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POWER-TO-GAS (PTG) HYDROGEN FOR CLEAN TRANSPORT: POWER-TO-GAS POLICY, INFRASTRUCTURE, AND STRATEGIES FOR NET-ZERO MOBILITY

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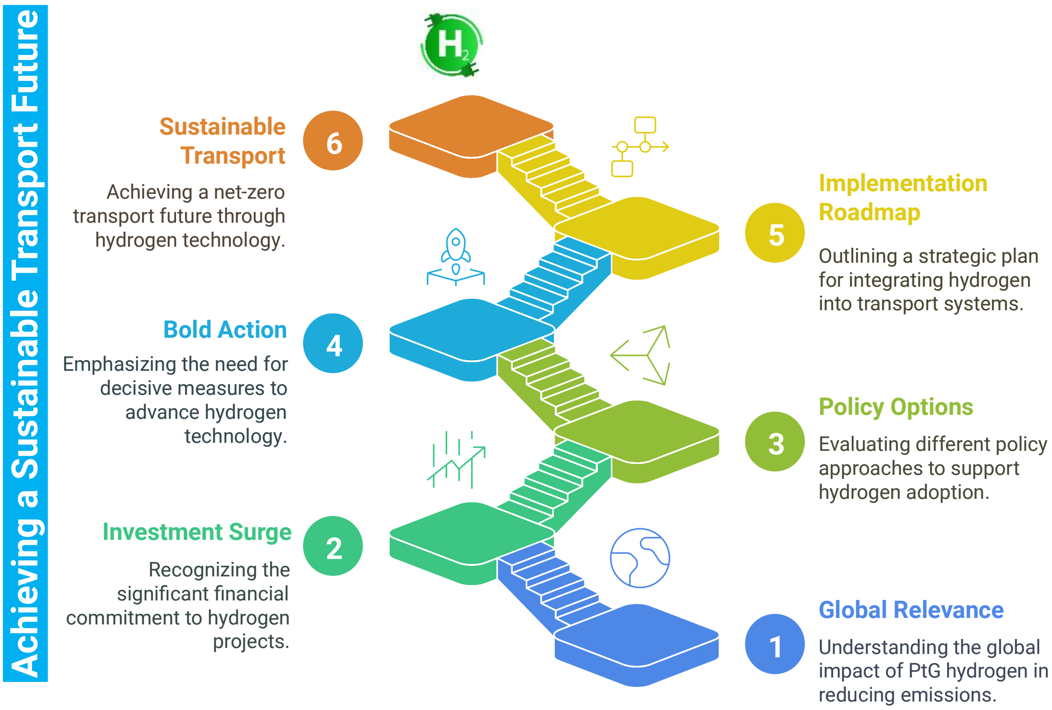
GRAPHICAL ABSTRACT



HIGHLIGHTS

- Power-to-Gas hydrogen framed as a pathway for net-zero transport policies
- Global case studies synthesized into a comparative policy framework
- Stakeholder analysis linked to barriers, enablers, and policy instruments
- Novel three-part contribution: context, SMART recommendations, and roadmap
- Findings stress urgency of policy action to scale investments and avoid stagnation

ABSTRACT

Power-to-Gas (PtG) hydrogen technology, which converts renewable electricity into hydrogen, is increasingly recognized as a pivotal solution for decarbonizing the transport sector. Transport contributes nearly one-quarter of global energy-related CO_2 emissions, and sectors such as heavy-duty vehicles, rail, shipping, and aviation remain difficult to electrify directly. PtG-based hydrogen offers a clean, flexible fuel option for fuel-cell electric vehicles (FCEVs) and hydrogen-derived e-fuels, positioning it as an important complement to direct electrification. This paper addresses the central research question of how PtG hydrogen can be effectively embedded into transport policy frameworks to accelerate decarbonization and unlock economic opportunities. Methodologically, the study combines comparative policy analysis, stakeholder mapping, and synthesis of international best practices. Drawing on case studies from Europe, Asia, and the Americas, the paper identifies both enablers and barriers to PtG adoption. Unlike conventional reviews, this work contributes a structured framework that links global lessons with actionable, measurable, and time-bound policy pathways. The novelty of the paper lies in its integrated three-part contribution: (i) contextualizing international experiences specifically for PtG transport applications, (ii) developing SMART-oriented recommendations—such as corridor-based refueling strategies, contracts-for-difference, and green bonds—that address cost and infrastructure barriers, and (iii) presenting an implementation roadmap that aligns policy instruments with timelines, financing mechanisms, and stakeholder responsibilities. Findings highlight that while more than $100 billion in public funds have been announced for hydrogen globally, project pipelines remain fragile, and strong policy support is required to achieve large-scale deployment. Conversely, bold policy frameworks could enable PtG hydrogen to deliver significant emissions reductions, enhance energy security, and foster industrial innovation. The study concludes with evidence-based recommendations for infrastructure deployment, regulatory alignment, public–private partnerships, and international collaboration. By equipping policymakers with a structured roadmap, this paper positions PtG hydrogen as a cornerstone of sustainable, net-zero transport.

Keywords: Power-to-Gas hydrogen; Green hydrogen for transport; Hydrogen fuel cell policy; Hydrogen infrastructure development; Net-zero mobility strategies; Energy transition and hydrogen; Green hydrogen

1. Power-to-Gas Hydrogen: Decarbonize Transport with Power-to-Gas to Cut 100% Emission

Transporting people and goods reliably without polluting the planet is one of the great challenges of our time. Power-to-Gas (PtG) technology offers a compelling solution by turning surplus renewable electricity into hydrogen gas – a clean fuel that can power vehicles, trains, and even ships [1-3]. PtG uses electrolysis (splitting water with electricity) to produce hydrogen, which can then be used as an energy-rich fuel.

Hydrogen produced via PtG can be used in fuel cell electric vehicles (FCEVs), which emit only water vapor [4, 5]. These vehicles provide long driving ranges and quick refueling, making hydrogen especially attractive for heavy-duty trucks, buses, trains, and marine transport where batteries may be impractical. By storing renewable energy in chemical form, PtG also helps balance the grid and provides a way to utilize excess wind or solar power.

This policy paper focuses on hydrogen for transport applications – examining why it's needed, how it's developing globally, and what policies can accelerate its deployment. We begin with background on the rise of PtG and hydrogen's role in transport, then review key findings from global case studies. We will compare policy options, discuss implications of action or inaction, and finally offer concrete recommendations and an implementation plan. The goal is to inform and encourage: with the right policies, PtG-based hydrogen can become a cornerstone of clean transport, driving us toward climate goals while stimulating economic growth. Figure 1 illustrates the key concept of power-to-gas (PtG) hydrogen technology.

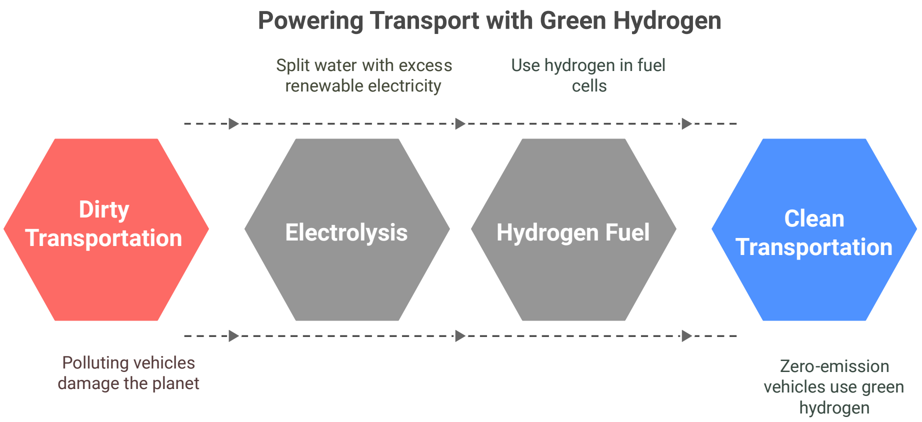


Figure 1. Power-to-Gas Green Hydrogen for Transport: Decarbonizing Mobility with Electrolysis and 100% Emission-Free Fuel

This study provides hydrogen policy by developing a novel integrated framework that connects case study evidence with actionable policy instruments. The contribution is threefold: first, a synthesis of global lessons contextualized for PtG transport; second, a SMART-oriented recommendation package with measurable targets; and third, an implementation roadmap linking timelines, financing levers, and stakeholder roles. Together, these elements distinguish this paper from existing reviews, positioning it as a policy design tool rather than a descriptive survey. Table 1 synthesizes the main contributions of previous PtG research, comparing electrolysis/methanation technologies, integration pathways, and techno-economic insights from early conceptual studies to recent applied models.

Table 1. Power-to-Gas (PtG) literature comparison: Focus, technologies, applications, scale, and key findings.

Author(s)	Core Focus	Electrolysis Technology	Methanation Approach	Application / Sector	Scale (Lab/Pilot/System)	Novelty / Contribution	Key Findings
Götz et al. [6]	Techno-economic analysis of PtG process chain	Alkaline, PEM, Solid Oxide	Catalytic (fixed-bed), novel (3-phase, micro), biochemical	Grid storage, synthetic methane	Lab to conceptual system	Comparative assessment of electrolysis & methanation	PEM and SOEC promising in future; CO_2 supply and economics critical
Wulf et al. [7]	Survey of 128 PtG projects in Europe	Various (not specified in detail)	Catalytic and biological	Grid injection, transport fuels, refineries	Demonstration projects	Empirical assessment of EU projects	PtG mainly for grid storage; refineries next frontier
Mazza et al. [8]	Literature review of PtG in electricity system	Focus on electrolyzers	Linked with CO_2 production	Generation, transmission, distribution, utilization	System-level	Conceptual framework for PtG in electricity value chain	Identifies role across electricity chain; future applications
Varone & Ferrari [9]	PtG and PtL in German Energiewende	Electrolysis (general)	Synthetic fuels via CO_2 recycling	Transport, industry, fuel synthesis	Scenario modeling	Economic assessment of PtG/PtL integration	RES-E conversion stabilizes system and reduces emissions
Lewandowska-Bernat & Desideri [10]	Review of PtG role in energy systems	General	General	Techno-economic, LCA, MCDA	Review level	Identifies problem-solving capacity of PtG	PtG supports long-term renewable storage, needs better integration
Wulf et al. [11]	106 PtG projects, focus on electrolysis & methanation	Alkaline, PEM, SOEC	Catalytic, biological	Transport, household, industry	Demonstration projects (mainly Germany)	Comparative system assessment	Local PtG potential varies by national systems
Schiebahn et al. [12]	System-level PtG paths and sector coupling	Electrolysis (general)	Methanation (optional)	Electricity, heating, transport	Conceptual framework	Sector coupling analysis	Hydrogen links electricity, heating, traffic

Author(s)	Core Focus	Electrolysis Technology	Methanation Approach	Application / Sector	Scale (Lab/Pilot/System)	Novelty / Contribution	Key Findings
Lewandowska-Bernat & Desideri [13]	PtG for large and small grids	General	General	RES integration in grids	System level	Comparative analysis of grid flexibility	PtG enables balancing in both large and remote grids
Ozturk & Dincer [14]	Review of PtG with hydrogen pathways	PEM, SOEC, others	Hydrogen focus (not methane)	Transport, NG distribution, thermal processes	Comparative analysis	Comparative environmental & cost evaluation	PEM-based hydrogen has lower environmental impacts
Sterner & Specht [15]	Concept origin of PtG and sector coupling	Water electrolysis	CO_2 methanation	Energy system integration, PtX	Demo sites	Historical development of sector coupling	Pioneered PtG and PtX, applied widely
Jensen et al. [16]	Biological methanation via archaea	Electrolysis-derived H_2	Biological methanation reactors	Gas grid, energy storage	Mostly lab-scale	Biological PtG reactor performance review	Gas-liquid transfer limits biological PtG
Barbaresi et al. [17]	Survey of 87 PtG R&D projects	Mixed	Mixed	Efficiency improvement, system integration	Mostly lab-scale	R&D focus mapping	Integration and efficiency are main research directions
Glenk et al. [18]	Cost learning curves of electrolysis	Alkaline, PEM, SOEC	Not central	Hydrogen production	Global system level	Regression-based cost analysis	Electrolytic H_2 cost projected $1.6–1.9/kg by 2030
Chen et al. [19]	Low-carbon IES model with P2G + CCS + CHP	Electrolysis	Methanation	CHP, CCS integration	Modeled system	Economic optimization	Daily cost reduced by 50% with PtG integration
Wang et al. [20]	Allam cycle + PtG multi-generation	Electrolysis	Methanation	Power, methane, desalination	Simulation	Innovative Allam cycle integration	Achieves zero-carbon power + water co-production

Author(s)	Core Focus	Electrolysis Technology	Methanation Approach	Application / Sector	Scale (Lab/Pilot/System)	Novelty / Contribution	Key Findings
Ma et al. [21]	CHP + CCS + P2G integration	Electrolysis	Methanation	CHP optimization	Modeled IES	Carbon-emission optimization	Lower costs and improved RES integration
Mehrjerdi et al. [22]	P2G in microgrid for water + power + H_2	Electrolysis + reforming	Fuel cell reconversion	Microgrid supply	Simulation	Multi-output system integration	P2G reduces fossil reliance, integrates storage
Kang et al. [23]	IES with ORC + P2G	Electrolysis	Methanation	Industrial parks	Simulation	ORC + PtG synergy	Expands thermoelectric ratio range for IES
Perpiñán et al. [24]	PtG integration in blast furnaces	Electrolysis	Syngas, SNG, H_2	Ironmaking	Systematic review	KPIs analysis	PtG + top gas recycling cuts CO_2 to 435 kg/tHM
Hu et al. [25]	Wind + P2G integration with GCPS	Electrolysis	Methanation + CCS	Wind integration	Robust optimization model	Environmental benefit analysis	81% wind curtailment reduction, 39% CO_2 reduction
Park et al. [26]	Green H_2 in PtG-to-Pt process	PEM	Methanation optional	Grid stability	Simulation	Reliability vs cost evaluation	H_2 improves wind-solar hybrid reliability
Al-Ismail [27]	Integrated electric power + gas (IEPG)	General	General	IES, CCS, CHP	Review level	Comprehensive IEPG overview	Identifies policy/regulation gaps
Calise et al. [28]	PV + AD driven PtG	SOEC	3-stage catalytic	Renewable SNG	Dynamic simulation	Thermoeconomic analysis	0.75 efficiency, <3 yr payback
Kim et al. [29]	Renewable natural gas + cryogenic CCS + PtG	Electrolysis	Methanation + RNG liquefaction	RNG supply chain	Case studies	Life-cycle GHG analysis	Up to 91% lower GHG than fossil NG

Author(s)	Core Focus	Electrolysis Technology	Methanation Approach	Application / Sector	Scale (Lab/Pilot/System)	Novelty / Contribution	Key Findings
Son & Kim [30]	Wind farms + PtG integration	Electrolysis	Methanation	Grid stability	Case study	Switch-control electrolyzer model	Curtailment reduced by 94.5%
Karrabi et al. [31]	Ammonia-solar CHP + PtG	Electrolysis	Methanation	Steel industry	Case study	Industrial poly-generation model	Supplies H_2 for FCEVs, cost-feasible
Lee & Kim [32]	PtG + nuclear in South Korea	Electrolysis	Methanation	EnergyPLAN modeling	National system	Sectoral integration	Optimal mix wind + PtG > solar
Shabanian-Poodeh et al. [33]	Reliability model for PtG-G2P	Electrolysis	Methanation	Reliability-constrained systems	Simulation (IEEE test systems)	Stochastic reliability optimization	Improves reliability by 12.5%, cuts costs
Valipour et al. [34]	Multi-microgrid hydrogen-based IPGN	Electrolysis	Methanation	Multi-carrier microgrids	Simulation	P-robust stochastic scheduling	Ensures reliability and fairness
Wang et al. [35]	Ship energy system with P2G + CCS + blending	Electrolysis	Methanation	Maritime decarbonization	Simulation	Hydrogen blending optimization	Cuts costs and emissions
Gao et al. [36]	IES with carbon trading + PtG	Electrolysis	Methanation + HFC	CHP, HFC, PV-wind	Simulation	Carbon trading integration	Reduces cost 2.4%, emissions 3.1%

2. Background & Context of PtG-Based Hydrogen: Scale Hydrogen Mobility by Targeting Energy and Transport

2.1. Historical Trends in Power-to-Gas Development

The concept of converting electricity to gas fuel has been explored for decades, but it gained momentum in the 2010s alongside the rapid growth of renewable energy [6, 37]. Early Power-to-Gas demonstrations appeared in Europe, particularly Germany, where ambitious renewable targets and occasional excess wind power prompted innovators to store energy as hydrogen. In 2013, projects like the Frankfurt “Thüga Group” PtG pilot showed the feasibility of using a PEM electrolyser to inject hydrogen into the natural gas grid [38]. Around the same time, Germany’s E.ON Falkenhagen project began using wind power to produce hydrogen at a 2 MW plant, blending it into the regional gas pipeline [38]. These early pilots proved the PtG concept and generated operational know-how, though their primary aim was energy storage and grid integration rather than transport fuel.

By the mid-2010s, attention turned to using PtG hydrogen directly for mobility [39]. Hydrogen fuel cell vehicles are seen as a complement to battery electrics – with fuel cells better suited for longer ranges and heavy loads. Automakers like Toyota and Hyundai introduced the first commercial hydrogen cars, and bus and truck prototypes rolled out in Asia, Europe, and North America. However, infrastructure was the chicken-and-egg dilemma: few hydrogen fueling stations meant few vehicles, and vice versa. This began to change as governments launched hydrogen mobility programs. For example, Japan promoted a “Hydrogen Society” ahead of the Tokyo 2020 Olympics, deploying fuel-cell buses and building dozens of H_2 stations in Tokyo and beyond [40, 41]. Germany, France, the UK, South Korea, and others also invested in early station networks and vehicle incentives, signaling a commitment to hydrogen transport. These efforts were often underpinned by PtG technology: many stations included onsite electrolyzers or sourced green hydrogen from pilot plants, ensuring the fuel was low-carbon.

In the late 2010s and early 2020s, global drivers – climate agreements, falling renewable costs, and energy security concerns – converged to put hydrogen firmly on the policy map. The Paris Agreement (2015) drove countries to seek deep emissions cuts, including in transport which accounts for roughly a quarter of global CO_2 emissions [42]. Batteries alone could not easily cover all transport needs (like long-haul trucking, aviation, maritime), so hydrogen gained traction as an essential piece of a multi-branched solution. Meanwhile, wind and solar became far cheaper, making electrolysis more economically viable; and the need for long-term energy storage (for days when the sun does not shine or wind does not blow) became evident – a niche hydrogen can fill. Thus, PtG moved from obscure pilot projects to a pillar of national energy strategies. By the early 2020s, many countries had explicitly included green hydrogen in their plans, often with transport as a key end-use [43]. This historical evolution – from concept to pilot to strategic priority – sets the stage for the current global focus on scaling up PtG for transport fuel. Figure 2 summarizes the historical trends in power-to-gas development.

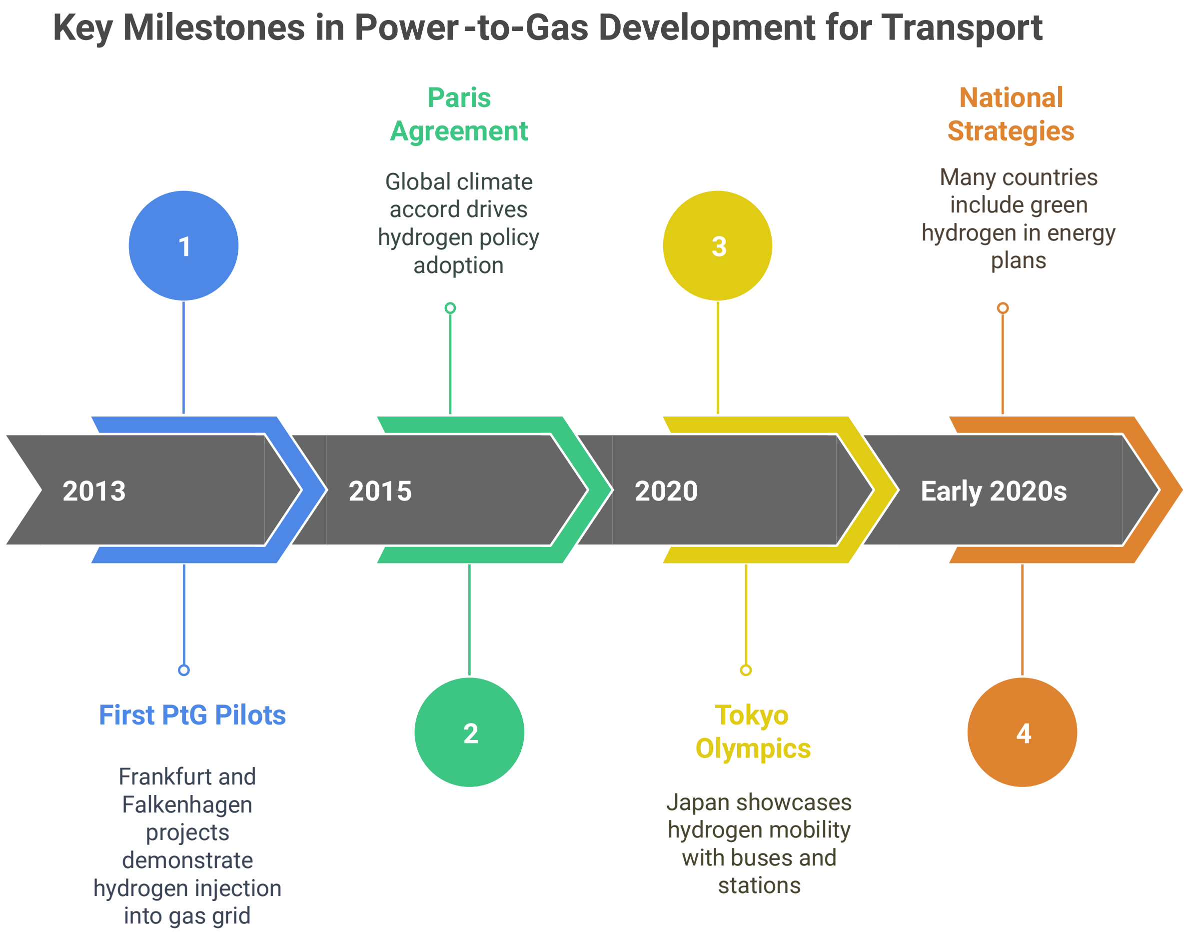


Figure 2. Power-to-Gas Hydrogen Strategies for Transport: Adoption, Global Milestones, and Policy Acceleration

2.2. Global Relevance of Hydrogen in Transport

Hydrogen's potential in transportation is globally recognized today as countries strive for net-zero emissions by mid-century. The appeal lies in hydrogen's unique attributes: it burns (or reacts in a fuel cell) without carbon emissions, it carries significant energy per weight (good for vehicles), and it can be made from abundant resources (water and renewable electricity). According to the Hydrogen Council, hydrogen could supply up to 20% of global energy needs by 2050, with a market value around $2.5 trillion [44]. A large portion of that would be in transport, from fueling cars, trucks and buses to trains and ships. This signals not only environmental importance but also economic opportunity – nations leading in hydrogen could capture new industries and jobs.

Transport is the fastest-growing source of greenhouse gases in many regions. As of the mid-2020s, oil still powers over 90% of transport, making the sector hard to decarbonize and heavily exposed to oil price and supply volatility [45, 46]. Hydrogen offers a path to diversify the transport energy mix while reducing emissions. It is particularly relevant for segments where batteries face limits. For instance, long-haul trucks and intercity buses require quick refueling and high energy density; hydrogen delivers both, whereas very large batteries would be heavy and slow to charge. Similarly, rail lines that are not electrified (common in many countries) can be decarbonized by retrofitting diesel trains with hydrogen fuel cells, avoiding costly overhead electrification. Maritime shipping and aviation may use hydrogen derivatives (like ammonia or synthetic jet fuel made from hydrogen) to cut carbon – an extension of PtG known as Power-to-Liquid when making fuels. These hard-to-abate transport modes make hydrogen indispensable in a net-zero scenario. The International Energy Agency (IEA) notes that by 2050, hydrogen and its derivatives could provide a significant share of transport energy, especially in heavy industry and long-distance transport uses [47].

At the same time, hydrogen's relevance extends beyond transport into energy security and grid resilience. Regions with abundant renewables (sunny deserts, windy coastlines) can export green hydrogen as a new energy commodity, somewhat analogous to exporting sunshine or wind in bottled form. This is attracting interest from countries in the Middle East, Australia, Latin America and Africa, looking to become future hydrogen suppliers. For oil-importing nations, domestically produced hydrogen promises improved energy independence. And because PtG hydrogen can be stored in tanks or underground caverns for months, it provides strategic energy storage for grids, enhancing resilience against seasonal fluctuations. All these factors elevate hydrogen from a niche technology to a global strategic priority. As of 2024, over 60 countries have national hydrogen strategies, collectively covering 84% of global CO_2 emissions [48] – a proof to hydrogen's perceived importance worldwide. Many of these strategies explicitly highlight transport as a focus area, alongside industry, indicating a broad consensus that PtG-based hydrogen will be a key push to decarbonize economies. Figure 3 summarizes global relevance of hydrogen in transport.

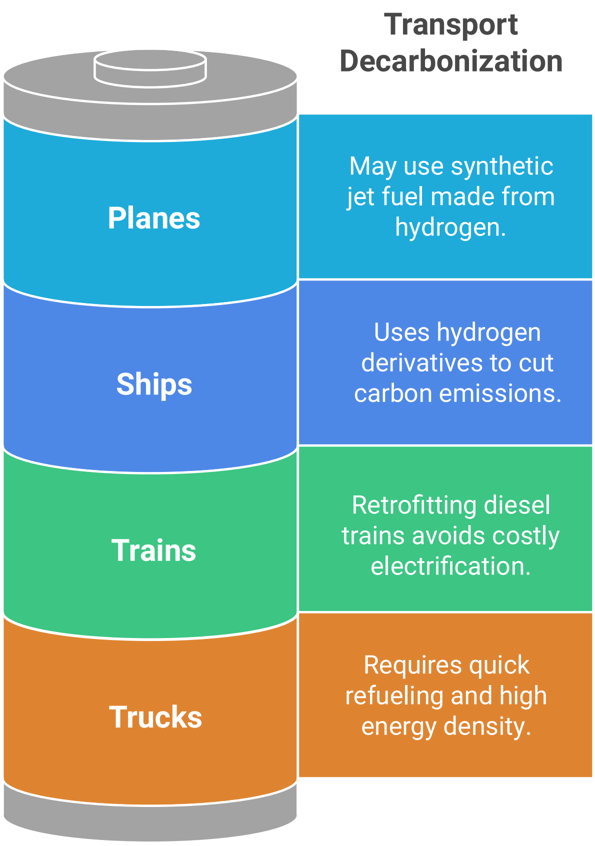


Figure 3. Power-to-Gas Hydrogen for Hard-to-Electrify Transport: Decarbonizing Planes, Ships, Trains, and Trucks Driving 60% of Emissions

2.3. Sectors and Stakeholders Affected by Power-to-Gas (PtG) Hydrogen Technology

Deploying PtG hydrogen for transport does not happen in a vacuum – it has ripple effects across multiple sectors and engages a wide range of stakeholders. Understanding who is affected helps in crafting policies that align interests and mitigate potential pushback.

2.3.1. Energy Sector

The power industry sees PtG as a new demand source for renewable electricity, which could help absorb surplus generation and justify further expansion of wind and solar farms. At the same time, the natural gas sector views hydrogen (particularly if converted to methane or used for blending) as a way to repurpose existing gas infrastructure for a low-carbon future. Gas pipeline operators, for instance, are investigating upgrades to carry hydrogen. Utilities and grid operators are stakeholders too: electrolysers can provide grid services (dynamic load balancing) and long-term storage, changing how grids are managed. Hence, energy companies – from renewable developers to gas utilities – have a keen interest in hydrogen policy. Many are actively investing in PtG projects or forming partnerships (e.g., oil & gas majors partnering with electrolyser companies and automakers) [49].

2.3.2. Transport & Automotive Sector

Vehicle manufacturers and the mobility sector are directly impacted. Automotive companies must adapt product lines to include fuel cell vehicles (as some already have). Toyota, Hyundai, and Honda were early movers in fuel-cell cars; now truck makers like Daimler, Volvo, and Hyundai are developing hydrogen trucks. Companies in rail (e.g., Alstom) are producing hydrogen trains, and aerospace firms are researching hydrogen or ammonia-fueled ships and planes. For these industries, clear policy signals (like targets or incentives for zero-emission vehicles) are critical to justify R&D and retooling investments. The fuel infrastructure industry – station operators, industrial gas suppliers (Air Liquide, Linde, etc.) – are also key stakeholders, as building hydrogen refueling stations and distribution networks will be a massive undertaking. Policies around codes, standards, and subsidies for fueling stations directly affect them.

2.3.3. Industrial Sector

Industries that currently use hydrogen (such as ammonia fertilizer producers, oil refineries, steelmakers) will be affected by a scale-up of green hydrogen, as it could replace their current fossil-derived hydrogen feedstock. While this is somewhat adjacent to our transport focus, it matters because economies of scale in hydrogen production for industry can drive down costs for transport uses too. Moreover, industries like steel or chemicals might become suppliers of hydrogen fuel (by capturing by-product hydrogen, or hosting large electrolysis facilities). Conversely, if transport demand takes off, it could tighten hydrogen supply for industrial users unless production expands – so coordination is needed.

2.3.4. Environmental and Social Stakeholders

The shift to hydrogen in transport will have environmental benefits (reduced air pollution and greenhouse gases) which interest public health and climate advocacy groups. These groups often push for faster adoption of zero-emission technologies, including hydrogen where appropriate. On the social side, workforce and community considerations arise. Training programs will be needed to skill workers in hydrogen tech (from handling hydrogen safely to maintaining fuel cell vehicles). Communities near large hydrogen production sites or transport corridors might voice questions about safety – hydrogen is flammable, though industry experience shows it can be handled as safely as gasoline with proper protocols. Public acceptance is crucial; strong safety standards and community engagement are needed to earn trust (indeed, experts stress the importance of "social license" for hydrogen projects, meaning early and transparent community consultations [47]).

2.3.5. Policymakers and Governments

Government agencies themselves are stakeholders – from national energy and transport ministries to local city governments that may operate transit bus fleets. Many governments see hydrogen as an avenue for industrial policy and job creation in addition to an environmental solution. For example, building a domestic electrolyser manufacturing industry or becoming a hydrogen fuel exporter can create new economic sectors. This has led to international competition and alliances (e.g., the EU's hydrogen strategy vs. efforts in China, or partnerships like the Hydrogen Energy Supply Chain between Australia and Japan). In forging policy, governments must balance interests of incumbents (oil, gas, automotive industries) with the imperative to support emerging clean tech players. The breadth of stakeholders means that policy frameworks must be inclusive, offering transition pathways for legacy industries (like upskilling oil and gas workers to hydrogen projects) while fostering innovators and ensuring public benefits (clean air, energy access).

In summary, scaling Power-to-Gas or PtG-based hydrogen for transport is a classic example of the energy transition's interconnected nature. Success will depend on aligning the power sector, fuel suppliers, vehicle makers, infrastructure developers, and the public around a shared vision – clean, sustainable mobility. History shows each major shift (from wood to coal) required coordinated action; the hydrogen transition is no different. Figure 4 summarizes the sectors and stakeholders affected

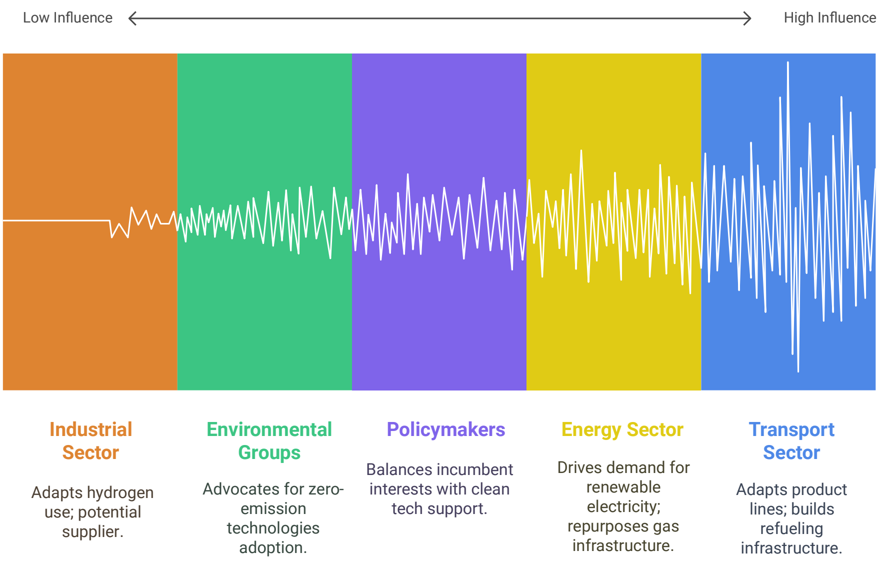


Figure 4. Power-to-Gas Hydrogen Adoption in Transport and Energy Sectors: Accelerating the Net-Zero Transition

To operationalize this stakeholder mapping, Table 2 links each group to the key barriers they face, potential enablers, and the most relevant policy instruments. For example, vehicle manufacturers face high upfront costs and uncertain demand, which can be addressed through fleet procurement mandates and purchase subsidies. Grid operators face integration challenges that can be mitigated through regulatory incentives for flexibility services. This structured linkage provides policymakers with a clearer picture of how to target interventions across the hydrogen value chain.

Table 2. Power-to-Gas Hydrogen in Transport: Stakeholder Barriers, Enablers, and Policy Instruments

Stakeholder	Key Barriers	Enablers	Relevant Policy Instruments
Energy sector (utilities, gas operators)	Grid integration, infrastructure retrofit costs	Surplus renewables, long-term storage value	Grid service payments, infrastructure investment grants
Automotive & transport sector	High vehicle cost, lack of stations	Proven FCEV prototypes, OEM commitment	Fleet procurement mandates, subsidies, ZEV credits
Industrial sector	Competition with existing hydrogen demand	Economies of scale in hydrogen production	Clean hydrogen standards, industrial offtake agreements
Environmental & social groups	Safety and acceptance concerns	Public health and climate benefits	Awareness campaigns, community engagement funds
Policymakers & governments	Coordination complexity	Economic growth and job creation potential	National hydrogen councils, cross-ministerial task forces

3. Methodolology

This study adopts a qualitative policy research design structured around comparative analysis, stakeholder mapping, and synthesis of best practices. The methodology is organized into four components, each supported by dedicated tables in the manuscript:

1. Comparative Policy and Technology Review – International hydrogen and Power-to-Gas strategies were systematically examined to identify trends in focus, technologies, applications, scale, and findings. This is summarized in Table 1, which positions the scope of major PtG studies within the transport context.
2. Stakeholder Mapping and Policy Linkages – Key actors across government, industry, utilities, and civil society were mapped, with their specific barriers, enablers, and policy instruments identified. This analysis, presented in Table 2, makes the stakeholder framework operational and directly relevant to PtG hydrogen deployment in transport.
3. Integration of Global Literature – Existing hydrogen economy and policy studies were compared across global, regional, and national levels, focusing on scope, methodology, frameworks, challenges, and key findings. This integration is captured in Table 3, providing the foundation for positioning the novelty of this study within the broader field.

4. Policy Framework Development – Insights from comparative analysis and stakeholder mapping were synthesized into an integrated policy framework. This is presented in Table 4, which outlines strategic levers, impacts, and actions needed to enable scalable and sustainable PtG hydrogen adoption in transport.

By combining these components, the paper provides descriptive analysis to deliver an actionable policy framework and roadmap. This ensures that global lessons are translated into context-specific recommendations for accelerating Power-to-Gas hydrogen adoption in transport systems.

4. Research Findings & Analysis of Power-to-Gas (PtG) Hydrogen: Hydrogen Transport at Scale by Replicating Proven Success Factors—Up to $100 Billion in Public Funding Backing the Shift

4.1. Trends and Global Data on Hydrogen Mobility

Worldwide data show that hydrogen in transport has moved from theory to practice, though it remains in early stages compared to conventional fuels. According to the International Energy Agency, global hydrogen demand reached ~97 million tonnes in 2023, almost entirely for industrial uses, with less than 1% met by low-emissions (green or blue) hydrogen [50]. Transport currently accounts for only a small fraction of that demand, since hydrogen fuel cell vehicles are just beginning to roll out. However, policies and investments are rapidly changing the outlook. The IEA projects that hydrogen demand could grow by 50% by 2030 under a net-zero trajectory, driven in part by new transport applications [50]. Particularly, one analysis indicates that by 2030, around 40% of all renewable hydrogen could be used in the transport sector, given strong policy support in the US, Europe, and China [51]. This is a remarkable shift – essentially, transport could become the second major market for clean hydrogen after industry within this decade.

Investment trends support this expectation. In the past year alone, governments worldwide announced nearly $100 billion in public funding related to hydrogen, a massive jump that reflects a move from planning to implementation [48]. Much of this money is directed at building electrolyser capacity and hydrogen supply (1.5 times more funding on supply-side than demand-side so far [48]), but funds are also flowing to transport end-uses. For example, the United States launched a $7 billion program to establish regional Hydrogen Hubs – several of which center on heavy-duty transportation corridors – and enacted a production tax credit (up to $3 per kg for green hydrogen) to jump-start supply [47]. Japan is expected to roll out a ¥3 trillion (~$20 billion) hydrogen demand package by 2024 to subsidize hydrogen usage in industries and transport [47]. Europe's funding includes multi-billion euro schemes like Important Projects of Common European Interest (IPCEIs) targeting hydrogen technologies, and countries such as Germany have dedicated € billions to spur hydrogen-powered steel, trucking, and shipping. These figures signal unprecedented public commitment. Importantly, 19 new national hydrogen strategies were published in the last year (many from emerging economies), bringing the total to 60 countries with hydrogen roadmaps [48] – indicating that interest is truly global, not limited to a few advanced economies.

4.2. Case Studies: Successes in PtG and Hydrogen Transport

Behind these numbers are concrete projects and "success stories" demonstrating what PtG and hydrogen can achieve in transport. A few illustrative cases from different regions are shown in Figure 5.

PtG and Hydrogen Transport Successes

	Europe (Germany)	Scotland (UK)	South Africa	California (USA)	National Strategies
Focus	Railway Line	Green Hydrogen Hubs	Heavy-Duty Trucks	Hydrogen Mobility	International Collaboration
Application	Regional rail transport	Public sector transport	Mining industry vehicles	Fuel cell vehicles, buses, trucks	Various sectors, international cooperation
Technology	Hydrogen fuel Cell trains	Hydrogen fuel Cell buses	Hydrogen-powered mine haul truck	Hydrogen refueling stations, fuel cell vehicles	Electrolysis, fuel cells
Impact	Eliminates 4,400 tonnes of CO_2 annually	Creates a green fueling system	Decarbonize heavy industrial vehicles	Growing market For hydrogen fuel	Scaling hydrogen production & use
Key factor	Government co-funding	City acts as a catalyst	Couple renewable energy with usage	Infrastructure-first approach	Internat'l finance and cooperation
Challenges	Upfront investment and coordination	Total demand of multiple fleets	Replicating the model globally	Fuel cost, station reliability	Establishing standards

Figure 5. Power-to-Gas Hydrogen Transport at Scale: Global Case Studies on Co-Funding, Public Demand, and Infrastructure-First Strategies

4.2.1. Europe's Hydrogen Railway Line (Germany)

In 2022, Germany inaugurated the world's first railway line fully powered by hydrogen fuel. Fourteen Coradia iLint hydrogen trains, supplied by Alstom, replaced diesel trains on a 100 km regional line in Lower Saxony [52]. The trains are refueled with green hydrogen and emit zero emissions, eliminating an estimated 4,400 tonnes of CO_2 annually that diesel would have produced [52]. This project demonstrated PtG's viability in rail: excess renewable power is converted to hydrogen, transported via tanker trucks or pipeline, and used to fuel trains that only emit water. It's a template now being studied and replicated in other areas – for instance, France, Italy, and the UK are all testing or ordering hydrogen trains for lines where electrification is too costly. The German case shows that even hard-to-decarbonize sectors like regional rail can be made clean with hydrogen, given upfront investment and coordination between technology providers, government (which co-funded the project), and transit operators.

4.2.2. Green Hydrogen Buses and Hubs (Scotland, UK)

The city of Aberdeen has become a pioneering "hydrogen city" through an integrated approach. It first ran pilot projects with hydrogen fuel-cell buses and city vehicles, learning by doing. Building on that success, in 2022 Aberdeen partnered with BP to develop the Aberdeen Hydrogen Hub, a commercial-scale green hydrogen production and distribution facility [53]. Powered by local renewable energy (wind power from the North Sea), this hub will produce hydrogen to fuel the city's expanding fleet of 15 hydrogen buses, with plans to supply trucks, refuse vehicles, and even ferries in the near future [53]. The project is phased: Phase 1 focuses on public sector transport needs (buses, municipal vehicles), Phase 2 will scale up for larger uses like rail and freight, and Phase 3 envisions hydrogen for heating and export [53]. By aggregating demand across multiple fleets and investing in production, Aberdeen aims to drive down hydrogen fuel costs and create a local market. This case illustrates how a city can act as a catalyst for hydrogen transport – coordinating stakeholders (city council, energy companies, bus operators) and leveraging PtG to create a resilient, green fueling system for public transport. It also underlines the economic co-benefits: the hub is expected to add hundreds of jobs and significant gross value to the regional economy as it matures [53].

4.2.3. Heavy-Duty Hydrogen Trucks (South Africa)

In May 2022, mining company Anglo American unveiled the world's largest hydrogen-powered mine haul truck at a platinum mine in South Africa – a 220-tonne behemoth using a 2 MW fuel cell powerplant [54]. This monster truck can haul 290 tonnes of ore, performing heavy work previously done by diesel trucks. What's groundbreaking is that it is part of an "ecosystem" approach: the mine site will use a 3.5 MW solar farm to produce green hydrogen on-site via PtG (electrolysis), fueling the truck and eventually a fleet of them [54]. South Africa's President Cyril Ramaphosa hailed it as "the genesis of an entire ecosystem powered by hydrogen" and a "gigantic leap" for the country's hydrogen future [54]. This project, while still a pilot, demonstrates that PtG hydrogen can tackle applications far beyond city buses – including off-road, heavy industrial vehicles in developing countries. It also showcases a smart coupling of renewable energy with usage: by integrating solar PV, electrolyser, and fuel cell truck at one site, it minimizes reliance on external fuel supply chains and proves out a model that could be replicated at mines globally. Given the mining sector's large carbon footprint and the heavy-duty equipment involved, this success in South Africa is being closely watched as a template for decarbonizing large vehicles (and doing so in a way that can bring investment into emerging economies). Notably, several countries (like Chile and Australia) with big mining industries are considering similar hydrogen mining truck programs.

4.2.4. California's Hydrogen Mobility Push (USA)

California, which often leads on clean transportation in the U.S., has built the country's most extensive hydrogen refueling network. As of 2025, 50 retail hydrogen stations are operating in California, serving a fleet of about 12,000 fuel cell cars (the largest such fleet in the world) h2fcp.org. These stations largely dispense green or low-carbon hydrogen, some generated via on-site solar-powered electrolysis and others trucked in from central PtG plants. California also has fuel cell electric buses in transit service (66 buses with over 100 more on order) and has started deploying hydrogen fueling for heavy trucks at key freight corridors) [55]. One enabling policy has been the state's Low Carbon Fuel Standard (LCFS), which awards credits to hydrogen fuel producers based on carbon reductions, effectively subsidizing green hydrogen at the pump. Additionally, California offers vehicle rebates for FCEVs and has set goals for zero-emission bus and truck adoption. The result is a slowly but steadily growing market: hydrogen fuel cell car sales in the state have been rising (albeit still under 0.1% of total car sales) and new stations are coming online each year. California's case shows the importance of infrastructure-first: the government co-funded many early stations to break the chicken-and-egg cycle. It also highlights challenges – hydrogen fuel remains relatively expensive (a point we will revisit) [56, 57], and station reliability and capacity need improvement. Nevertheless, it stands as a real-world laboratory for hydrogen mobility: data from California's network informs the world about usage patterns, safety, and best practices in customer experience for hydrogen fueling. This feedback is valuable for other regions now launching hydrogen corridors.

4.2.5. National Strategies and International Collaboration

Beyond local projects, some broader initiatives deserve mention. South Korea, for example, has a national roadmap aiming for 6 million hydrogen vehicles on its roads by 2040 with a network of 1,200 fueling stations [58, 59] – one of the most ambitious per-capita targets globally. By 2022 they targeted 79,000 FCEVs and had built over 300 stations as intermediate milestones [59]. The government is heavily subsidizing vehicles and infrastructure and even deploying hydrogen fuel cell power for homes and buildings, creating an integrated hydrogen economy. China is rapidly catching up: it set a goal of 50,000 hydrogen vehicles by 2025 and is funding "hydrogen city" pilots and industrial parks to develop fuel cell buses and trucks [60]. As of 2022, China already had around 17,000 fuel cell vehicles (mostly buses) on the road [61], and dozens of cities were deploying hydrogen bus fleets with central electrolysers using solar or wind power. China's central government committed to produce 100,000–200,000 tons of green hydrogen annually by 2025 to ensure supply for these vehicles [60]. Meanwhile, in Latin America, Chile stands out: it aims to leverage its vast solar and wind resources to produce some of the world's cheapest green hydrogen. Chile's national strategy targets 5 GW of electrolysis capacity by 2025 and 25 GW by 2030, with hydrogen priced as low as $1 per kg by 2030 [62]. While a chunk of this hydrogen is intended for export (as ammonia or synthetic fuels), Chile also foresees domestic use in long-distance trucks and mining vehicles. International finance is flocking in – e.g., the EU's investment bank and others put up over $700 million in loans and funds to support Chile's hydrogen projects [62]. This international backing underscores a trend: cross-border cooperation to scale hydrogen. The EU is helping fund hydrogen hubs in Africa (Namibia, South Africa) and Latin America, while countries are forming alliances (such as the IPHE – International Partnership for Hydrogen and Fuel Cells in the Economy, and various Mission Innovation initiatives) to share best practices and establish standards.

4.3. Analysis of Success Factors

Across these cases, common ingredients for success emerge. Firstly, strong public policy support was critical – whether direct funding (grants, loans), favorable regulation, or government purchases of hydrogen vehicles to create early demand. Germany's train and Scotland's bus projects were enabled by government co-financing and procurement commitments. California's network was seeded by public funds and performance-based credits. Secondly, integration of renewables with demand proved valuable: projects that co-locate production (electrolyser + renewable source) with use (vehicles) avoid many distribution hurdles and improve economics (South Africa's mine, Aberdeen's hub, etc.). Thirdly, partnerships matter: these projects often involve consortia of public agencies, private companies, and sometimes research institutions. For example, the Aberdeen Hydrogen Hub brings together city officials, an oil major, economic development agencies, and bus manufacturers. Such collaboration pools expertise and shares risk. Fourth, phased scaling and learning-by-doing is a clear pattern. No one jumps to a nation-wide hydrogen economy overnight; instead, pilots lead to larger demos, which lead to scaling. Each of the highlighted cases started with small pilots (a few buses here, a prototype train there) before expanding, allowing lessons on safety, reliability, and economics to be incorporated. Finally, successful cases addressed the “soft” aspects too – training local technicians, informing the public (for instance, community events to demystify hydrogen), and developing safety protocols and standards. This holistic approach builds the ecosystem needed for hydrogen to thrive.

Despite these successes, challenges and disparities remain. Many hydrogen transport projects are still subsidized and not yet cost-competitive with fossil options without support. Infrastructure is unevenly distributed (e.g., Europe, East Asia, California are relatively ahead, while large parts of the world have little to no hydrogen fueling yet). However, the trendlines are encouraging: costs of electrolyzers and fuel cells are coming down with scale, and each year brings record new hydrogen investment. The case studies provide proof-of-concept that PtG hydrogen can work in transport, and now the task for policymakers is to replicate and expand these successes, tailoring them to local contexts. Figure 6 summarizes the policy implications.

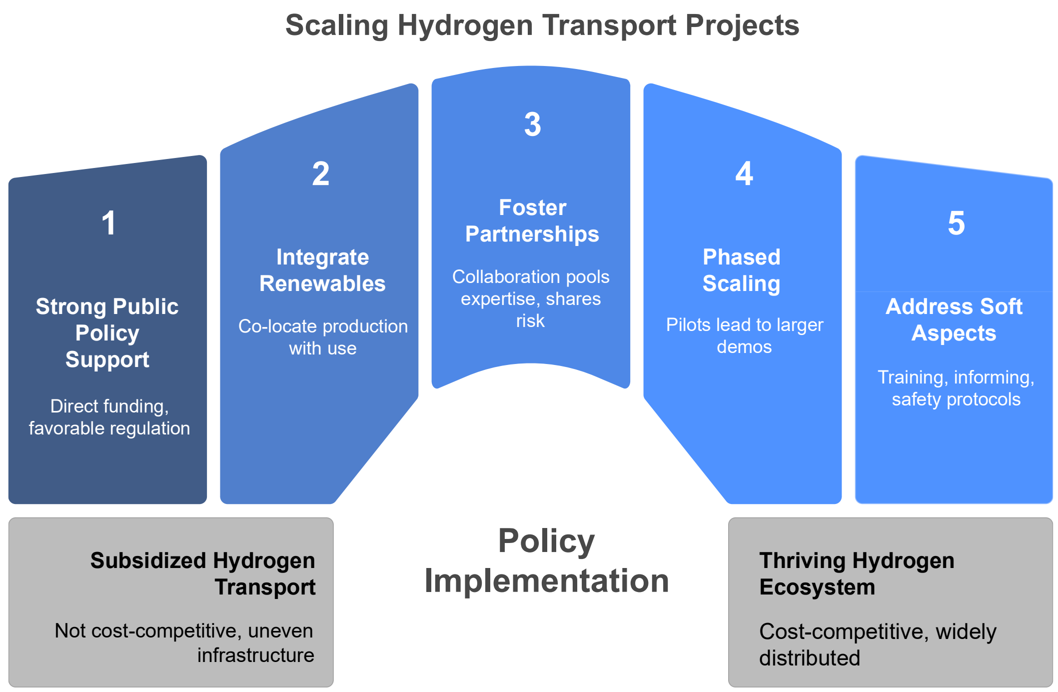


Figure 6. Power-to-Gas Hydrogen Transport for Cost Competitiveness: 5 Policy Levers to Scale Beyond Subsidized Pilots

5. Policy Options & Alternatives for Power-to-Gas (PtG) Hydrogen

Table 3 synthesizes hydrogen policy research worldwide, comparing economic, technological, and governance perspectives to highlight gaps, innovations, and strategic pathways for a sustainable hydrogen economy. Policymakers looking to promote PtG-based hydrogen for transport have a spectrum of strategies available. Broadly, these options range from a unrestrictive-faire market approach to aggressive government intervention, with various combinations in between. Below we compare several distinct policy approaches, highlighting their features, advantages, and drawbacks:

Table 3. Hydrogen economy and policy: Comparative literature analysis across global, regional, and national contexts, focusing on scope, methodology, policy frameworks, challenges, and key findings.

Author(s)	Core Focus	Scope / Region	Methodology	Policy Dimension	Main Challenges	Novelty / Contribution	Key Findings
Solomon & Banerjee [63]	Global survey of H_2 R&D and policy	Global	Survey, review	National policies, auto industry	High cost, fossil reliance, lack of certainty	Broad global overview	Hydrogen still fossil-based short–mid term, few nations with renewable H_2 plans
Falcone et al. [64]	Hydrogen & UN SDGs	Global	Policy review	SDG linkage	Lack of literature connecting H_2 & SDGs	First explicit H_2–SDG review	Hydrogen can support SDG 7, acts as game-changer
Demirbas [65]	Future hydrogen economy	Global	Literature review	Policy needs for developing countries	Cost, R&D investment, social transition	Highlights hydrogen as geography-independent	Developing nations face dilemma on H_2 investment
Bleischwitz & Bader [66]	EU policy framework	EU	Policy analysis	Energy, regulation, spending	Fragmented policy, weak incentives	EU case study	EU policy not hindering but not strongly pushing H_2 either
Ajanovic & Haas [67]	Economics of H_2 in transport	Global, focus transport	Economic modeling	Policy support for FCVs	Cost competitiveness, learning curves	Connects renewables storage with transport	FCVs feasible only with strong policy + cost reduction
Zhang et al. [68]	Policy optimization for H_2 in China	China (provincial)	Text-mining (153 policies)	Provincial policy design	Weak storage/transport policies	Quantitative content analysis	Focus on HFCVs, infrastructure; storage policy lagging
Ruijven et al. [69]	H_2 in climate policy scenarios	Global	TIMER 2.0 energy model	Climate policy vs no policy	Fossil-based H_2 can raise CO_2	Long-term scenario analysis	With CP, H_2 flexible; without

Author(s)	Core Focus	Scope / Region	Methodology	Policy Dimension	Main Challenges	Novelty / Contribution	Key Findings
							CP, emissions rise
Chapman et al. [70]	Societal penetration of H_2	Global to 2050	Global optimization model	Carbon targets	Limited penetration	Integrated scenario modeling	H_2 supplies ~2% global energy by 2050, transport key
Cheng & Lee [43]	National H_2 strategies	28 countries	Text analysis + typology	Regulatory stringency	Weak green commitment	Typology of “scale first vs green now”	Most adopt “scale first, clean later”
Lee et al. [71]	H_2 policy agenda, South Korea	South Korea	Expert survey + semantic analysis	Institutional vs technological	Institutional gaps	Socio-technical perspective	Institutions must co-evolve with technology
Ballo et al. [72]	H_2 potential in ECOWAS	ECOWAS	Policy/legal review	Legal basis	No hydrogen-specific policies	First ECOWAS H_2 review	Frameworks missing, need reforms for green H_2
Sasanpour et al. [73]	H_2 in 100% RES European system	Europe	Energy system optimization	Strategic policy targets	Low efficiency	Strategic scenario modeling	H_2 reduces system costs 14–16%, critical in low RES countries
Beasy et al. [74]	Renewable H_2 & energy democracy	Australia	Content analysis	Democratic participation	Centralization risk	Energy democracy lens	Calls for civic engagement in H_2 transition
Jaradat et al. [75]	H_2 technologies, policy, market	Global	Review + bibliometrics	Global policies, incentives	Cost, resource limits	Broad techno-policy-market review	Green/blue H_2 pivotal, need intl. cooperation
Griffiths et al. [76]	H_2 in industrial decarbonization	Global (hard-to-abate sectors)	Systematic review	Industrial policy options	High cost, logistics	Socio-technical framing	H_2 promising but industrial use remains costly

Author(s)	Core Focus	Scope / Region	Methodology	Policy Dimension	Main Challenges	Novelty / Contribution	Key Findings
Huang et al. [77]	H_2 potential in China	China (cities, regions)	Multi-indicator framework	Policy + supply-demand	Uneven regional development	Four-pattern typology	Regional clusters drive H_2 transition
Wang et al. [78]	Green H_2 policy and tech review	US, EU, Japan, China	Policy & tech review	Electrolysis focus	Tech immaturity	Comparative global review	RES electrolysis promising; wind+PV critical
Kumar et al. [79]	Hydrogen storage technologies	Global	Techno-economic review	Storage policy	Safety, cost	Comprehensive storage overview	Compression, liquefaction, solid-state, chemical reviewed
Bade & Tomomewo [66]	US governance of H_2	US	Legal/regulatory review	Federal + state frameworks	Fragmentation, underfunding	Comprehensive US regulatory overview	Calls for cohesive national framework
Steinbach & Bunk [80]	EU hydrogen market design	EU	Expert interviews	Market development & trading	Design uncertainty	Commodity market lens	Proposed EU H_2 market regulations
Quitzow et al. [81]	Germany's international H_2 strategy	Germany/global	Policy review + interviews	International strategy	Implementation gaps	Germany compared to peers	Germany pushes intl. H_2 role, unique among peers
Wei et al. [82]	Global vs China H_2 policies	Global + China	Bibliometrics + topic modeling	Policy evolution	Regional imbalance	Spatial/thematic comparison	China focuses industrial deployment; global green H_2
Fakhreddine et al. [83]	Hydrogen trade models	Global	Critical review	Trade policy	Uncertainty in scale-up	First comparative review of trade models	No model captures full H_2 trade complexity yet
Koutsandreas & Keppo [84]	Green H_2 macroeconomic effects	Greece transport sector	OSeMOSYS + CGE	Cost allocation scenarios	Economic burden	Coupled optimization + GE modeling	Household vs govt cost allocation

Author(s)	Core Focus	Scope / Region	Methodology	Policy Dimension	Main Challenges	Novelty / Contribution	Key Findings
							changes impacts
Shan & Kittner [85]	Sector-specific H_2 adoption	California (IRA subsidies)	Simulation	Tax credits & subsidies	High cost	Consumer vs supplier subsidy focus	Alternative credit allocation boosts adoption + cuts cost
Hoogsteyn et al. [86]	Policy distortions in green H_2	EU-inspired	Equilibrium modeling	Cap-and-trade interactions	Waterbed effect	Policy interaction analysis	Capacity-based support less distortionary
Hernandez & Kirchofer [87]	LCA disparities in H_2 incentives	US & EU	LCA review	Incentive programs (LCFS, 45V, RED)	CI methodology divergence	Policy-LCA interface	Incentives favor certain H_2 tech unfairly
Odenweller & Ueckerdt [88]	Green H_2 ambition vs reality	Global (190 projects)	Empirical tracking	Subsidy policies	Implementation gap	Ambition-implementation gap quantified	Only 7% projects on time; huge subsidy gap
Li et al. [89]	Microgrid H_2 policy scheduling	Microgrid (simulation)	Stochastic MINP + ISSA	Policy for MG profitability	Market uncertainty	Hybrid scheduling model	+15% profits with CHP+H_2, 95% ISSA success

5.1. Option 1: Market-Driven Evolution

“Hands-off” approach, minimal government intervention. The idea here is to set general decarbonization signals (like carbon pricing or emission standards) and let market forces determine if and where hydrogen fits in. Governments would fund basic R&D but avoid picking winners.

Pros: Low fiscal cost; innovation driven by competition; flexibility for industry to choose best solutions (be it batteries, hydrogen, or others) for each use-case.

Cons: Risk of slow adoption of hydrogen since initial costs are high and infrastructure won’t materialize without coordination; potential to miss climate targets if market hesitates to invest in needed infrastructure.

Implication: Hydrogen in transport might remain stuck in pilot phase because there’s no strong incentive to overcome the chicken-and-egg problem of vehicles vs. stations. This approach relies heavily on a robust carbon price or equivalent—which, if not high enough, would not make green hydrogen competitive with cheap fossil fuels in the near term.

5.2. Option 2: Battery-Electric Focus (Hydrogen Minimal)

Prioritize electrification of transport almost exclusively, using hydrogen only in niche cases. In this scenario, policy support (subsidies, infrastructure investments) is funneled mostly to battery electric vehicles (BEVs) and charging networks, under the view that most transport can be directly electrified. Hydrogen is considered a last resort for truly hard-to-electrify segments.

Pros: Simplicity of message and infrastructure – “electric-first” strategy builds on the already growing EV momentum; avoids potentially duplicative investment in two parallel infrastructures (charging and hydrogen) except where absolutely necessary; higher energy efficiency in many cases (BEVs are more energy-efficient than FCEVs per mile).

Cons: Some transport sectors might remain unsolved or sub-optimally served – e.g., long-haul trucks might be forced to use very large batteries resulting in cargo penalties, or ships and planes might have to wait for biofuels or other solutions; misses out on the grid storage benefits of PtG hydrogen (excess renewables would have fewer outlets); places all eggs in one technological basket, which could be risky if supply chains for batteries (lithium, etc.) face constraints.

Implication: Hydrogen development could stagnate, and if batteries fall short in any sector, there may be a rush later to catch up on hydrogen. This path could achieve near-term emission reductions faster in light-duty transport, but potentially at the cost of long-term flexibility.

5.3. Option 3: Hydrogen-Centric Push

Make hydrogen a strategic priority with strong government backing across the value chain. This involves heavy investment in electrolysers (PtG plants), hydrogen distribution and refueling infrastructure, and direct support for hydrogen vehicle adoption. Policies could include capital subsidies, tax credits, public procurement of hydrogen vehicles (buses, etc.), and perhaps mandates (e.g., requiring a percentage of heavy vehicle sales to be FCEVs by a certain date).

Pros: Accelerates development of the full hydrogen ecosystem; economies of scale can drive down costs, making hydrogen more viable long-term; ensures that hard-to-abate sectors (trucks, industry, etc.) have a solution ready in time for climate targets. Additionally, countries taking this route may gain an industrial leadership edge in hydrogen technologies (electrolysers, fuel cells) and associated job creation.

Cons: High upfront public spending and risk of picking a winner – if hydrogen does not turn out as hoped (due to unforeseen technical or economic barriers), money could be wasted that might have been spent on other solutions; infrastructure roll-out could overshoot vehicle uptake, leading to underutilized assets in the short term. Also, coordination challenges are significant: aligning power generation, grid upgrades, gas pipelines, and transport manufacturing is complex.

Implication: If executed well, this option can catalyze a rapid transition to hydrogen in appropriate sectors and possibly drive global costs down. If executed poorly, it could lead to expensive infrastructure that is not used optimally. International cooperation can mitigate some risk (by sharing standards and lessons).

5.4. Option 4: Balanced “Portfolio” Approach

Pursue a mixed strategy: support both battery electrification and hydrogen, each where they make most sense, and invest in PtG mainly for targeted transport niches and energy storage. In practice, this means crafting policies that carve out roles for each technology. For example, encourage BEVs for passenger cars and short urban trips, while simultaneously funding hydrogen for heavy-duty and long-range applications. Policies could include mandates or targets per segment (e.g. “X% of city buses must be zero-emission by 2030” allowing either batteries or hydrogen, but provide extra incentives for hydrogen buses on longer routes), infrastructure plans that ensure both fast chargers and hydrogen stations along highways, and R&D investments in both battery and hydrogen improvements.

Pros: Diversified risk – if one technology faces a setback, the other can fill gaps; recognizes that one size may not fit all in a diverse transport sector; fosters competition between tech, potentially stimulating faster innovation and cost reduction.

Cons: More complex policy design – essentially running two parallel transitions requires careful calibration to avoid redundant spending or one technology crowding out the other in an inefficient way; could be costlier overall as funds are split. There’s also a communication challenge to avoid confusing consumers or industry (they might prefer clarity on what direction to invest in).

Implication: Many experts advocate this balanced route, noting that heavy industry and long-haul transport likely need hydrogen while light-duty and some heavy vehicles will be electric [47]. The key is ensuring neither approach is neglected: hydrogen needs enough support to get past the valley of initial high costs, and electrification needs continued grid and charging investment. This option tries to harness the best of both worlds, aligning with the idea that a mix of solutions will be required to fully decarbonize transport.

In this context, it is important to emphasize that hydrogen is not positioned as a silver bullet but as a complementary vector alongside direct electrification and, in certain sectors, synthetic fuels. Passenger vehicles and short-haul transport are likely to be dominated by battery-electric technologies, while aviation and maritime may rely more heavily on hydrogen-derived e-fuels. A balanced policy framework therefore requires tailoring support mechanisms to ensure each vector can scale where it offers the greatest comparative advantage, with synergies rather than competition shaping long-term decarbonization pathways.

5.5. Option 5: Delay and Wait (Conservative Innovation)

A final alternative is to take a “wait-and-see” stance on hydrogen for transport. Governments would focus on immediate emissions cuts through efficiency and incremental improvements (like improving vehicle fuel economy, promoting hybrid vehicles or natural gas trucks) and hold off major hydrogen investments until the technology matures further in other countries or costs drop automatically.

Pros: Saves public money in the short term; avoids committing to infrastructure that might become obsolete if, say, a superior battery or alternative emerges; allows learning from others’ mistakes (a country could adopt hydrogen later, benefiting from standardization and cost declines paid for by early movers).

Cons: High risk of falling behind, both in emissions goals and industrial capability. If hydrogen does become a cornerstone, late adopters might be dependent on foreign technology and imports (losing economic opportunities). Also, delaying action in transport emissions means continued reliance on fossil fuels with associated climate and health damages.

Implication: This path may appeal to countries with less capacity to invest now, but even those could miss opportunities to pilot small-scale projects that prepare the ground. From a global perspective, if too many adopt “wait-and-see,” the overall hydrogen transition could stall due to lack of collective scale-up.

The five options as summarized in Figure 7 are not entirely mutually exclusive, and indeed many jurisdictions are effectively choosing a hybrid approach – for instance, the EU’s strategy is largely a balanced approach (#4), leaning towards batteries for cars but strongly pushing hydrogen for trucks, industry, and seasonal storage (with heavy funding in those areas). What’s crucial is that policymakers make a clear-eyed assessment of where hydrogen adds the most value (often in synergy with renewable power and in hard-to-electrify transport segments) and design policies accordingly. In the next section, we consider the implications of pursuing – or not pursuing – robust hydrogen policies, which will further clear the stakes involved.

Characteristic	Option 1: Market-Driven Evolution	Option 2: Battery-Electric Focus (H2 Minimal)	Option 3: Hydrogen-Centric Push	Option 4: Balanced Portfolio Approach	Option 5: Delay and Wait
Features	Hands-off approach, minimal intervention	Prioritizes electrification, hydrogen for niche cases	Strong government backing across the value chain	Supports both batteries and hydrogen where suitable	Waits for technology to mature, avoids major investments
Advantages	Low fiscal cost, innovation driven by competition	Simplicity, builds on EV momentum	Accelerates ecosystem development, economies of scale	Diversified risk, recognizes sector diversity	Saves short-term money, learns from others
Disadvantages	Risk of slow adoption, potential to miss targets	Some sectors unsolved, misses grid storage benefits	High upfront spending, risk of picking a winner	Complex policy design, potential for redundant spending	Risk of falling behind, dependence on foreign tech
Implications	Hydrogen stuck in pilot phase	Hydrogen development could stagnate	Catalyzes rapid transition if executed well	Heavy industry likely needs hydrogen	Overall hydrogen transition could stall

Figure 7. Power-to-Gas Hydrogen Policy: 5 Strategic Pathways to Prevent Stagnation and Accelerate Deployment

6. Policy Implications of Power-to-Gas (PtG) Hydrogen: Avoid Billions in Climate and Energy Costs Using Strategic PtG Hydrogen Policies to Cut Tens of Gigatons of CO_2 by 2050

Decisions made (or not made) today on PtG and hydrogen policy will resonate through the coming decades. Here we outline the key implications in two scenarios: one where strong action is taken to promote hydrogen for transport, and one where such action is delayed or weak.

6.1. If We Act (Bold Hydrogen Deployment)

Aligning policies to support PtG hydrogen in transport can yield transformative outcomes. In the action scenario, by 2030 we could see meaningful penetration of hydrogen in heavy transport: for example, hydrogen fuel-cell trucks running on main freight corridors, fuel-cell buses common in cities (providing quiet, zero-emission transit), and even hydrogen-powered trains replacing most diesel on non-electrified lines. This would directly cut greenhouse gas emissions and local air pollutants (NOx, particulate matter) from those vehicles, improving public health and helping cities meet air quality standards. A proactive hydrogen rollout also means harnessing surplus renewables: instead of curtailing wind farms at night or solar at noon when demand is low, that electricity produces hydrogen, effectively storing energy and stabilizing grids. This makes it easier for countries to integrate higher shares of renewables, supporting broader climate goals. Moreover, countries that lead in hydrogen deployment position themselves as technology leaders and exporters. They accumulate expertise in electrolyser manufacturing, fuel cell production, and hydrogen handling, potentially capturing a significant slice of a future hydrogen economy that, as noted, could be worth trillions of dollars. For instance, manufacturing jobs building hydrogen equipment and constructing infrastructure would grow.

An active policy could also spur innovation: as demand rises, companies will compete to improve electrolysers, fuel cells, and storage methods, likely driving costs down faster. According to IEA analysis, current policies are insufficient to hit long-term climate goals, but if ramped up, hydrogen could avoid tens of gigatons of CO_2 emissions by mid-century [90]. In short, acting decisively on hydrogen opens a pathway to a more sustainable and secure energy system. It mitigates climate risks, creates economic opportunities in new industries, and reduces reliance on oil (improving energy security by diversifying fuel sources). It also provides resilience: a diverse energy mix with hydrogen is better able to handle shocks (like oil price spikes or electricity shortages) because hydrogen can be produced and stored domestically.

6.2. If We Do Not Act (Business-as-Usual / Inaction)

Conversely, a lack of significant support for PtG hydrogen in transport could have several negative consequences. Firstly, climate targets would become harder to reach. Transport emissions, which are still rising in many regions, would continue on a high trajectory if we rely solely on incremental improvements. The risk is especially acute for heavy-duty and long-range transport: without hydrogen or a viable alternative, these may remain fossil-fueled and undermine overall decarbonization efforts. The window to keep global warming within 1.5–2°C is closing, and inaction in a quarter of emissions (transport) could necessitate more drastic (and possibly economically disruptive) action later. Secondly, there's an opportunity cost: countries that do not invest in hydrogen now may find themselves importing technology and fuel later. For example, if by 2035 hydrogen trucks become the norm (due to early movers making them cost-effective), late adopters might have to buy all their trucks and hydrogen fuel from abroad, missing out on local value creation. Such countries could also become dumping grounds for older, polluting tech if others move on (e.g., older diesel trucks might continue operating in jurisdictions without strong clean transport policies, along with their pollution). Thirdly, failing to prepare the infrastructure (like not zoning for H_2 stations or not updating safety codes) can lead to future bottlenecks. If and when the market eventually shifts (perhaps driven by external factors like global fuel prices or regulations), trying to build infrastructure last-minute can be costlier and chaotic.

There's also a strategic consideration: energy security. In a future where green hydrogen becomes a major energy commodity, countries without their own production capacity or strategy might remain tied to fossil fuel imports or be forced to import hydrogen, which could be expensive. They also miss the grid benefits of PtG, potentially facing higher renewable curtailment and less grid flexibility. Inaction could even hamper the global progress if major economies hold back – the lack of unified demand signals might mean fewer projects reach final investment decision (currently, less than 5% of announced renewable hydrogen projects had reached FID by 2024, partly due to demand uncertainty [91]). On the social front, continuing with status quo means continued urban air pollution and its health toll, and continued noise and vibration from diesel engines, which have quality-of-life impacts. Figure 8 summarizes the strategic hydrogen deployment for a sustainable future.

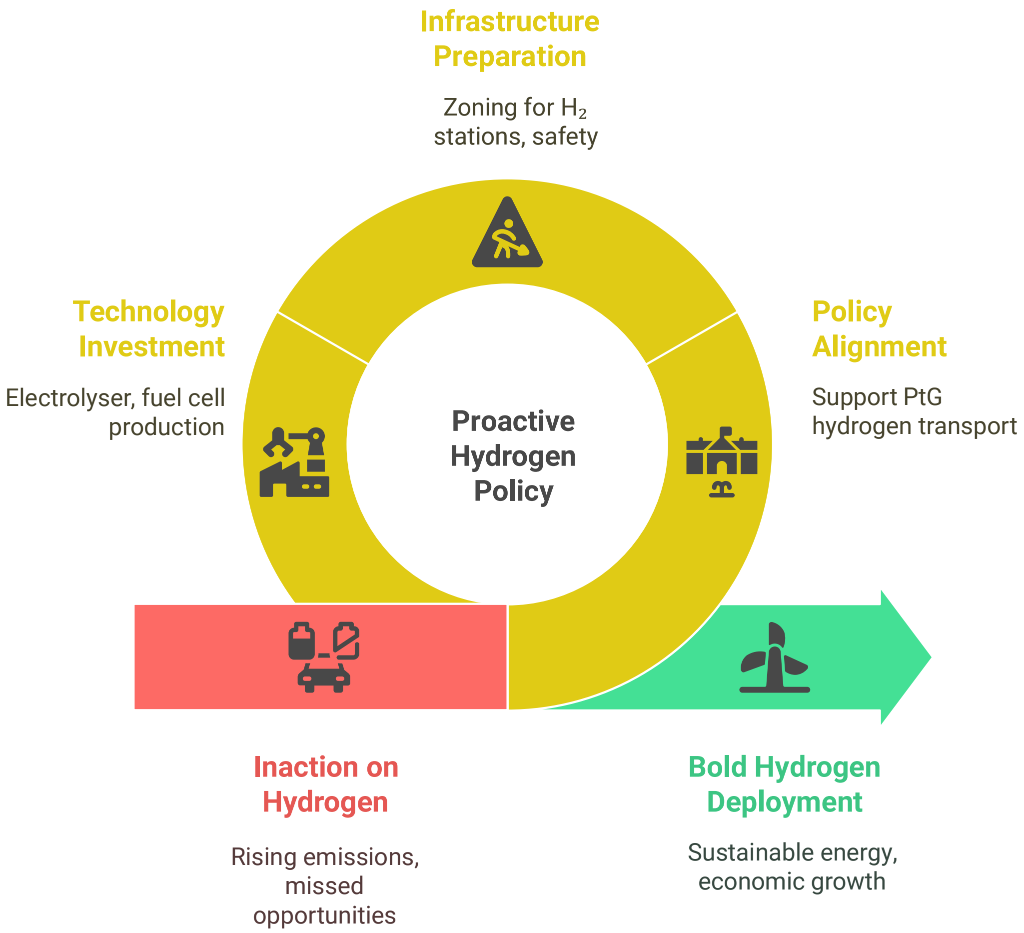


Figure 8. Power-to-Gas Hydrogen Policy for Sustainable Growth: 3 Priority Actions to Cut Emissions and Accelerate Deployment

In summary, the outcomes of robust action vs. inaction are stark as outlined in Figure 8. Action leads to a virtuous circle of innovation, cost decline, and emissions reduction; inaction risks a vicious cycle of stalled technology, persistent emissions, and reliance on old technologies. It is worth noting that pursuing hydrogen for transport does not mean abandoning other solutions – indeed it complements electrification and efficiency. But without hydrogen in the toolkit, a fully decarbonized transport sector is likely out of reach. The implications of inaction thus include scrambling later to adopt hydrogen under pressure, rather than shaping its adoption proactively now. Therefore, the sensible path for policymakers is clear: facilitate the growth of PtG hydrogen in a strategic, well-managed way to reap its rewards and hedge against the alternatives' shortcomings. The next section provides specific recommendations on how to do exactly that.

7. Policy Recommendations for Power-to-Gas (PtG) Hydrogen: Avoid Climate and Competitiveness Risks with Strategic Levers to Secure a $2.5 Trillion Opportunity

Drawing on the above analysis, we propose a set of specific, actionable policy recommendations to enable and accelerate Power-to-Gas hydrogen deployment for transport. These recommendations aim to be SMART – Specific, Measurable, Achievable, Relevant, and Time-bound – and are grounded in successful case studies and expert insights:

7.1. Develop Hydrogen Fueling Infrastructure Networks (Bridging Gaps)

Build out the refueling backbone to instill confidence for vehicle adoption. We recommend that governments, in coordination with industry, invest in a comprehensive hydrogen refueling network along key transport corridors and in urban centers. For example, the EU's AFIR regulation now mandates hydrogen stations every ~200 km along core highways and in all major cities by 2030 [92] – other regions should adopt similar targets or guidelines. This could involve public co-funding for initial stations, streamlining permitting, and public-private partnerships to ensure stations are in place before large vehicle fleets arrive. Specifically, by 2025 establish hydrogen corridors for heavy-duty trucks on at least 2–3 major freight routes in each region (e.g., the US could target West Coast I-5 and a Midwest corridor; India might target the Delhi-Mumbai industrial corridor). By 2030, ensure coverage of all major highway networks with stations at 150–200 km intervals, as well as in every city over 1 million population.

Success metric: number of hydrogen stations and coverage (e.g., X stations covering Y% of national highways). Robust infrastructure is the foundation; without it, even willing fleet operators cannot use hydrogen. Governments can also require that a portion of these stations produce hydrogen on-site from renewables (where feasible) to showcase PtG integration and provide resiliency (off-grid fueling capability).

7.2. Kickstart Demand with Fleet Targets and Procurement

Cultivate early hydrogen vehicle markets via fleet mandates and public procurement. A critical policy is to create assured demand for hydrogen vehicles so that manufacturers and fuel suppliers scale up. We recommend setting zero-emission vehicle (ZEV) targets for specific fleet segments where hydrogen is suitable: for instance, "By 2030, at least 30% of new heavy-duty truck sales must be zero-emission (electric or hydrogen)" with sub-targets or incentives favoring hydrogen for long-range trucks. California and Europe are already moving in this direction for trucks and buses. Additionally, public procurement should lead by example: transit agencies and government fleets (buses, municipal trucks, utility vehicles) should include hydrogen FCEVs in their purchases. For example, mandate that from 2025 onward, all new city bus purchases in major cities be zero-emission, and provide dedicated funding for transit agencies to acquire hydrogen buses where routes require longer range or fast refueling. National postal or logistics fleets could commit to trialing hydrogen trucks for long-haul routes. Japan's government, for instance, helped subsidize hydrogen buses for the Tokyo Olympics to build initial scale.

Success metric: number of hydrogen buses/trucks deployed and percentage of fleet conversions. Policies like purchase grants (e.g. a subsidy per hydrogen truck to equalize the upfront cost with diesel) or operational incentives (like exemption from road tolls or access to low-emission zones for FCEVs) can further encourage adoption. By creating anchor demand (through fleets that refuel at central depots or regular routes), this recommendation also ensures new H_2 stations will have utilization, improving their economics.

7.3. Support Green Hydrogen Production and PtG Projects at Scale

Ensure adequate supply of affordable clean hydrogen by scaling electrolysis. On the supply side, governments should implement measures to vastly increase green hydrogen production capacity, which is the linchpin of PtG. Key actions include capital grants or tax credits for electrolyser installations, and innovative financing tools like contracts-for-difference (CfD) or offtake agreements that guarantee a price for green hydrogen to producers (thus de-risking investment). For example, Germany's H_2Global program acts as an intermediary to buy green hydrogen (or e-fuels) under long-term contracts and sell to end-users, bridging the price gap with subsidiesiea.org. We recommend more countries establish similar mechanisms to assure hydrogen producers that if they build it, demand will be there. Set national targets such as "Deploy X gigawatts of electrolysis by 2030" (the EU set 40 GW as a combined domestic + import target). As a concrete step, by 2025 each major economy should aim to have at least one PtG project in operation at 50–100+ MW scale dedicated to transport fuel (for context, projects of that size are now under development in Europe, the Middle East, and Australia). By 2030, scale this to the GW level – e.g., clusters of electrolyzers at ports or renewable hubs supplying multiple fueling stations or export. Success metric: cost of green hydrogen per kg (target <$4–5/kg by 2025 in many regions, and ~$2/kg by 2030 with economies of scale), and total production volume vs. demand. Importantly, ensure these projects use additional renewable power (to keep hydrogen truly low-carbon) and pair them with flexibility (like using electrolyzers to absorb off-peak power). Supporting R&D in next-gen electrolysis (e.g., new materials for higher efficiency or reversible fuel cells) is also part of this, to improve the PtG process over time.

7.4. Implement Incentives for End-Users and Industry Adoption

Make hydrogen a financially attractive choice for end-users. Even with infrastructure and supply, the fuel and vehicle cost must be compelling. We recommend time-bound incentives such as tax credits, rebates, or operational subsidies to narrow the cost gap between hydrogen and incumbent fuels during the scale-up phase. For example, a fuel tax exemption or credit for green hydrogen used in transport can lower its price at the pump to consumers. California's Low Carbon Fuel Standard credit is an example that effectively subsidizes each kg of H_2 by rewarding its carbon benefit. Another lever is reducing taxes or road fees for hydrogen vehicles (many countries waive highway tolls or city congestion charges for zero-emission vehicles already). We also suggest incentivizing the industrial side: encourage sectors like steel, ammonia, or refining to source green hydrogen (perhaps via a clean product standard or mandate). This creates synergy – the more industries buy green hydrogen, the more supply scales up and costs drop for transport uses. A 2024 analysis pointed out that only a symbolic <1% of hydrogen today is low-carbon [91], indicating huge room for growth; coordinated demand-pull across sectors can change that. Success metric: increase in hydrogen demand from transport (e.g., measure tons of H_2 sold for vehicles), and price parity timelines (track how incentives bring forward the year when running a hydrogen truck is cheaper than diesel on a total cost basis). Policymakers can sunset these incentives as targets are met and the market matures – the goal is not permanent subsidy but jump-starting a self-sustaining market.

7.5. Establish Robust Standards, Regulations, and Safety Protocols

Create a supportive regulatory environment with clear rules of the road. Governments should develop and implement comprehensive standards for hydrogen fuel and technology – this includes everything from fuel quality standards (so that hydrogen purity at any station is suitable for all fuel cells) to technical standards for hydrogen tanks, valves, and nozzles (ensuring any vehicle can refuel at any station globally, much as gasoline nozzles are standardized). Harmonizing these standards internationally is critical, and forums like ISO and the IPHE should be leveraged; indeed, 37 governments at COP28 committed to mutual recognition of certification schemes for hydrogen [48]. We recommend accelerating work on a global green hydrogen certification (to verify emissions for each batch of H_2) which enables cross-border trade and assurance of sustainability. On safety, regulators must update codes for hydrogen production sites, storage, and vehicles – drawing on industrial hydrogen's long track record – to ensure safe deployment at scale and to educate local authorities (fire departments, etc.). Streamlining permitting processes for PtG plants and hydrogen stations can significantly speed up implementation; this could involve designating hydrogen infrastructure as strategically important with fast-track approvals, provided safety and environmental criteria are met. Furthermore, regulatory clarity on issues like whether hydrogen pipelines fall under natural gas regulations or new ones, how to handle hydrogen in gas grids, and vehicle regulations (for example, allowing slightly heavier trucks to accommodate hydrogen tanks without sacrificing payload, a policy Europe adopted) will remove roadblocks. Success metric: time taken to approve new hydrogen projects (should decrease), and zero major safety incidents as deployment scales (indicating regulations and training are effective). Clear regulations also help alleviate public concerns and counteract any NIMBYism (not-in-my-backyard opposition) by demonstrating that hydrogen is being managed with rigorous oversight.

7.6. Foster Innovation and Skills Through Research & Training Programs

Invest in the human and intellectual capital needed for a hydrogen economy. We recommend dedicated funding for R&D in next-generation PtG and hydrogen technologies – for instance, improving electrolyzer efficiency (perhaps through solid oxide or novel catalysts), developing hydrogen storage materials (like solid hydrogen carriers or better composites for tanks), and enhancing fuel cell durability and power density for vehicles. Governments could establish hydrogen innovation centers or public-private research partnerships (similar to how battery research got a boost in many countries). Another aspect is supporting workforce development: create training programs at technical colleges and through workforce initiatives to certify technicians for hydrogen equipment maintenance, first responders for hydrogen safety, and engineers specializing in hydrogen systems. This ensures that as infrastructure and fleets grow, there is a competent labor force to design, build, and operate them safely. Tied to this, public awareness campaigns about hydrogen – focusing on its safety (dispelling myths), environmental benefits, and proper usage – can build social acceptance. Consider incorporating hydrogen topics into existing STEM educational curricula or energy literacy programs. Success metric: number of new patents or breakthroughs in hydrogen tech (as a proxy for innovation vitality), and number of trained professionals entering the hydrogen sector. A well-prepared workforce will reduce delays and costs for projects and attract private investment (companies go where talent is available). Additionally, innovation can lead to cost reductions making the whole transition more affordable. For example, breakthroughs in electrolysis could cut electricity use or allow more flexible operation, directly lowering hydrogen cost. Continuous improvement will keep PtG competitive and adaptive.

7.7. Encourage International Collaboration and Trade Frameworks

Leverage global cooperation to accelerate learning and market formation. Given that hydrogen development is happening worldwide, collaboration can prevent duplication and drive faster progress. Policymakers should actively participate in international partnerships – such as sharing best practices for hydrogen safety, coordinating on infrastructure that crosses borders (e.g., a pan-European hydrogen highway network or hydrogen shipping lanes), and aligning subsidy schemes to avoid a zero-sum subsidy race. One concrete recommendation is to create or join “Hydrogen Valleys” or regional hubs in collaboration with neighboring countries, where each country can specialize in part of the value chain (for instance, one with abundant renewables produces hydrogen, another with vehicle manufacturing expertise builds fuel cell vehicles, and both share the resulting benefits/trade). The Global Clean Energy Ministerial Hydrogen Initiative and Mission Innovation challenge on hydrogen are existing platforms to reinforce. Additionally, work through trade agreements to reduce tariffs on hydrogen technologies and establish certification for green hydrogen imports/exports (similar to how renewable electricity certificates work). Countries like Chile, Australia, Morocco (renewables-rich) are forging export agreements with import-aiming countries like Japan, Germany – these should be facilitated with clear rules and possibly financial support (e.g., guarantees or political risk insurance for first-of-a-kind international hydrogen supply chains). Success metric: number of bilateral or multilateral hydrogen cooperation agreements signed, volume of hydrogen or derivative fuels traded internationally by 2030. The aim is to create a global market for clean hydrogen where supply from the best renewable locations can meet demand in industrial or population centers, to the benefit of all. This will also help align standards (as noted) and avoid each country reinventing the wheel on safety and regulation. Moreover, a coordinated global push can send a consistent demand signal to manufacturers (for electrolysers, fuel cells, vehicles), leading to larger production runs and lower unit costs – a virtuous cycle.

Each of these recommendations reinforces the others; together they form an integrated policy package. For instance, building infrastructure (Rec #1) is far more effective when coupled with fleet targets (Rec #2) that guarantee usage. Supporting production (Rec #3) ensures the infrastructure has something clean to dispense, while incentives (Rec #4) make sure consumers come to the table. Standards (Rec #5) underpin everything by building trust and interoperability. Innovation and skills (Rec #6) sustain the momentum long-term, and international collaboration (Rec #7) expands the scale and reduces costs globally. Policymakers should adapt the specific numbers and timelines to their national context – but the overall blueprint remains: invest, enable, and connect the dots across the hydrogen value chain to make hydrogen in transport viable. Evidence from early projects shows that when these elements come together, hydrogen mobility can flourish. The next section sketches an implementation roadmap – essentially, how to operationalize these recommendations with assigned roles, timelines, and financing. Figure 9 summarizes the policy recommendations for power-to-gas technology.

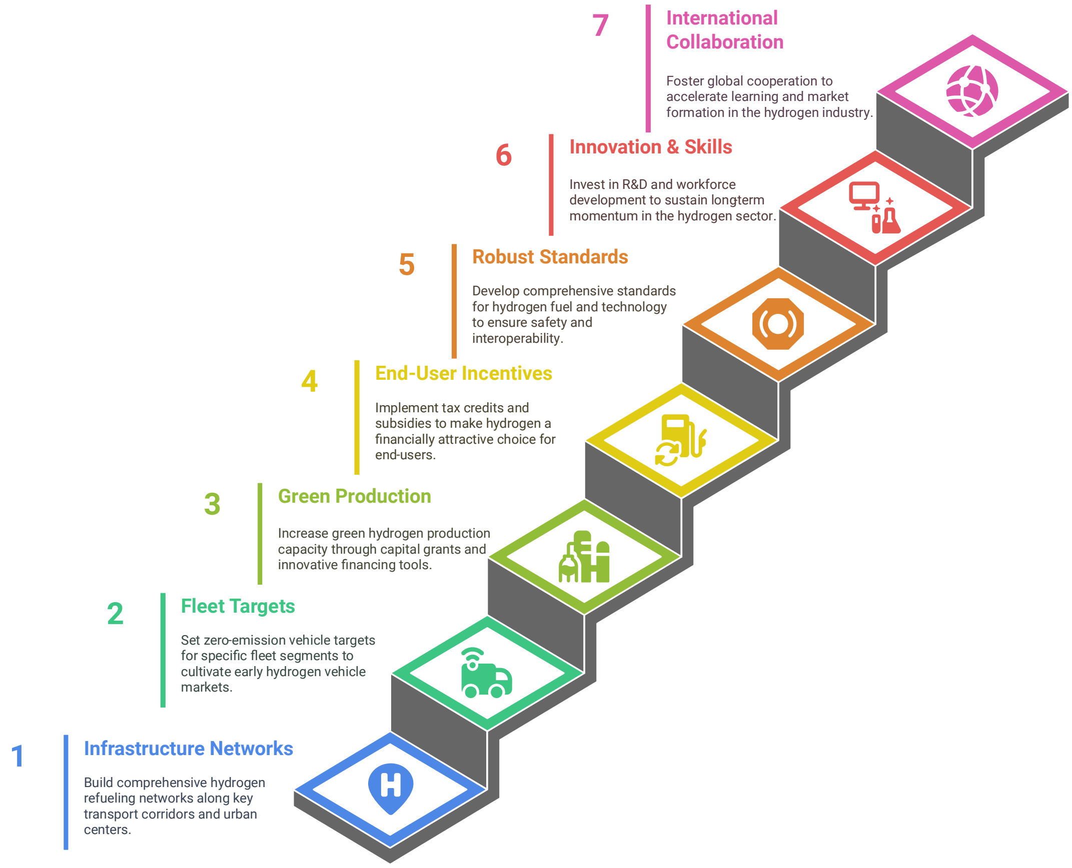


Figure 9. Power-to-Gas Hydrogen Transport in 7 Steps: From Infrastructure to International Collaboration for a Cost-Competitive Ecosystem

Table 4 provides a comprehensive roadmap for governments and stakeholders to scale Power-to-Gas (PtG) hydrogen technology for clean transport. It outlines ten critical intervention areas—ranging from regulatory design and financial incentives to infrastructure development and national energy alignment—each analyzed across five dimensions: key challenges, strategic responses, expected impacts, policy implications, and actionable plans. This matrix serves as both a diagnostic and a solution blueprint, offering policymakers a structured approach to overcome implementation barriers, coordinate multi-actor efforts, and maximize the environmental and economic benefits of PtG deployment. Designed to be adaptable to local contexts, the framework bridges long-term vision with short-term action, enabling measurable progress toward decarbonized mobility systems.

Table 4. Power-to-Gas Hydrogen Policy Framework: Strategic Levers for Scalable and Sustainable Transport Transformation

Policy Area	Challenges	Strategy	Impact	Implication	Action Plan
Regulatory Framework	Fragmented and outdated regulations hindering PtG adoption	Enact unified national hydrogen codes and standards	Streamlined approval and accelerated project implementation	Requires cross-ministerial coordination and regular updates	Establish hydrogen-specific permitting framework by 2025
Financial Incentives	High upfront costs and uncertain ROI for private investors	Offer capital subsidies, tax credits, and carbon contracts-for-difference	De-risked investments and faster market uptake	Significant short-term public expenditure justified by long-term savings	Implement performance-based subsidy programs by 2026
Stakeholder Engagement	Lack of coordination among key actors	Create a national hydrogen task force involving public and private stakeholders	Improved alignment and collaboration across sectors	Institutional support and regular engagement forums are critical	Launch stakeholder platform with quarterly reviews
Research and Development Support	Insufficient funding for hydrogen-specific R&D	Launch targeted hydrogen R&D funding and demonstration grants	Accelerated technology readiness and innovation cycles	Need for international collaboration to leverage global advancements	Fund 10 flagship R&D projects and publish annual findings
Capacity Building and Training	Limited availability of trained workforce	Develop hydrogen training curricula with industry-academia partnerships	Increased workforce readiness and project efficiency	National skills inventory and upskilling strategy must align	Deploy regional training centers by 2026 with 1,000+ trainees/year
Sustainability Standards	Absence of harmonized sustainability metrics for hydrogen	Align PtG deployment with lifecycle emissions and water usage criteria	Ensured environmental integrity and social license to operate	Monitoring tools and verification mechanisms must be established	Publish hydrogen sustainability benchmarks and adopt in procurement
Monitoring and Evaluation	Lack of transparent and consistent tracking mechanisms	Institute key performance indicators and milestone reviews	Enabled evidence-based adjustments and accountability	High-quality data collection essential for adaptive policymaking	Report annually on hydrogen KPIs and adjust support levels
Public Awareness and Education	Low public understanding and trust in hydrogen technologies	Run national awareness campaigns and educational initiatives	Boosted consumer acceptance and smoother adoption	Must address misinformation and ensure inclusive messaging	Incorporate hydrogen into school curricula and media outreach
Infrastructure Development	Limited refueling infrastructure and grid integration	Fund hydrogen corridors and co-locate production with renewable sources	Reduced range anxiety and increased end-user confidence	Grid compatibility, land access, and permitting must be streamlined	Complete 100 H_2 refueling stations along key transport routes by 2030
Integration with National Energy Plans	Hydrogen not clearly reflected in long-term energy plans	Embed hydrogen targets and timelines in national decarbonization strategies	Coherent policy execution and resource optimization	Periodic reviews to ensure integration with evolving energy scenarios	Align hydrogen policy with national climate and energy plans by 2027

8. Implementation Plan for Power-to-Gas (PtG) Hydrogen Technology: Mobilize $300 Billion through 6 Financing Levers to Scale Power-to-Gas Hydrogen by 2050

Translating policy recommendations into on-the-ground reality requires careful planning. In this section, we outline an implementation plan for scaling up PtG hydrogen in transport, detailing the key actors, timelines, and funding mechanisms involved. This plan is structured in phases – recognizing that building a hydrogen economy is a gradual process – and assigns responsibilities to ensure accountability.

8.1. Key Actors and Responsibilities for PtG

Achieving a hydrogen-powered transport sector is a multidisciplinary endeavor. Figure 10 summarizes key actors and responsibilities for PtG-based hydrogen technology.

Figure 10. Power-to-Gas Hydrogen Transport Ecosystem: 6 Key Stakeholders Driving a Unified Approach to Scale Mobility

8.1.1. National Governments and Agencies

These set the strategic vision, provide funding, and enact regulations. Ministries of energy, transport, environment, and finance all play roles. For example, energy ministries might oversee electrolyser deployment programs, transport departments might handle vehicle and infrastructure standards, and finance ministries may create tax incentives. Governments should designate a lead coordinating body or task force (e.g., a National Hydrogen Council) that brings together these agencies to align policies. They also represent the country in international forums.

8.1.2. Local Governments and Cities

City and regional authorities often operate transit fleets and can pilot hydrogen buses or trucks for waste collection, etc. They handle local permitting for stations and can offer local incentives (such as allowing H_2 vehicles in low-emission zones or preferential parking). Coordination between national and local levels is vital: for instance, national funding for a bus comes to fruition when a city agrees to deploy that bus and has fueling ready. Cities like Aberdeen or Los Angeles have shown leadership in hydrogen projects – scaling this up means engaging many more city governments through information-sharing networks (e.g., C40 Cities Hydrogen Network, if established).

8.1.3. Industry (Private Sector)

This includes vehicle manufacturers (developing FCEVs across different platforms), fuel suppliers (electrolyser companies, industrial gas firms, oil & gas transitioning to hydrogen), and infrastructure developers. The private sector will do the bulk of project execution – building plants, stations, and vehicles – especially as the market matures. To implement, clear signals and public-private partnership (PPP) models are needed. For example, a consortium of a truck OEM, a hydrogen producer, and a retailer might jointly invest in a corridor project. Industry also co-funds R&D and training initiatives (Rec #6), working with universities and training institutes on curricula for hydrogen tech.

8.1.4. International Organizations and Alliances

Bodies such as the International Energy Agency (IEA), International Renewable Energy Agency (IRENA), and development banks (World Bank, regional development banks) can facilitate funding, provide technical assistance, and help standardize best practices. For developing nations especially, multilaterals can offer concessional financing or guarantees for hydrogen projects – reducing the perceived risk for private investors. Alliances like the Hydrogen Council (an industry group) and inter-governmental partnerships can help align efforts. In implementation, these actors might run knowledge exchanges, publish progress reports, or manage international funding programs (like a global fund for clean hydrogen deployment in emerging markets).

8.1.5. Academia and Research Institutes

Universities and labs will carry out the R&D needed, supported by government grants and industry collaborations. During implementation, they can also act as third-party monitors or evaluators for pilot projects, documenting performance and suggesting improvements. For instance, a national lab might collect data on hydrogen bus performance in different climates to inform future procurement.

8.1.6. Civil Society and Public

Non-governmental organizations (NGOs) focusing on clean air, climate, or technology can support by raising awareness, ensuring transparency, and holding stakeholders accountable to safety and environmental standards. The public at large is an important stakeholder – their acceptance will determine how smoothly projects proceed. Public engagement (hearings, community benefits agreements for big projects, educational outreach) should be integrated at each stage.

Each actor has defined responsibilities but also must communicate and collaborate. A possible governance structure is to create a multi-stakeholder Hydrogen Implementation Task Force that meets regularly to review progress, troubleshoot issues, and adjust actions. This could be mirrored at different levels (national task force, local hydrogen working groups, etc.).

8.2. Timeline (Short, Medium, Long-Term Milestones) for PtG

A phased timeline helps manage priorities. Here's a suggested timeline with milestones:

8.2.1. Short-Term (2025–2027)

Laying the groundwork. In this phase, focus on pilot projects and preparatory actions. Key milestones:

- By 2025, launch infrastructure pilots: at least 3–5 hydrogen refueling stations in each participating country's key corridors or cities (if starting from zero), or significant expansion if already started. Ensure these pilots include a mix of production methods (some on-site electrolysis using renewables, some delivered hydrogen) to gain experience.
- By 2025, deploy early fleets: e.g., 50–100 hydrogen buses in public transit across several cities, and 50+ hydrogen trucks in real commercial service (perhaps through a funded demonstration program with logistics companies). Also put a few hydrogen trains in service if rail lines are available.
- By 2025, enact enabling legislation/regulations: finalize standards for fueling (nozzle, pressure standards, etc.), safety codes updated, and any ZEV mandate regulations legally in force to start influencing manufacturer plans.
- Initiate the training programs and academic R&D grants by 2024, so that by 2025 the first cohort of hydrogen technicians and engineers are in training.
- By 2026, have the financial mechanisms up and running: e.g., the first contracts-for-difference signed for green hydrogen supply, first hydrogen hub grants disbursed (like the US hubs, which are slated to break ground mid-decade).
- An important milestone is cost monitoring: by 2027, aim for green hydrogen production cost to fall (in best-case projects) to around $4/kg or less, and fuel cell system costs to decline (track $/kW of fuel cell, hoping to get near $500/kW or below in volume).

8.2.2. Medium-Term (2028–2035)

Scale-up and integration. This period sees expansion from pilots to commercial scale.

- By 2030, achieve the infrastructure coverage goals: e.g., hydrogen stations every 200 km on highways and in all cities >500k people in Europe; similarly ambitious coverage in Japan, Korea, parts of US, China's designated hydrogen clusters, etc. Developing countries might target key trade routes and major urban centers by 2035.
- By 2030, vehicle rollout: targets could be, for instance, at least 25% of new city buses are hydrogen FCEVs (especially in large/medium cities), at least 10,000 hydrogen trucks on roads globally (with representation across North America, Asia, Europe), and hydrogen trains replacing diesel on 10% of unelectrified rail routes in Europe and 5% in other adopting regions. China's goal of 50k FCEVs by 2025 implies perhaps 100k+ by 2030; similarly, Korea's goal of ~0.5–1 million by 2035 might be on the horizon.
- The 2030 milestone for production: ensure sufficient green hydrogen supply to meet the demand. For example, the EU's target of 10 million tonnes of domestic renewable H_2 production by 2030 [93]– if on track, transport should comprise a healthy fraction of its uptake (40% per IEA projection [51]). Other countries should have proportional targets (like India might target a few million tons by 2030, etc.).
- Integration means linking sectors: by 2030–2035, start using hydrogen storage for energy system resilience (e.g., surplus summer solar stored as hydrogen for winter power or transport). Demonstrate a couple of power-to-hydrogen-to-power systems at grid scale (some countries plan "hydrogen turbines" or fuel cells feeding grid as backup).
- Cost milestones: aim for delivered hydrogen fuel cost to parity with diesel on a per-km basis in at least some uses by 2030 (this could be around \$3–4/kg H_2, which in an efficient fuel cell truck approximates the cost per km of diesel). Fuel cell system cost < \$200/kW by 2030 is a goal set by DOE and others, which would dramatically improve vehicle economics.
- Mid-term review: around 2030, conduct a comprehensive review of progress and adjust policies. If some targets lag (e.g., heavy truck uptake), consider tightening mandates or increasing incentives in that area. If some technologies leap ahead (say, battery improvements reduce need for hydrogen in certain uses), refocus hydrogen efforts where most valuable (like maybe more in aviation/maritime).

8.2.3. Long-Term (2036–2050)

Maturation and optimization. In this phase, hydrogen in transport moves to full maturity as a normal part of the energy system.

- By 2040, the expectation is hydrogen and electric dominate new sales in their respective optimal domains. For example, near 100% of new buses and trucks sold in leading markets are zero-emission (with hydrogen taking a significant portion in long-range categories). Countries like South Korea envision ~6 million hydrogen cars by 2040 [58] – globally, we might see tens of millions of FCEVs by 2040 if all goes well, especially as older fleets retire.

- Infrastructure by 2040 would be dense: not only along highways, but also at ports (for ships, material handling equipment) and airports (fuel for hydrogen or e-fuel aircraft, and baggage tractors, etc.). Possibly pipelines dedicated to hydrogen connecting industrial zones and fueling depots are operational, reducing reliance on trucked delivery.
- Hydrogen production in 2040–2050 likely becomes a commodity business: large-scale international trade may emerge (e.g., shipping ammonia or liquid hydrogen from Australia to Japan, or North Africa to Europe). The implementation plan should ensure regulatory and physical connections for that (port facilities, import terminals) are built in the 2030s.
- By 2050, the vision is that transport is near full decarbonization. Hydrogen (including synthetic fuels from hydrogen) might supply on the order of 15–20% of transport energy globally (with electricity covering much of the rest), aligning with net-zero scenarios [44]. The plan's ultimate milestone is the contribution of hydrogen to climate goals: by 2050, hydrogen could abate ~80 Gt CO_2 cumulatively [90] if scaled across sectors, a meaningful dent in climate change. Transport's share of that would be significant.
- At this stage, government roles shift more to oversight and ensuring fair markets (since hopefully subsidies are phased out by then and hydrogen is self-sustaining). The hydrogen sector becomes part of the broader clean energy economy. Emphasis might turn to efficiency and optimization (e.g., ensuring that hydrogen is used where most sensible and that renewable capacity keeps up to supply it without diverting from direct electrification).

This timeline is ambitious but illustrates the need for early action and sustained effort. Regular checkpoints (e.g., 2025, 2030, 2040) allow for recalibration. It's also important for countries with different starting points to tailor the timeline – some may reach certain milestones later, but the sequence (pilot → scale → mainstream) generally holds. Figure 11 shows the timeline (short, medium, long-term milestones).

8.3. Funding and Financing Mechanisms for PtG

Implementing this plan will require significant investment, and smart financing can maximize impact while minimizing public burden. Key financing elements include:

8.3.1. Public Investment

Government budgets will initially fund a lion's share of infrastructure pilots, R&D, and incentives. This can be through direct budget allocations (e.g., a national hydrogen program fund), dedicated revenues (like hypothecated carbon pricing revenue or fuel taxes redirected to clean fuels), or stimulus packages (as seen in post-COVID recovery plans emphasizing green hydrogen). For example, Europe's "Next Generation EU" recovery instrument allocated billions to hydrogen. Public financing should be designed to crowd-in private capital, not permanently replace it. For instance, offer matching funds for companies that invest in hydrogen stations or vehicles, or use public money to de-risk projects (through guarantees or taking first-loss equity in projects).

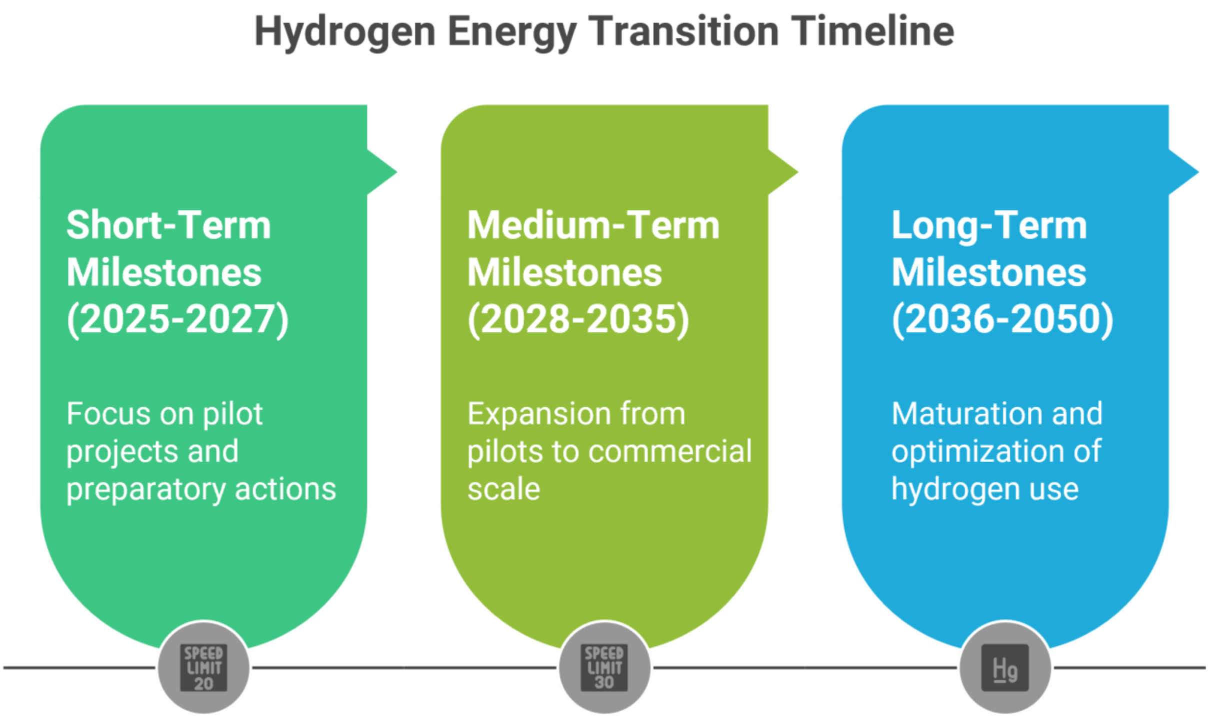


Figure 11. Power-to-Gas Hydrogen Impact Across 3 Milestones: Pilot, Scale, and Optimize from 2025 to 2050

8.3.2. Private Investment and PPPs

As the sector proves its business case, private investors (energy companies, infrastructure funds, venture capital in technology, etc.) will finance most large-scale projects. Governments should establish clear frameworks for Public-Private Partnerships: e.g., a government might tender out the development of a network of H_2 stations to consortia, offering some subsidy but expecting private co-investment and operation. Likewise, city bus deployments can be structured as turnkey contracts where a provider delivers buses and hydrogen fuel as a service, with the city paying per kilometer (this transfers some risk to the provider). Private capital can also be tapped via green bonds or sustainable finance instruments – issuing green hydrogen bonds to raise money for electrolyser plants or infrastructure, repayable from future revenue of hydrogen sales.

8.3.3. International and Development Funding

Especially for developing economies, securing funding from sources like the World Bank, regional development banks (ADB, AfDB, IDB, etc.), and climate funds (Green Climate Fund, Global Environment Facility) can be pivotal. These institutions are increasingly interested in green hydrogen as a decarbonization tool. They can provide soft loans, grants for technical assistance, or guarantees that reduce risk for private investors. A concrete example: the European Investment Bank and others provided a €225 million fund for Chile's hydrogen strategy [62] – other countries can similarly leverage international climate finance. There's scope for new blended finance facilities that combine public, private, and philanthropic funds to underwrite early hydrogen projects that have high climate impact but are not yet bankable commercially.

8.3.4. Cost-sharing and User Pays Models

Over time, costs can be passed to beneficiaries. For instance, once trucks realize operational savings from hydrogen (if fuel becomes cheap and maintenance is lower than diesel), fleet operators can pay usage fees that recoup infrastructure investment. Road tolling schemes could charge higher for polluting vehicles and less or zero for clean vehicles – effectively making polluters indirectly fund the infrastructure for cleaners. Also, incorporate hydrogen in existing energy tariffs or portfolio standards: e.g., utilities might invest in electrolysers as part of obligations to store renewable energy, with the cost spread across energy consumers (this model was used in some places to fund grid batteries, etc.).

8.3.5. Economic Incentive Alignment

Use market tools to make hydrogen attractive economically. Carbon pricing is one – a robust carbon tax or emission trading price makes fossil fuels more expensive relative to H_2. Another is things like feebate systems (apply fees on high-emission vehicles and use the revenue to subsidize low-emission ones). The plan should integrate such mechanisms by, say, 2025–2030 once initial systems to measure and enforce are ready. If, for example, a logistics firm has to pay for its CO_2 emissions, investing in hydrogen trucks becomes more logical financially. Some countries might opt for low-carbon fuel standards or mandates that fuel suppliers blend in a certain share of renewable fuels (could include hydrogen for refueling networks), creating a guaranteed market.

8.3.6. Monitoring and Adjusting Financial Support

Over the implementation period, financial support should be adjusted as technology matures. Subsidies can be structured to phase out as targets are met – e.g., a subsidy per kg of hydrogen could automatically taper once hydrogen price falls below a threshold or after X years of operation. This ensures fiscal sustainability. Transparency in funding is important too: annual reports on how much public money went into hydrogen and what outcomes achieved (stations built, etc.) will help maintain political support and allow course corrections.

In terms of scale, various analyses indicate that reaching a truly global hydrogen economy will require on the order of hundreds of billions of dollars in investment over the next 30 years. While that number is large, it is comparable to what was invested historically in oil & gas infrastructure – the key is phasing and leveraging private capital. For an individual nation, the plan might budget, say, $1–2 billion in public funding over the first 5 years (for a mid-sized economy) to catalyze tens of billions in private follow-on investment by 2030. Wealthier regions (EU, US, East Asia) are indeed already mobilizing such sums (the US IRA alone offers roughly ~$9.5 billion specifically for hydrogen plus the uncapped tax credits which could total tens of billions by 2030).

In summary, implementation requires: clear assignment of who does what (actors), a timeline with checkpoints, and ample but well-structured funding. It is a complex undertaking, but the roadmap above breaks it into manageable pieces. Each phase builds on the previous, derisking the next. By taking these steps, policymakers can move from strategy to execution – turning the promise of PtG hydrogen for transport into a tangible, operational reality. Figure 12 summarizes the funding and financing mechanisms for PtG.

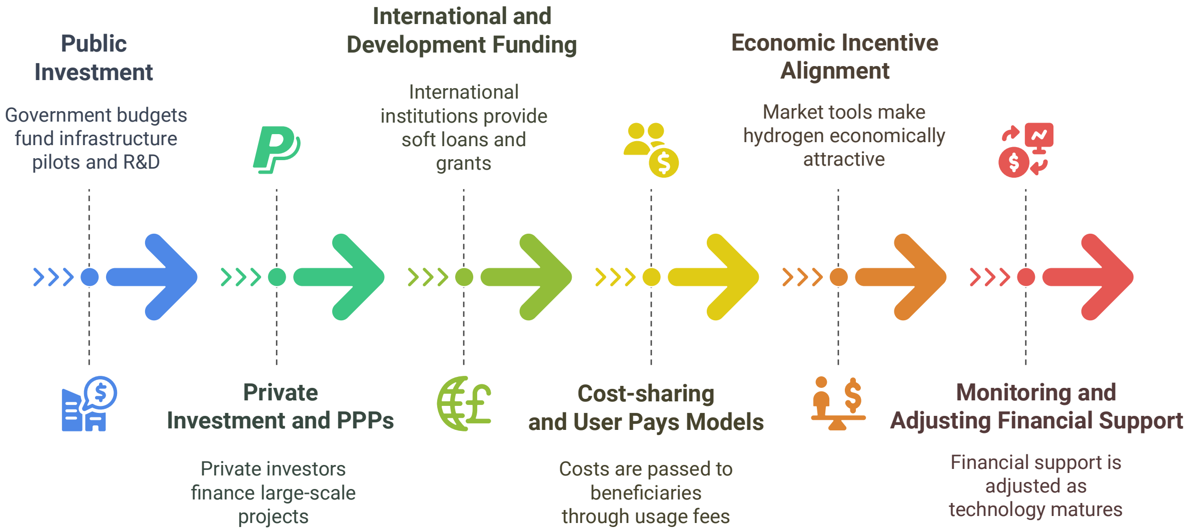


Figure 12. Power-to-Gas Hydrogen Scale-Up with 6 Financing Levers: From Public Investment to Cost-Sharing Models

9. Conclusion: Seizing Hydrogen Transport Opportunity by Turning Power-to-Gas from Promise to Policy

Transporting people and goods reliably without polluting the planet is one of the great challenges of our time. PtG offers free mobility by converting surplus renewables into hydrogen fuel. If the electricity comes from wind, solar, or other renewables, the resulting hydrogen is entirely green and carbon-free. This approach effectively links the power sector with the gas and transport sectors, enabling renewable energy to fuel mobility.

Hydrogen has been regarded by many as promising fuel. With Power-to-Gas technology and strong policy support, that future is now within reach – particularly in the transport sector where hydrogen's advantages truly shine. This global policy brief has examined why and how hydrogen from PtG can power the next generation of clean mobility, from buses and trucks to trains and ships. The evidence is clear: hydrogen can drastically cut emissions and pollution from transport, complementing direct electrification and filling crucial gaps in our decarbonization toolkit. Countries worldwide have recognized its potential, as seen by the wave of hydrogen strategies and investments pouring forth in recent years. Yet, realizing this potential requires coordinated action today.

For policymakers, the task is to translate ambition into implementation. That means building the infrastructure before it's needed, nudging industries and consumers through incentives and standards, and collaborating across borders to share success stories and lessons learned. It means being proactive – seizing the economic opportunities of hydrogen (jobs, technology leadership, energy security benefits) rather than reacting later to global shifts. The analysis of options showed that a balanced approach – one that pairs hydrogen with other solutions in the right places – is both feasible and prudent. The recommendations provided, from infrastructure rollout to R&D investment, form a comprehensive playbook that decision-makers can adapt to local contexts.

The stakes of inaction are high: continued oil dependence, missed climate targets, and possibly abandoning leadership in a promising hydrogen economy. By contrast, the benefits of decisive action include cleaner air, a safer climate, and participation in what could be one of the major industries of the 21st century. Recall how South Africa's president described the hydrogen mining truck project – not just as one machine, but as "the genesis of an entire ecosystem powered by hydrogen" [54]. This highlights the transformative power that lies in getting hydrogen right: it sparks an ecosystem change, linking renewable energy with transport and heavy industry in a virtuous cycle.

In conclusion, Power-to-Gas for hydrogen transport is a policy opportunity we cannot afford to miss. It aligns technology with policy for a sustainable outcome that benefits both the planet and the economy. The road ahead will have challenges – costs, coordination, public perception – but with international cooperation and sustained commitment, these can be overcome. Policymakers reading this policy paper are encouraged to take the next steps: convene stakeholders, set concrete targets, and allocate resources per the implementation plan. The experiences from around the world provide confidence that we know what needs to be done; now it is a matter of doing it. By acting now, we can ensure that hydrogen moves from promise to practice, fueling a cleaner future for global transport.

Competing Interest

The author declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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The author solely carried out the conception, analysis, writing, and revision of the manuscript.

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References

[1] U. Neuling and N. Bullerdiek, "Classification of Power-to-Gas (PtG) and Power-to-Liquid (PtL) Processes," in *Powerfuels*: Springer, 2025, pp. 493-513.

[2] A. Meydani, H. Shahinzadeh, G. B. Gharehpetian, M. M. Hayati, and M. Abapour, "Power-to-X: Pioneering the Future of Sustainable Energy," in *Power-to-X in Regional Energy Systems*: CRC Press, 2025, pp. 1-56.

[3] A. Meydani, H. Shahinzadeh, G. B. Gharehpetian, M. M. Hayati, and M. Abapour, "Exploring the Role of Power-to-X in Energy Hubs," in *Power-to-X in Regional Energy Systems*: CRC Press, pp. 129-183.

[4] A. Ciancio, G. L. Basso, L. M. Pastore, and L. de Santoli, "Carbon abatement cost evolution in the forthcoming hydrogen valleys by following different hydrogen pathways," *International Journal of Hydrogen Energy,* vol. 64, pp. 80-97, 2024.

[5] H. Madi, T. Schildhauer, and E. Moioli, "Comprehensive analysis of renewable energy integration in decarbonised mobility: Leveraging power-to-X storage with biogenic carbon sources," *Energy Conversion and Management,* vol. 321, p. 119081, 2024.

[6] M. Götz *et al.*, "Renewable Power-to-Gas: A technological and economic review," *Renewable Energy,* vol. 85, pp. 1371-1390, 2016/01/01/ 2016, doi: https://doi.org/10.1016/j.renene.2015.07.066.

[7] C. Wulf, J. Linßen, and P. Zapp, "Review of Power-to-Gas Projects in Europe," *Energy Procedia,* vol. 155, pp. 367-378, 2018/11/01/ 2018, doi: https://doi.org/10.1016/j.egypro.2018.11.041.

[8] A. Mazza, E. Bompard, and G. Chicco, "Applications of power to gas technologies in emerging electrical systems," *Renewable and Sustainable Energy Reviews,* vol. 92, pp. 794-806, 2018/09/01/ 2018, doi: https://doi.org/10.1016/j.rser.2018.04.072.

[9] A. Varone and M. Ferrari, "Power to liquid and power to gas: An option for the German Energiewende," *Renewable and Sustainable Energy Reviews,* vol. 45, pp. 207-218, 2015/05/01/ 2015, doi: https://doi.org/10.1016/j.rser.2015.01.049.

[10] A. Lewandowska-Bernat and U. Desideri, "Opportunities of power-to-gas technology in different energy systems architectures," *Applied Energy,* vol. 228, pp. 57-67, 2018/10/15/ 2018, doi: https://doi.org/10.1016/j.apenergy.2018.06.001.

[11] C. Wulf, J. Linssen, and P. Zapp, "Chapter 9 - Power-to-Gas—Concepts, Demonstration, and Prospects," in *Hydrogen Supply Chains*, C. Azzaro-Pantel Ed.: Academic Press, 2018, pp. 309-345.

[12] S. Schiebahn, T. Grube, M. Robinius, V. Tietze, B. Kumar, and D. Stolten, "Power to gas: Technological overview, systems analysis and economic assessment for a case study in Germany," *International Journal of Hydrogen Energy,* vol. 40, no. 12, pp. 4285-4294, 2015/04/06/ 2015, doi: https://doi.org/10.1016/j.ijhydene.2015.01.123.

[13] A. Lewandowska-Bernat and U. Desideri, "Opportunities of Power-to-Gas technology," *Energy Procedia,* vol. 105, pp. 4569-4574, 2017/05/01/ 2017, doi: https://doi.org/10.1016/j.egypro.2017.03.982.

[14] M. Ozturk and I. Dincer, "A comprehensive review on power-to-gas with hydrogen options for cleaner applications," *International Journal of Hydrogen Energy,* vol. 46, no. 62, pp. 31511-31522, 2021/09/08/ 2021, doi: https://doi.org/10.1016/j.ijhydene.2021.07.066.

[15] M. Sterner and M. Specht, "Power-to-Gas and Power-to-X—The History and Results of Developing a New Storage Concept," *Energies,* vol. 14, no. 20, p. 6594, 2021. [Online]. Available: https://www.mdpi.com/1996-1073/14/20/6594.

[16] M. B. Jensen, L. D. M. Ottosen, and M. V. W. Kofoed, "H2 gas-liquid mass transfer: A key element in biological Power-to-Gas methanation," *Renewable and Sustainable Energy Reviews,* vol. 147, p. 111209, 2021/09/01/ 2021, doi: https://doi.org/10.1016/j.rser.2021.111209.

[17] A. Barbaresi, M. Morini, and A. Gambarotta, "Review on the Status of the Research on Power-to-Gas Experimental Activities," *Energies,* vol. 15, no. 16, p. 5942, 2022. [Online]. Available: https://www.mdpi.com/1996-1073/15/16/5942.

[18] G. Glenk, P. Holler, and S. Reichelstein, "Advances in power-to-gas technologies: cost and conversion efficiency," *Energy & Environmental Science,* vol. 16, no. 12, pp. 6058-6070, 2023.

[19] M. Chen, H. Lu, X. Chang, and H. Liao, "An optimization on an integrated energy system of combined heat and power, carbon capture system and power to gas by considering flexible load," *Energy,* vol. 273, p. 127203, 2023/06/15/ 2023, doi: https://doi.org/10.1016/j.energy.2023.127203.

[20] L. Wang, S. M. Alirahmi, and H. Yu, "Development and analysis of a novel power-to-gas-to-power system driven by the Allam cycle for simultaneous electricity and water production," *Energy Conversion and Management,* vol. 319, p. 118934, 2024/11/01/ 2024, doi: https://doi.org/10.1016/j.enconman.2024.118934.

[21] Y. Ma *et al.*, "Modeling and optimization of combined heat and power with power-to-gas and carbon capture system in integrated energy system," *Energy,* vol. 236, p. 121392, 2021/12/01/ 2021, doi: https://doi.org/10.1016/j.energy.2021.121392.

[22] H. Mehrjerdi, H. Saboori, and S. Jadid, "Power-to-gas utilization in optimal sizing of hybrid power, water, and hydrogen microgrids with energy and gas storage," *Journal of Energy Storage,* vol. 45, p. 103745, 2022/01/01/ 2022, doi: https://doi.org/10.1016/j.est.2021.103745.

[23] L. Kang *et al.*, "Research on energy management of integrated energy system coupled with organic Rankine cycle and power to gas," *Energy Conversion and Management,* vol. 287, p. 117117, 2023/07/01/ 2023, doi: https://doi.org/10.1016/j.enconman.2023.117117.

[24] J. Perpiñán, M. Bailera, and B. Peña, "Outline of all potential Power to Gas integrations in blast furnace ironmaking: A systematic review," *Renewable and Sustainable Energy Reviews,* vol. 201, p. 114605, 2024/09/01/ 2024, doi: https://doi.org/10.1016/j.rser.2024.114605.

[25] J. Hu, Y. Zou, and Y. Zhao, "Robust operation of hydrogen-fueled power-to-gas system within feasible operating zone considering carbon-dioxide recycling process," *International Journal of Hydrogen Energy,* vol. 58, pp. 1429-1442, 2024/03/08/ 2024, doi: https://doi.org/10.1016/j.ijhydene.2024.01.337.

[26] J. Park, S. Kang, S. Kim, H. Kim, H.-S. Cho, and J. H. Lee, "Enhancing the economic viability and reliability of renewables based electricity supply through Power-to-Gas-to-Power with green hydrogen," *Energy Conversion and Management,* vol. 310, p. 118485, 2024/06/15/ 2024, doi: https://doi.org/10.1016/j.enconman.2024.118485.

[27] F. S. Al-Ismail, "A Comprehensive and Critical Review on Integrated Electric Power and Gas Networks," *IEEE Access,* vol. 12, pp. 143042-143057, 2024, doi: 10.1109/ACCESS.2024.3424890.

[28] F. Calise, F. L. Cappiello, L. Cimmino, M. Dentice d'Accadia, and M. Vicidomini, "Dynamic analysis and thermoeconomic optimization of a Power-to-Gas

system driven by renewables," *Energy Conversion and Management,* vol. 313, p. 118647, 2024/08/01/ 2024, doi: https://doi.org/10.1016/j.enconman.2024.118647.
[29] Y. Kim, I. Moon, J. Kim, and J. Lee, "Renewable natural gas value chain based on cryogenic carbon capture, utilization and storage, and power-to-gas for a net-zero CO2 economy," *Renewable and Sustainable Energy Reviews,* vol. 212, p. 115425, 2025/04/01/ 2025, doi: https://doi.org/10.1016/j.rser.2025.115425.
[30] Y. G. Son and S. Y. Kim, "Distributionally robust planning for power-to- gas integrated large wind farm systems incorporating hydrogen production switch control model," *Energy,* vol. 314, p. 134210, 2025/01/01/ 2025, doi: https://doi.org/10.1016/j.energy.2024.134210.
[31] M. Karrabi, F. Jabari, and A. A. Foroud, "A green ammonia and solar-driven multi-generation system: Thermo-economic model and optimization considering molten salt thermal energy storage, fuel cell vehicles, and power-to-gas," *Energy Conversion and Management,* vol. 323, p. 119226, 2025/01/01/ 2025, doi: https://doi.org/10.1016/j.enconman.2024.119226.
[32] J. Lee and J. Kim, "Balancing hydrogen and nuclear: How nuclear expansion reshapes power-to-gas and hydrogen storage in a carbon neutral energy system," *Energy,* vol. 336, p. 138437, 2025/11/01/ 2025, doi: https://doi.org/10.1016/j.energy.2025.138437.
[33] M. Shabanian-Poodeh, R.-A. Hooshmand, and M. Shafie-khah, "Reliability-constrained configuration optimization for integrated power and natural gas energy systems: A stochastic approach," *Reliability Engineering & System Safety,* vol. 254, p. 110600, 2025/02/01/ 2025, doi: https://doi.org/10.1016/j.ress.2024.110600.
[34] E. Valipour, R. Nourollahi, K. Zare, and S. Ghassem Zadeh, "Balancing Renewable-Dominated Power and Gas Distribution Networks with P2p Trading and P2g Technology Under Regret Assessment," *Available at SSRN 5339775,* 2025.
[35] Z. Wang, P. Liao, F. Long, Z. Wang, and F. Han, "Coordinated optimization of multi-energy systems in sustainable ships: synergizing power-to-gas, carbon capture, hydrogen blending, and carbon trading mechanisms," *International Journal of Hydrogen Energy,* vol. 165, p. 150755, 2025/09/05/ 2025, doi: https://doi.org/10.1016/j.ijhydene.2025.150755.
[36] J. Gao, Q. Meng, J. Liu, and Z. Wang, "Thermoelectric optimization of integrated energy system considering wind-photovoltaic uncertainty, two-stage power-to-gas and ladder-type carbon trading," *Renewable Energy,* vol. 221, p. 119806, 2024/02/01/ 2024, doi: https://doi.org/10.1016/j.renene.2023.119806.
[37] G. Gahleitner, "Hydrogen from renewable electricity: An international review of power-to-gas pilot plants for stationary applications," *International Journal of Hydrogen Energy,* vol. 38, no. 5, pp. 2039-2061, 2013/02/19/ 2013, doi: https://doi.org/10.1016/j.ijhydene.2012.12.010.
[38] Wikipedia, "Power-to-Gas," ed: Wikipedia, 2024.
[39] B. Decourt, "Weaknesses and drivers for power-to-X diffusion in Europe. Insights from technological innovation system analysis," *International journal of hydrogen energy,* vol. 44, no. 33, pp. 17411-17430, 2019.
[40] Y. Hattori. "Tokyo Aims To Realize Hydrogen Society By 2020." Government of Japan.

https://www.japan.go.jp/tomodachi/2016/spring2016/tokyo_realize_hydrogen_by_2020.html (accessed.
[41] F. S. T. Media. "Fired Up For Hydrogen." FST Media. https://www.fst.com/news-stories/2020/fired-up-for-hydrogen/ (accessed.
[42] United Nations. "Causes and Effects of Climate Change." United Nations. https://www.un.org/en/climatechange/science/causes-effects-climate-change (accessed.
[43] W. Cheng and S. Lee, "How Green Are the National Hydrogen Strategies?," *Sustainability,* vol. 14, no. 3, p. 1930, 2022. [Online]. Available: https://www.mdpi.com/2071-1050/14/3/1930.
[44] Hydrogen Energy Supply Chain Project. "The Potential of Hydrogen." HESC Project. https://www.hydrogenenergysupplychain.com/about-the-pilot/hydrogen-energy/ (accessed.
[45] F. International Transport, "ITF Transport Outlook 2023," 2023. [Online]. Available: https://www.itf-oecd.org/sites/default/files/docs/itf-transport-outlook-2023-launch.pdf
[46] U. Stanford. "Energy for Transportation." https://understand-energy.stanford.edu/energy-services/energy-transportation (accessed.
[47] O. Tatarenko *et al.* "Hydrogen State of the Union: Where We Stand in 2024." RMI. https://rmi.org/hydrogen-state-of-the-union-where-we-stand-in-2024/ (accessed.
[48] International Energy Agency, "Global Hydrogen Review 2024: Policies," International Energy Agency (IEA), 2024. [Online]. Available: https://www.iea.org/reports/global-hydrogen-review-2024/policies
[49] K. Zhang *et al.*, "The role of hydrogen in the energy transition of the oil and gas industry," *Energy Reviews,* vol. 3, no. 4, p. 100090, 2024/12/01/ 2024, doi: https://doi.org/10.1016/j.enrev.2024.100090.
[50] International Energy Agency, "GHR24 Technical Webinar Presentation, Paris, 26 November 2024," IEA, 2024. [Online]. Available: https://iea.blob.core.windows.net/assets/bd45fecc-8bc0-45cd-88e6-46c8098a772c/GHR24_technical_webinar_presentation.pdf
[51] International Energy Agency, "IEA Renewable Fuels Are Essential To Energy Transitions, But Growth Is Lagging Behind," IEA Bioenergy, 2024. [Online]. Available: https://www.ieabioenergy.com/blog/publications/iea-renewable-fuels-are-essential-to-energy-transitions-but-growth-is-lagging-behind/
[52] Al Jazeera, "Germany Inaugurates World’s First Hydrogen-Powered Train Fleet," ed: Al Jazeera, 2022.
[53] Aberdeen City Council, "Aberdeen Hydrogen Hub," Aberdeen City Council, 2022. [Online]. Available: https://www.aberdeencity.gov.uk/net-zero-aberdeen/h2-aberdeen-hydrogen-here/aberdeen-hydrogen-hub
[54] Al Jazeera, "South Africa Launches World’s Biggest Hydrogen-Fuelled Truck," ed: Al Jazeera, 2022.
[55] M. Post, "Hydrogen Fuel Cell Electric Bus (FCEB) Evaluations in US Public Transit Service," ed, 2023.
[56] E. Curcio, "Techno-economic analysis of hydrogen production: Costs, policies, and scalability in the transition to net-zero," *International Journal of Hydrogen Energy,* vol. 128, pp. 473-487, 2025/05/15/ 2025, doi: https://doi.org/10.1016/j.ijhydene.2025.04.013.
[57] J.-W. Ding, Y.-S. Fu, and I. Y. Lisa Hsieh, "The cost of green: Analyzing the economic feasibility of hydrogen production from offshore wind power," *Energy*

Conversion and Management: X, vol. 24, p. 100770, 2024/10/01/ 2024, doi: https://doi.org/10.1016/j.ecmx.2024.100770.
[58] International Energy Agency, "Korea Hydrogen Economy Roadmap 2040," International Energy Agency, 2020. [Online]. Available: https://www.iea.org/policies/6566-korea-hydrogen-economy-roadmap-2040
[59] Food and O. Agriculture, "Hydrogen Economy Roadmap of Korea," Food and Agriculture Organization, 2019. [Online]. Available: https://www.fao.org/faolex/results/details/en/c/LEX-FAOC209756/
[60] M. Xu and D. Patton, "China Sets Green Hydrogen Target for 2025, Eyes Widespread Use," ed: Reuters, 2022.
[61] Fuel Cells Works, "China Plans for 50,000 Hydrogen Fuel Cell Vehicles by 2025," ed: Fuel Cells Works, 2022.
[62] P. Day, "Chile Leads Latin American Push to Clean Hydrogen," ed: Reuters, 2024.
[63] B. D. Solomon and A. Banerjee, "A global survey of hydrogen energy research, development and policy," *Energy Policy,* vol. 34, no. 7, pp. 781-792, 2006/05/01/ 2006, doi: https://doi.org/10.1016/j.enpol.2004.08.007.
[64] P. M. Falcone, M. Hiete, and A. Sapio, "Hydrogen economy and sustainable development goals: Review and policy insights," *Current Opinion in Green and Sustainable Chemistry,* vol. 31, p. 100506, 2021/10/01/ 2021, doi: https://doi.org/10.1016/j.cogsc.2021.100506.
[65] A. Demirbas, "Future hydrogen economy and policy," *Energy Sources, Part B: Economics, Planning, and Policy,* vol. 12, no. 2, pp. 172-181, 2017/02/01 2017, doi: 10.1080/15567249.2014.950394.
[66] R. Bleischwitz and N. Bader, "Policies for the transition towards a hydrogen economy: the EU case," *Energy Policy,* vol. 38, no. 10, pp. 5388-5398, 2010/10/01/ 2010, doi: https://doi.org/10.1016/j.enpol.2009.03.041.
[67] A. Ajanovic and R. Haas, "Economic prospects and policy framework for hydrogen as fuel in the transport sector," *Energy Policy,* vol. 123, pp. 280-288, 2018/12/01/ 2018, doi: https://doi.org/10.1016/j.enpol.2018.08.063.
[68] Q. Zhang, W. Chen, and W. Ling, "Policy optimization of hydrogen energy industry considering government policy preference in China," *Sustainable Production and Consumption,* vol. 33, pp. 890-902, 2022/09/01/ 2022, doi: https://doi.org/10.1016/j.spc.2022.08.017.
[69] B. van Ruijven, D. P. van Vuuren, and B. de Vries, "The potential role of hydrogen in energy systems with and without climate policy," *International Journal of Hydrogen Energy,* vol. 32, no. 12, pp. 1655-1672, 2007/08/01/ 2007, doi: https://doi.org/10.1016/j.ijhydene.2006.08.036.
[70] A. Chapman, K. Itaoka, H. Farabi-Asl, Y. Fujii, and M. Nakahara, "Societal penetration of hydrogen into the future energy system: Impacts of policy, technology and carbon targets," *International Journal of Hydrogen Energy,* vol. 45, no. 7, pp. 3883-3898, 2020/02/07/ 2020, doi: https://doi.org/10.1016/j.ijhydene.2019.12.112.
[71] Y. Lee, M. H. Cho, M. C. Lee, and Y. J. Kim, "Policy agenda toward a hydrogen economy: Institutional and technological perspectives," *International Journal of Hydrogen Energy,* vol. 54, pp. 1521-1531, 2024/02/07/ 2024, doi: https://doi.org/10.1016/j.ijhydene.2023.12.129.
[72] A. Ballo *et al.*, "Law and Policy Review on Green Hydrogen Potential in ECOWAS Countries," *Energies,* vol. 15, no. 7, p. 2304, 2022. [Online]. Available: https://www.mdpi.com/1996-1073/15/7/2304.

[73] S. Sasanpour, K.-K. Cao, H. C. Gils, and P. Jochem, "Strategic policy targets and the contribution of hydrogen in a 100% renewable European power system," *Energy Reports,* vol. 7, pp. 4595-4608, 2021/11/01/ 2021, doi: https://doi.org/10.1016/j.egyr.2021.07.005.
[74] K. Beasy, S. Lodewyckx, and F. Gale, "An Analysis of Emerging Renewable Hydrogen Policy through an Energy Democracy Lens: The Case of Australia," *Sustainability,* vol. 16, no. 6, p. 2226, 2024. [Online]. Available: https://www.mdpi.com/2071-1050/16/6/2226.
[75] M. Jaradat, S. Almashaileh, C. Bendea, A. Juaidi, G. Bendea, and T. Bungau, "Green Hydrogen in Focus: A Review of Production Technologies, Policy Impact, and Market Developments," *Energies,* vol. 17, no. 16, p. 3992, 2024. [Online]. Available: https://www.mdpi.com/1996-1073/17/16/3992.
[76] S. Griffiths, B. K. Sovacool, J. Kim, M. Bazilian, and J. M. Uratani, "Industrial decarbonization via hydrogen: A critical and systematic review of developments, socio-technical systems and policy options," *Energy Research & Social Science,* vol. 80, p. 102208, 2021/10/01/ 2021, doi: https://doi.org/10.1016/j.erss.2021.102208.
[77] Y. Huang, Y. Zhou, R. Zhong, C. Wei, and B. Zhu, "Hydrogen energy development in China: Potential assessment and policy implications," *International Journal of Hydrogen Energy,* vol. 49, pp. 659-669, 2024/01/02/ 2024, doi: https://doi.org/10.1016/j.ijhydene.2023.10.176.
[78] L. Wang, W. Liu, H. Sun, L. Yang, and L. Huang, "Advancements and Policy Implications of Green Hydrogen Production from Renewable Sources," *Energies,* vol. 17, no. 14, p. 3548, 2024. [Online]. Available: https://www.mdpi.com/1996-1073/17/14/3548.
[79] N. Kumar, S.-Y. Lee, and S.-J. Park, "Advancements in hydrogen storage technologies: A comprehensive review of materials, methods, and economic policy," *Nano Today,* vol. 56, p. 102302, 2024/06/01/ 2024, doi: https://doi.org/10.1016/j.nantod.2024.102302.
[80] S. A. Steinbach and N. Bunk, "The future European hydrogen market: Market design and policy recommendations to support market development and commodity trading," *International Journal of Hydrogen Energy,* vol. 70, pp. 29-38, 2024/06/12/ 2024, doi: https://doi.org/10.1016/j.ijhydene.2024.05.107.
[81] R. Quitzow, A. Nunez, and A. Marian, "Positioning Germany in an international hydrogen economy: A policy review," *Energy Strategy Reviews,* vol. 53, p. 101361, 2024/05/01/ 2024, doi: https://doi.org/10.1016/j.esr.2024.101361.
[82] S. Wei, Y. Liu, S. Xiao, and P. Wu, "Hydrogen policy evolution in China and globally: A spatial and thematic comparison," *Renewable and Sustainable Energy Reviews,* vol. 224, p. 116087, 2025/12/01/ 2025, doi: https://doi.org/10.1016/j.rser.2025.116087.
[83] J. Fakhreddine, P. E. Dodds, and I. Butnar, "Global hydrogen trade pathways: A review of modelling advances and challenges," *International Journal of Hydrogen Energy,* vol. 129, pp. 236-252, 2025/05/19/ 2025, doi: https://doi.org/10.1016/j.ijhydene.2025.04.203.
[84] D. Koutsandreas and I. Keppo, "On the macroeconomic and societal ramifications of green hydrogen policies — The case of Greek transport sector," *Energy,* vol. 315, p. 134389, 2025/01/15/ 2025, doi: https://doi.org/10.1016/j.energy.2025.134389.

[85] R. Shan and N. Kittner, "Sector-specific strategies to increase green hydrogen adoption," *Renewable and Sustainable Energy Reviews,* vol. 214, p. 115491, 2025/05/01/ 2025, doi: https://doi.org/10.1016/j.rser.2025.115491.

[86] A. Hoogsteyn, J. Meus, K. Bruninx, and E. Delarue, "Interactions and distortions of different support policies for green hydrogen," *Energy Economics,* vol. 141, p. 108042, 2025/01/01/ 2025, doi: https://doi.org/10.1016/j.eneco.2024.108042.

[87] S. Gonzalez Hernandez and A. Kirchofer, "Incentivizing hydrogen: A perspective review of lifecycle analysis methodology disparities affecting hydrogen incentives in policy frameworks," *Energy and Climate Change,* vol. 6, p. 100172, 2025/12/01/ 2025, doi: https://doi.org/10.1016/j.egycc.2024.100172.

[88] A. Odenweller and F. Ueckerdt, "The green hydrogen ambition and implementation gap," *Nature Energy,* vol. 10, no. 1, pp. 110-123, 2025/01/01 2025, doi: 10.1038/s41560-024-01684-7.

[89] S. Li, C. Tian, and H. Faraji, "Probabilistic optimization of coordinated fuel Cell-CHP and renewable energy policy in microgrid integrated with hydrogen storage for optimizing system profitability," *International Journal of Hydrogen Energy,* vol. 102, pp. 129-145, 2025/02/10/ 2025, doi: https://doi.org/10.1016/j.ijhydene.2025.01.010.

[90] D. Wilson, "Toward a Cross-Border, Global Hydrogen Trade Market," Hydrogen Council, 2022. [Online]. Available: https://hydrogencouncil.com/en/toward-a-cross-border-global-hydrogen-trade-market/

[91] D. Wilson, "Hydrogen Guardrails Report: Guiding Hydrogen Deployment for Industrial and Heavy Transport Decarbonization," Future Cleantech Architects, 2022. [Online]. Available: https://fcarchitects.org/content/hydrogen-guardrails/

[92] L. Collins, "EU Nations Agree to Install Hydrogen Fuelling Stations in All Major Cities and Every 200km Along Core Routes," ed: Hydrogen Insight, 2023.

[93] Ey and Hyvolution, "European Hydrogen Index 2025: Bridging the Gap Between Ambition and Action," EY, 2025. [Online]. Available: https://www.ey.com/content/dam/ey-unified-site/ey-com/fr-fr/insights/climate-change-sustainability-services/documents/ey-hyvolution-ey-european-hydrogen-20250214.pdf