effectiveness, followed by sustainability, efficiency, optimisation, and reliability. Scalability and reliability are key concerns for electrolysers, with growing interest in optimisation and no studies on their failure.

Solar and wind energy were most linked to scalability, while biomass and biomethane received less attention, with no studies on quality control, operational safety or stability. Though viable, biofuel reforming was not associated with renewable ethanol or glycerine, as CH_4 and natural gas prevailed. Biomass-based low-carbon hydrogen is currently recognised as complementary route to electrolysis, despite limited reflection in long-term research. Hydrogen production from urban/agricultural biomass remains underexplored regarding optimisation, efficiency, and scalability. Stability was linked to sensors and monitoring equipment, leak detection, quality assurance and regulation, as continuous monitoring and regulatory stability mitigate environmental-ecological, economic, and institutional risks.

Among 38 articles on hydrogen cost-effectiveness, 29% cited carriers – transport, storage and dehydrogenation efficiency –, 24% mentioned pipeline transport, followed by compressed gas storage (18%) – with concerns related to logistics and reliability –, maritime (16%) and road and railway (13%) transport in long-term. Cryogenic, geological and solid storage receive less academic attention, possibly due to ammonia/LOHC advancements and solid storage maturity. Underground storage projects demonstrate high recovery rates (e.g., HyStorage in Germany, 90%) and scalability (e.g., HyStock in the Netherlands, 216 GWh capacity), but still need cost reduction and optimisation (Duartey *et al.*, 2025).

Only one study broadly addressed equipment failure and included all ‘risk mitigation strategy’ terms (Patel *et al.*, 2024). Minimal emphasis was given to emergency response planning, failure prevention, and predictive maintenance, revealing a gap in cost-effective and scalable risk mitigation solutions. In other taxonomies, risk mitigation

was linked to electrolysers, pipelines, compressed storage, and green ammonia, reflecting growing concern over supply chain vulnerabilities.

Quantitative results across roadmap stages show positive impacts on mitigating specific decarbonisation risks. Growing interest in integrating renewables, especially solar and wind, with hydrogen production reduces fossil fuel dependence and exposure to carbon market price volatility. While often linked to reducing fossil emissions, which may intensify fossil fuel lock-in, advances in CCUS improve land use and scalability via underground storage. Optimised biomass integration valorises waste and reduces global landfill GHG risks.

Infrastructure build-out risks are mitigated by pipeline retrofits and monitoring technologies, enhancing networks and limiting new construction. Optimising financial, technological and spatial resources enhances project viability and resource efficiency. Technology selection via optimisation models supports informed comparisons, avoiding politicised 'picking winners'. Advances in safety devices, monitoring, quality assurance and emissions reduction improve public perception, while biomass use and decentralised options boost energy access across regions.

Despite electrolysis focus, water and critical mineral availability (e.g., platinum, nickel) received little attention, as did the risk of prolonged fossil dependence via CCUS, natural gas and thermal processes. Social aspects and human factors remain overlooked, with no approaches addressing fair economic benefit distribution or socioeconomic transitions in the low-carbon hydrogen economy. Geophysical, socio-cultural, institutional and geopolitical risks are underexplored gaps hindering global hydrogen economy progress, demanding greater innovation and research.

4.3 Insights for Brazilian Low-Carbon Hydrogen Policy

Brazil's onshore wind potential is 143–440 GW, while offshore ranges from 57 GW (up to 10 km from the coast) to 1,780 GW (200 miles). Onshore solar potential stands out with maximum irradiation level of 6.2 kWh/m².day and 506 TWh per year, while offshore could reach 94,706 TWh per year (EPE, 2018). Subsidies to enhance electrolyser efficiency and cost align with Brazilian renewable potential, reducing fossil hydrogen reliance in transitional scenarios.

The National Low-Carbon Hydrogen Policy (Law nº 14.948/2024) and Special Incentive Regime for Low-Carbon Hydrogen Production (Rehidro), established in August 2024, offer five-year tax incentives from 2025 for qualified beneficiaries (Brazil, 2024a). The Future Fuel Law (Law nº 14.993/2024), enacted in October 2024, promotes sustainable fuels in terrestrial, maritime, and aerial transportation and sets the CCUS regulatory framework (Brazil, 2024b). In 2022, 70% of global hydrogen production came from natural gas, 30% from coal and less than 1% was low-carbon (IEA, 2023). Hydrogen versatility requires multisectoral demand creation via technology imposition or LCA-based subsidies, enabling a comprehensive distribution network that serves key sectors with economies of scale. Life cycle impacts of large-scale hydrogen storage remain underexplored (Mehr *et al.*, 2024).

Given natural gas dominance, early policy could focus on retrofitting oil infrastructure with CCUS and reforming domestic biofuels (e.g., ethanol and biomethane), until renewable hydrogen becomes economically viable. Pilot funding is expected to showcase feasibility in hard-to-abate sectors, e.g., renewable hydrogen replacing coke in steel production, as noted by the Brazilian National Confederation of Industry (CNI, 2022). Brazil's regulatory cap of 7.0 kg CO_2-eq./kg H_2 produced could gradually align with international best practices (e.g., the United States limit of 4 kg CO_2), driving innovation and competitiveness (ANP, 2024).

In 2022, Brazil's natural gas consumption was concentrated in the Southeast (50.3%), with industry as the largest consumer (65.4%), followed by power generation and co-generation (22.7%) and transport (8.0%) (EPE, 2025). The gas grid extends 9,244 km (8,582 km integrated) – modest compared to the United States (485,751 km) or China (43,452 km). BRL 29.3 billion is allocated to expand it by 2,333.5 km and integrate biomethane (EPE, 2025). Pipelines are concentrated along the coasts, linking key industrial hubs like the ports of Santos and Pecém (EPE, 2014). Large-scale low-carbon hydrogen projects are planned at Pecém (Ceará), Suape (Pernambuco), and Açu (Rio de Janeiro) ports (EPE, 2021).

Technology selection based on regional factors (energy costs, land, renewable potential, and demand) can minimise infrastructure costs (Lahnaoui *et al.*, 2021). At low demand, decentralised production ensures supply with minimal transport variation. As

demand grows, centralised systems face rising transport costs (Lahnaoui *et al.*, 2021). Supporting small-scale models could mitigate supply risks and transport expenses.

Low-carbon hydrogen can be integrated into the circular economy via reforming biogas from agroforestry waste, landfills and wastewater, providing regional economies and sustainability (MME, 2024). Biomethane from biogas does not compete with food production. Besides, biofuels like sugarcane ethanol and soybean biodiesel can reduce carbon footprint via carbon capture from the life-cycle photosynthesis of agricultural resources (ANP, 2024). Organic waste-based hydrogen aligns with the National Strategy of Circular Economy (Law nº 12.082/2024), enacted in June 2024, promoting resource efficiency to preserve material value and finance circular economy (Brazil, 2024c). Recycling critical materials, especially platinum-group metals, reduces environmental impact and virgin material demand (Lotrič *et al.*, 2021). Policies must address end-of-life recycling of electrolysers and storage equipment, contributing to resource availability.

Beyond solid-state and LOHC (ANP, 2024), funding should support compression, cryogenics, high-sensitivity leak detection sensors and real-time monitoring. Improved storage, ventilation, and safety measures mitigate risks in compressed systems and unstable fuelling conditions (Patel *et al.*, 2024). Pipeline upgrades accounting for hydrogen permeability, alongside blending with natural gas for heavy mobility, could bolster energy transition and resilience.

Conclusions

This work aimed to explore the technological and scientific landscape of low-carbon hydrogen via patent and literature analysis, aiming to assess key mitigation strategies to decarbonisation risks across time-based development horizons.

The roadmap reveals a growing synergy between industry, academia, and government to scale hydrogen technologies via cost-effective and exergetic-efficient supply chains. Notable efforts are directed at reducing costs through optimisation models and net-zero strategies across multiple sectors (e.g., industry, food, mobility).

Short-term innovation centres on metallurgy, data systems, and operational risk management, with advances linked to circular economy principles. The medium term emphasises chemical engineering and control systems, supporting risk mitigation across supply chains. In the long term, focus shifts to CCUS, ammonia, and electrolysis, although biomass and recycling remain underexplored. Spatial analysis and regionalised planning emerged as critical for optimising infrastructure, resource allocation, and CO_2 storage deployment.

Growing interest in metallurgy and data processing systems or methods for management from short- to medium-term was observed, with remarkable advances towards a circular economy. Medium-term route suggests technological shifts associated with chemical engineering and control systems. Long-term results suggest broad interest in CCUS, ammonia and electrolysis for low-carbon setups, yet biomass and recycling aspects are not well reflected in this scientific output. Spatial resolution is essential for decarbonisation, guiding infrastructure siting and resource allocation by regional factors (e.g., renewable availability, distances and CO_2 storage locations), emphasising where hydrogen is most effective for emission reduction.

Moreover, flexible and integrated bioenergy systems were also research and intellectual property hotspots, especially in academic investigations and pending patents. The wide-ranging end-use applications reported in roadmap horizons emphasised the effective role of low-carbon hydrogen in industry decarbonisation, particularly across the iron, steel, battery, recycling, waste-to-energy and public transport sectors. A resilient supply chain must account for market fluctuations and

geopolitical risks, relying on national demand creation to overcome the chicken-egg paradox while avoiding short-lived transition plans.

Roadmap results confirmed positive impacts on specific risk sub-categories, particularly within technological and economic domains. Continuous monitoring, pipeline retrofitting, and quality assurance have demonstrably improved infrastructure readiness and cost-effectiveness, while reducing exposure to fossil price volatility and infrastructure expansion pressures.

Model-driven technology selection reduces polarising narratives over state intervention, helping depoliticise policy acceptance and enable balanced decision-making. Advances in CCUS contribute to enhanced land availability and carbon storage readiness, while integration with biomass valorises waste and curbs lifecycle GHG emissions.

Nonetheless, real-time monitoring, electrolyser failure mitigation, and training remain weakly addressed. Electrolyser efficiency, equipment recyclability, and cheaper catalyst development remain pressing priorities. Despite the proliferation of electrolysis-related research, water stress, critical mineral constraints, and fossil lock-in risks remain insufficiently considered. Human-centred design and distributional justice also lag, as do global equity, institutional robustness, and geopolitical resilience.

Future studies should focus on optimising failure prevention, predictive maintenance and emergency response systems, integrating ventilation and obstacle design, and proper training. Biomass and alternative biofuels (e.g., ethanol, glycerine, biogas) as scalable inputs and equipment recyclability, remain underexplored. R&D and funding must prioritise electrolyser efficiency, low-energy processes, and cheaper catalysts for renewable hydrogen, while hydrogen from fossil fuels remains more affordable.

A limitation of this study is that its conclusions are inherently shaped by the selected methodology and the choices made during its application, meaning that alternative but comparable methods might lead to different results.

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Curso: Mestrado em Engenharia de Produção e Sistemas
Título: Technology roadmap of low-carbon hydrogen: Trends for risk management strategies
Autor(es): Danielle Rodrigues de Moraes
Orientador: Ronney Arismel Mancebo Boloy

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