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Benjamin Trouvé*†

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Abstract

Reaching global net-zero by 2050 requires rapidly scaling low-carbon hydrogen, but deployment is hindered by market uncertainty, high capital costs, and weak supply-demand coordination. This paper examines whether liberalizing international hydrogen and ammonia trade can accelerate deployment and how such policies interact with technological innovation. We develop a hybrid framework combining a global TIMES-based energy-system model (KiNESYS-IFPEN) with a stochastic logistic diffusion model calibrated to historical renewable energy growth under imperfect expectations. We find that trade liberalization alone has limited global impact, and mainly reallocates production geographically: the Middle East, North America, Latin America, and China expand as exporters, while Asia Pacific, Europe and Africa become structural importers. Innovation-driven electrolyzer cost reductions raise significantly global deployment success shifting production toward electrolysis. When policies are combined, innovation dominates, while trade openness reinforces regional specialization. These results underscore the central role of technological progress, credible expectations, and the trade-off between cost-efficient specialization and hydrogen supply security.

Keywords: Hydrogen, Trade Policies, Technology diffusion, TIMES-Markal model.
JEL Classification: F13, Q55, Q43, Q56, Q48.

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1 Introduction

Over the past decade, hydrogen has gained renewed attention as a cornerstone of global decarbonization strategies. More than sixty countries have now published national hydrogen strategies (Corbeau and Kaswiyanto, 2025), reflecting growing expectations about its role in achieving Net-Zero Emissions (NZE) pathways. According to the International Energy Agency (IEA), hydrogen is projected to account for 12% of final energy consumption by 2050, contributing to a cumulative 4% reduction in global CO_2 emissions (IEA, 2021). These projections place hydrogen at the forefront of debates on the future of sustainable energy systems.

Currently, hydrogen consumption reaches 97Mt/year (IEA, 2024). In 2022, this energy carrier accounted for 2.5% of the final energy consumption (IEA, 2022). To reach the NZE target by 2050, the electrolyzer installed capacities need a 6,000 fold increase (IRENA, 2023) while only 9% of the announced projects for 2030 have reached final investment decision stage (IEA, 2025). The rapid expansion necessitates the simultaneous emergence of both hydrogen supply and demand —a phenomenon without precedent in the evolution of energy markets. Ball and Weeda (2015) underscore the "chicken-and-egg" problem, which effectively illustrates the economic challenges of scaling hydrogen infrastructure. This generates significant market uncertainty and high risks, which in turn undermine investment decisions in emerging hydrogen technologies.

A body of research highlights that early investments in clean technologies depend critically on expectations about future market size, policy credibility, and the perceived durability of support schemes (Acemoglu and Linn, 2004; Agnolucci and McDowall, 2007; Dedehayir and Steinert, 2016; Kriechbaum et al., 2021). In principle, trade liberalization could help break this coordination trap by expanding potential markets, reducing demand uncertainty, and facilitating international specialization based on comparative advantages in resource endowments and technology costs (Burstein and Melitz, 2011; Ravikumar et al., 2019; Perla et al., 2021). However, whether openness to hydrogen and ammonia trade can materially accelerate global deployment—or simply reshuffle production geographically—reaching carbon neutrality in 2050 remains an open question.

The answer is made more complex by the limitations of the modelling tools typically used to analyze long-term energy transitions. Most global hydrogen assessments rely on bottom-up energy-system optimization models (ESOMs) such as TIMES, which identify the least-cost configuration of technologies and investments under perfect foresight and

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frictionless adjustment (Loulou and Labriet, 2008; Pfenninger et al., 2014; Prina et al., 2020). Their detailed techno-economic structure and system-wide consistency make them valuable for evaluating cost-optimal pathways. Yet, these models are normative in the sense that they describe what an ideal social planner would implement in a perfectly coordinated world. In doing so, they tend to ignore behavioral inertia, policy uncertainty, infrastructure bottlenecks, and other frictions that slow diffusion (Geels, 2002; McDowall, 2014; Pfenninger et al., 2014). As a result, ESOMs may produce overly optimistic deployment trajectories, particularly for emerging technologies such as low-carbon hydrogen (Geels, 2002). In contrast, technology diffusion models provide a complementary, empirically grounded perspective. They capture the S-shaped pattern of technology adoption observed in renewables and other innovations (Schilling and Esmundo, 2009; Rogers et al., 2014; Hansen et al., 2017), reflecting sequential phases of emergence, acceleration, and saturation driven by learning, expectations, and network effects. However, diffusion models lack the structural and physical constraints of energy-system frameworks: they do not represent energy balances, competition for resources, or endogenous policy goals. They are thus descriptive rather than prescriptive, and cannot on their own assess the welfare or efficiency implications of policy choices.

Bridging these two paradigms—normative optimization and empirical diffusion—has become increasingly necessary to understand the dynamics of low-carbon transitions. Energy-system models provide a benchmark for what is technically and economically optimal, while diffusion models illuminate what is realistically achievable given uncertainty and institutional inertia. Combining the two provides a more comprehensive view: it allows assessment not only of how policies modify the optimal configuration of the energy system, but also how they influence the pace, probability, and regional distribution of actual deployment.

The objective of this paper is to develop and apply such a hybrid-modelling framework that combines a global energy-system optimization model with a probabilistic logistic diffusion model to assess how trade liberalization and innovation policies interact to shape the deployment of low-carbon hydrogen. The framework couples KiNESYS-IFPEN, a TIMES-based least-cost optimization model, with an empirically calibrated diffusion module that reproduces the historical patterns of technology uptake in renewables, following Odenweller et al. (2022)' approach. By soft-linking these two approaches, the analysis captures both the economically optimal evolution of hydrogen markets and the feasible pace of their diffusion under uncertainty.

The integrated model represents twenty-nine world regions and incorporates alternative policy environments featuring different degrees of trade openness, innovation support, and expectation horizons. The latter reflect how far investors look into the future when forming beliefs about market size: short horizons represent high uncertainty and myopia, whereas long horizons correspond to credible, stable policies extending over one or two decades. This allows the model to simulate how the credibility of long-term strategies affects investment behavior and diffusion speed. The empirical application reveals that trade liberalization alone exerts only a modest impact on global deployment, although it strongly influences the geography of production by favoring resource-rich exporters such as the Middle East, Latin America, and North America. Innovation policies, by contrast, have a much stronger effect: accelerated cost reductions and learning spillovers enhance global low-carbon hydrogen capacity compared with the baseline. When the two policies are combined, they reinforce each other, producing both faster diffusion and a technological shift toward electrolysis. Longer expectation horizons amplify these benefits, highlighting the central role of credible policy commitments in mobilizing private investment.

Beyond these empirical findings, the paper contributes conceptually by providing a quantitative framework that links economically optimal transitions with realistic diffusion trajectories. By integrating system-wide optimization with stochastic adoption dynamics, it becomes possible to evaluate not only what policies should achieve in theory but also what they are likely to deliver in practice under imperfect coordination. The approach yields a probabilistic measure of deployment success that can inform policy design and international cooperation on hydrogen.

The remainder of the paper is structured as follows. Section 2 presents the methodology, the policy scenarios and evaluation method. Section 3 discusses the main results, while Section 4 analyzes their policy implications. Section 5 concludes.

2 Methodology

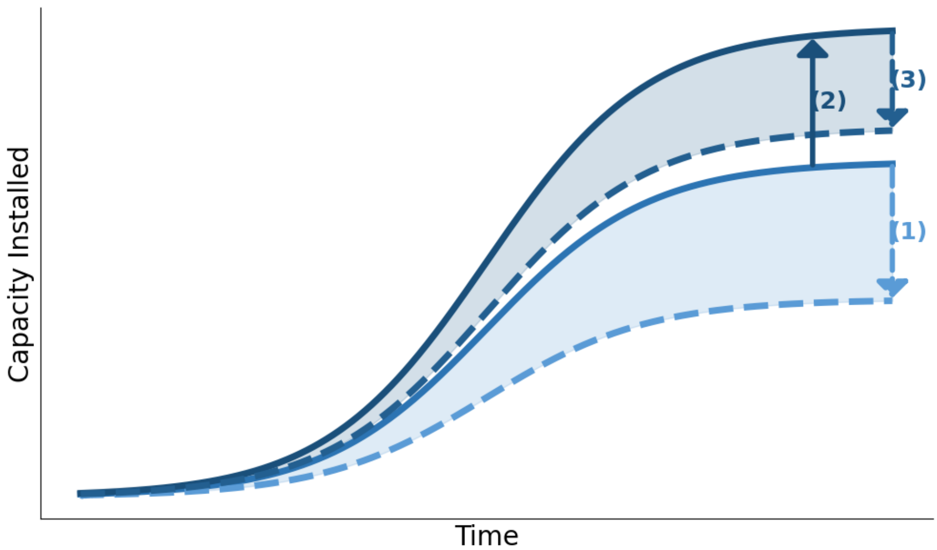
2.1 General framework

As stated above, we develop a hybrid-modelling framework that combines a bottom-up energy-system optimization model (ESOM) with an empirically grounded diffusion model to evaluate how trade liberalization and innovation policies shape the deployment of low-carbon hydrogen. The framework soft-links the two models sequentially, capturing both the economically optimal and the realistically achievable trajectories of hydrogen deployment under uncertainty. The logic of integration is straightforward. The energy-system model (KiNESYS-IFPEN, based on the TIMES generator) determines the least-cost configuration of technologies and investments needed to satisfy energy-service demands while meeting climate targets. It provides normative outputs—most notably the evolution of hydrogen demand and production capacities by region and time period—that define a dynamic upper bound for feasible diffusion.

The diffusion model then simulates how actual deployment evolves toward that upper bound, given historical patterns of technology adoption and imperfect foresight. By coupling these two dimensions, the framework bridges the gap between the theoretical potential identified by optimization and the empirically plausible diffusion pathways observed in real-world energy transitions.

Figure 1 illustrates the concept. The solid blue line represents the least-cost hydrogen trajectory derived from ESOM, corresponding to a perfect-foresight social planner. However, this pathway does not automatically translate into real-world deployment. In practice, numerous frictions—financial, institutional, behavioral—reduce the pace and extent of technology adoption. These frictions generate a gap, illustrated by (1) in Figure 1, leading to an actual deployment path shown as the dashed light blue line. Diffusion models can capture this observed trajectory, which reflects the cumulative impact of real-world constraints. Yet, to design policies that address these barriers, it is necessary to understand how far actual deployment deviates from the optimal trajectory. In many cases, the unconstrained pathway would not deliver the capacity levels required for deep decarbonization. Therefore, policy interventions are needed to shift the expected deployment upward, with the goal of aligning actual adoption closer to the optimal benchmark. This upward shift, represented by (2) in Figure 1, results in a new policy-induced trajectory (solid dark blue line), which is then subject to a new set of real-world frictions, illustrated by the downward deviation (3) and the dashed dark blue line.

Figure 1: Technology deployment pathways



Note: This figure illustrates the different technology deployment pathways under various sets of assumptions.

More formally, our general framework, summarized in Figure 2, comprises three main components. First, we define a set of policy scenarios targeting the hydrogen sector (see Section 2.4). Second, we use a bottom-up partial equilibrium energy system model to determine the economically optimal hydrogen deployment pathway under each policy scenario. This component, labeled (A) in Figure 2, provides the optimal hydrogen demand over time, accounting for techno-economic constraints. Third, we apply an adapted logistic diffusion model to estimate the feasible deployment trajectory, incorporating socio-technical constraints (component (B) in Figure 2). This model is characterized by three parameters: the initial installed capacity of low-carbon hydrogen (B1), a compound annual growth rate (CAGR) (B2), and a time-varying maximum capacity (B3), which corresponds to the optimal hydrogen demand derived from the energy system model. The time-varying maximum capacity serves as a dynamic proxy for future market potential, capturing rational expectations about market size and reflecting the demand-pull effect of policy implementation in our framework.

To incorporate uncertainty in deployment pathways, we estimate a probability distribution for the CAGR based on historical data for wind and solar capacity additions (Appendix A.3.2). In parallel, we vary the length of market expectations by considering alternative time horizons over which the time-varying maximum capacity evolves, thereby capturing different assumptions about how far into the future agents anticipate market saturation (Section 2.2).

This integrated framework allows us to project a probabilistic range of low-carbon hydrogen deployment trajectories over time under various policy scenarios, as shown by the blue shaded area in Figure 2.

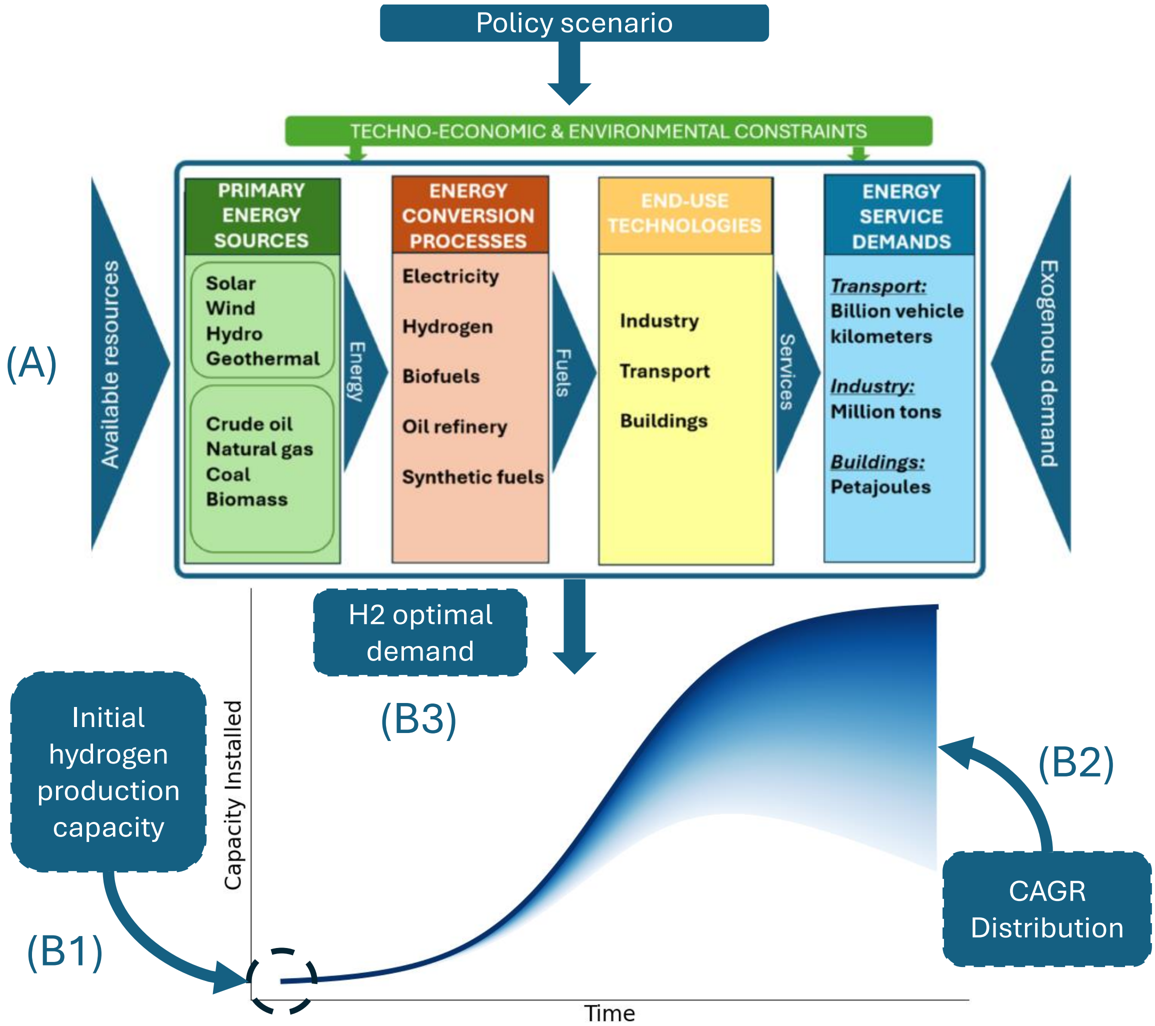
2.2 Energy-system optimization model (KiNESYS-IFPEN)

The core of KiNESYS-IFPEN is developed by Kanors-EMR[1] using TIMES model generator of IEA-ETSAP (Loulou and Labriet, 2008). The model is a bottom-up linear programming energy system optimization model that determines a partial equilibrium in the energy sector. It maximizes the total net surplus of the system subject to a set of constraints, over the time horizon 2019–2070, with optimization performed at five-year intervals.[2] By solving for partial equilibrium in the energy market, the model ensures a balance between supply and demand in each period. It optimizes energy delivery to end-use services by considering techno-economic characteristics and evaluating all available options. The model encompasses the entire energy value chain, from primary energy resource extraction and raw material processing to energy conver-

[1]For more information, see https://www.kanors-emr.org/models

[2]All costs are expressed in US Dollars 2021.

Figure 2: General framework



Note: (A) represents the KiNESYS-IFPEN model. (B1), (B2) and (B3) are respectively the initial hydrogen production capacity, the compound annual growth rate distribution and the optimal hydrogen demand response, that are three input parameters in the adapted logistic diffusion model.

sion technologies and final end-use services. At each stage, technologies compete based on cost, energy efficiency, and a set of other techno-economic and policy constraints. Additionally, KiNESYS-IFPEN incorporates a global spatial breakdown, representing twenty-nine regions displayed in Figure A3 in Appendix.

The optimization problem can be formulated as follows:

$$Max \sum_{i \in I} \sum_{t \in T} (p^0_{i,t} [D^0_{i,t}]^{\frac{-1}{E_i}} \times D_{i,t}^{1+\frac{1}{E_i}}) - cX \tag{1}$$

$$\text{subject to} \quad \sum_{k \in K} ACT_{k,i} \geq D_{i,t} \tag{2}$$

$$BX \geq b \tag{3}$$

Equation (1) defines the objective function, which represents the discounted net total surplus of the energy system. This surplus includes the marginal cost of production $p^0_{i,t}$, the consumers surplus expressed as

$$[D^0_{i,t}]^{-1/E_i} \times D_{i,t}^{1+1/E_i},$$

where $D^0_{i,t}$ is the reference demand calibrated, $D_{i,t}$ the price-elastic demand, and E_i the price elasticity of demand. The total discounted system cost is represented by cX, where c is the vector of all costs (in constant USD 2021), and X is the vector of decision variables.

The objective function is maximized subject to two sets of constraints. Equation (2) imposes technology activity constraints, where $ACT_{k,i}$ denotes the activity level of end-use technology k in region i. Equation (3) represents a broader set of techno-economic and policy constraints.

In this model, hydrogen is represented as a distinct energy carrier with eleven production technologies relying on Seck et al. (2022)'s assumptions (for more details, see Table A1 in Appendix A.1), including coal gasification with and without carbon capture, steam methane reforming (SMR) with and without carbon capture, autothermal reforming (ATR) with carbon capture, methane pyrolysis, and both proton exchange membrane (PEM) and alkaline electrolysis technologies, each considered under grid-connected and off-grid configurations.

Hydrogen consumption is modeled across five end-use sectors: industry, transport, power, residential, and commercial. In the industrial sector, hydrogen can be used in a wide range of sub-sectors, including iron and steel, non-metallic minerals, chemicals (e.g., ammonia and methanol), non-ferrous metals, mining and construction, transport equipment and machinery, food processing, pulp and paper, and other industrial activities. In the transport sector, hydrogen consumption is limited to specific vehicle categories—passenger cars, buses, heavy-duty trucks, and light commercial vehicles—as well as domestic and international aviation and shipping. In the power sector, blended hydrogen is primarily used in gas turbines for electricity generation. Hydrogen is also used in heat plants to produce industrial heat. In the residential and commercial sectors, hydrogen is primarily consumed for space and water heating applications.[3] Further details on the KiNESYS-IFPEN modeling and calibration are provided in Appendix A.1.

2.3 Adapted logistic diffusion model

To translate the normative output of KiNESYS-IFPEN into a realistic time path of hydrogen adoption, we implement a stochastic logistic diffusion model. Specifically, following Odenweller et al. (2022)'s methods, we use a probabilistic space projection for low-carbon hydrogen production installed capacities based on an adapted logistic diffusion model, which contains three parameters: initial capacity, compound annual growth rate (CAGR), and time-varying maximum capacity. We define the model as follows:

$$C_t^r = \frac{C_{t+h,max}^r}{1 + e^{-\hat{\beta}^r (t-t_o)}} \qquad \text{with } h \in \{1, 5, 10, 20\} \tag{4}$$

C_t^r is the amount of capacity in time t in region r, $\hat{\beta}^r$ is the region-specific compound annual growth rate, $C_{t+h,max}^r$ the hydrogen production capacity in horizon h in region r, and t_0 the initial period. Here, we interpret $C_{t+h,max}^r$ as the expected market size for the period $t + h$ in region r.

We differentiate and discretize, and we obtain the capacity installed dynamics with different anticipation horizons used effectively to project the level of low-carbon hydrogen capacity:

$$C_{t+1}^r = C_t^r + \hat{\beta}^r C_t^r (1 - \frac{C_t^r}{C_{t+h,max}^r}) \tag{5}$$

In this framework, the initial capacity corresponds to current regional low-carbon hydrogen production capacities, based on data from the IEA Hydrogen Production Projects Database regional hydrogen production capacities.[4] More details on the calibration of this parameter are provided in Appendix A.3.1. The region-specific compound annual grow rate follows a stochastic distribution calibrated from historical renewable-energy growth rates (wind and solar), estimated via non-linear least squares

[3] The calibration of all techno-economic parameters for these processes is based on data from the U.S. Environmental Protection Agency's EPAUS9rT energy systems database. For more information, see EPAUS9rT Database documentation and complemented by techno-economic assumptions on future technologies from E3 Modeling.

[4] Detailed project-level data—including capacity, technology, and status—are available at the IEA Hydrogen Production Projects Database.

over rolling ten-year windows. More details on the estimation and calibration of this parameter are provided in Appendix A.3.2.

To evaluate how different penetration rates influence the diffusion of low-carbon hydrogen production technologies, we construct two scenarios based on the assumptions in Odenweller et al. (2022): *CAGR No Emergency* and *CAGR Emergency*. The *CAGR No Emergency* scenario allows penetration rates to vary across the full historical range—from the lowest observed values to the highest. In contrast, the *CAGR Emergency* scenario reflects a context of strong policy and market support, excluding the lower tail of the distribution by removing diffusion rates below the 15% quantile. This design enables us to capture how relaxing or tightening constraints on technological diffusion shapes potential deployment pathways.

To analyze the impact of expectations on low-carbon hydrogen production installed capacities, we define four anticipation scenarios: no expectations, short-term (5 years), medium-term (10 years), and long-term (20 years) expectations. These ranges capture expectations from high uncertainty to relative stability concerning the policy's outcomes.

2.4 Policy scenarios and evaluation

We define a set of four scenarios, which are summarized in Table 1.

The *Reference* scenario explores the cost-optimal energy system evolution with a CO_2 emissions constraint following NZE pathway globally until 2050 provided by the IEA. This baseline scenario assumes no evolution in the techno-economic characteristics for hydrogen production technologies, and hydrogen and ammonia commodities are not allowed to be traded internationally.

The *Trade Liberalization* scenario simulates a global cooperation on hydrogen markets through trade liberalization within NZE pathway. Indeed, current tariffs on hydrogen and ammonia are cut[5] and a harmonized regulatory framework emerges with common standards on the carbon content of hydrogen and ammonia production, and also on infrastructure technical standards (WTO and IRENA, 2023). Technical issues make the scaling-up of new and low-cost hydrogen production technologies impossible. The techno-economic characteristic remain the same. Under this scenario, investments in hydrogen and ammonia trade infrastructure are permitted, simulating a fully open international market. The associated value chains—from exporting to importing regions—are illustrated in Figure A2 in Appendix. All techno-economic parameters for infrastructure investment and transport are based on data from Moritz et al. (2023)

[5]To see more details on the import tariffs applied to hydrogen and ammonia worldwide see WTO Tariff & Trade Data

and regional distance calculations provided by the Commissariat à l'Énergie Atomique (CEA). Specifically, investment costs for new hydrogen and ammonia pipelines follow the "low-cost" scenario outlined by Moritz et al. (2023), while assumptions for maritime transport infrastructure—such as liquefaction, regasification terminals, and shipping costs—are drawn from their "optimistic" scenario. The cost of building new trade infrastructure is modeled as a function of the distance between the origin and destination regions. Distances are calculated as the shortest path between the nearest ports of the two regions, based on CEA's geospatial analysis. This approach captures both cost variability and geographic constraints in the development of international hydrogen and ammonia trade routes.

The *Innovation* scenario simulates complete autarky in hydrogen and ammonia sectors where the regions are making simultaneous and strong efforts to innovate in producing low-carbon hydrogen at low-cost within the NZE pathway. This scenario assumes strong R&D subsidies (exogenous to this study), and learning-by-doing effects implying a decline in capital expenditure for the installation of new hydrogen production capacity. As the installed capacities expand, the associated costs decrease through cumulative learning effects, enhancing the economic viability of hydrogen technologies over time. We define the learning curve following the literature such as Schoots et al. (2008) and Weiss et al. (2010):

$$C_t = C_0(\frac{P_t}{P_0})^{-\alpha} \tag{6}$$

where the progress ratio is given by $pr = 2^{-\alpha}$, and the learning rate by $lr = 1 - pr$, α is the learning index, P_t and P_0 respectively the production at time t and 0, and C_0 the initial hydrogen investment cost.

Due to computational time issues, the investment cost dynamics is exogenous. We calculate the learning curve using the hydrogen production from the *Reference* scenario. The alkaline electrolysis is assumed to follow a 15% learning rate, the PEM electrolysis 18% learning rate and the ATR (and SMR) with carbon capture 6% following Schoots et al. (2008)'s findings. Note that we take the most optimistic learning rate for electrolyzers and the most pessimistic one for ATR (or SMR) to capture the effect of strong effort developing low-cost electrolyzers by policymakers and firms.

The *Combined Policies* scenario combines technology-led cost reductions with institutional progress in international market design. This scenario tests for the potential changes in trade-induced specialization triggered by the capital expenditure decline in new low-carbon hydrogen production. It is the combination of the *Trade Liberalization* and *Innovation* scenarios (Grossman and Helpman, 1991; Costantini and Melitz, 2008).

Table 1: Policy scenario description

Scenario name	**CO_2 target**	**Trade regime**	**Cost assumptions**
Reference	Net-Zero Emissions	No H_2 and NH_3 Trade (Autarky)	Current techno-economic parameters
Trade Liberalization	Net-Zero Emissions	H_2 and NH_3 Trade (Liberalization)	Current techno-economic parameters
Innovation	Net-Zero Emissions	No H_2 and NH_3 Trade (Autarky)	Innovation-driven cost reductions
Combined Policies	Net-Zero Emissions	H_2 and NH_3 Trade (Liberalization)	Innovation-driven cost reductions

Note: This table summarizes the characteristics of the four policy scenarios considered in the paper.

To evaluate the impact of each scenario, we simulate the probabilistic distribution of low-carbon hydrogen deployment across the 29 regions defined in the KiNESYS-IFPEN model (see Appendix A.2). From these regional projections, we extract deployment values for the year 2050.

Let $F^r_{S_i}(x)$ denote the cumulative distribution function (CDF) of projected hydrogen deployment in region r under scenario S_i, and let x^*_r be the target deployment level in region r as defined by the *Reference* scenario. We then compute the probability that the deployment under scenario S_i in region r is less than or equal to its *Reference* target:

$$F^r_{S_i}(x^*_r) = p^*_r, \tag{7}$$

where $p^*_r = \mathbb{P}(X \leq x^*_r)$.

The probability of success—i.e., the likelihood that deployment exceeds the reference level—is then defined as:

$$D^r_{S_i} = 1 - p^*_r. \tag{8}$$

To evaluate the global effects of each policy scenario, we construct the aggregated distribution across all 29 regions. We do so by summing the regional projections at each quantile level τ, forming the global quantile function $Q_{S_i}(\tau)$. The corresponding global cumulative distribution function $F_{S_i}(x)$ is then obtained as the inverse of Q_{S_i}. The global probability of success is calculated using the same procedure applied to the regional distributions.

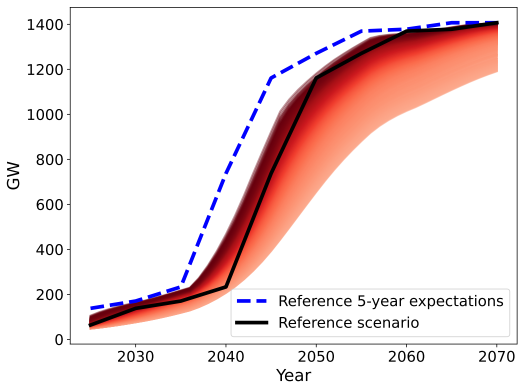
3 Results

3.1 Global deployment dynamics

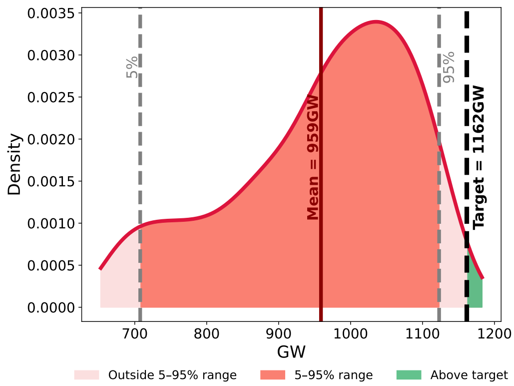
In this section, we assess the global deployment of low-carbon hydrogen under the different policy scenarios in 2050. Figure 3 presents the evolution of installed low-carbon hydrogen capacities over time in the *Reference* scenario, assuming that expectations about future market size extend five years ahead and that the compound annual growth rate follows the trajectory of the *Emergency* scenario.

In the *Reference* scenario, the optimal deployment pathway exhibits a three-phase expansion, with the most pronounced increase occurring between 2040 and 2050. This pattern is primarily driven by the CO_2 constraint becoming increasingly stringent after 2040 in order to reach NZE by 2050. Beyond the optimal pathway, the probabilistic projections indicate that uncertainty in the development rate of low-carbon hydrogen technologies leads to substantial dispersion in deployment outcomes. For instance, Figure 3b) shows that only 0.5% of the simulated trajectories in 2050 reach the optimal capacity level of the *Reference* scenario, with the average deployment falling 203 GW (–17.4%) short of the *Reference* optimal target. This result implies that expecting hydrogen to deploy at the level of the *Reference* target corresponds to a low probability of success, reflecting the structural rigidities constraining the global scale-up of these technologies.

Figure 3: Global low-carbon hydrogen deployment in the *Reference* scenario



(a) Evolution over time



(b) Distribution in 2050

Note: The figure (a) shows the evolution over time from 2025 to 2070 of probabilistic projection of low-carbon hydrogen installed capacities in the *Reference* scenario assuming *Emergency* on the CAGR (diffusion rate) and 5-year expectations on the future market size. The figure (b) displays the probability density distribution of the projection in 2050 compared to the *Reference* target in 2050 from the *Reference* scenario estimated with KiNESYS-IFPEN.

Examining the effect of the policy scenarios, Figure 4 shows the cumulative distribution function (CDFs) for each scenario including the *Reference* scenario.

Firstly, the distribution of low-carbon hydrogen deployment in the *Trade Liberalization* scenario is broadly similar to that of the *Reference* scenario, achieving a comparable rate of success—1.2% versus 0.5% in the *Reference* scenario. Moreover, when averaging across all combinations of *CAGR* assumptions and expectation horizons, as reported in Table 2, the *Trade Liberalization* scenario reduces the overall success rate by 1.3 percentage points. This result indicates that, from a technology development perspective, liberalizing trade in hydrogen and ammonia alone does not generate an overall improvement in deployment outcomes.

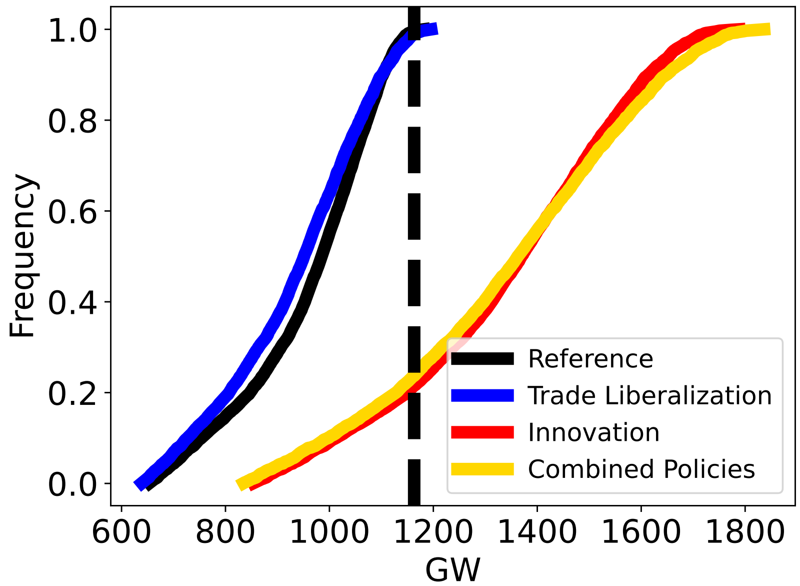
In contrast, the *Innovation* scenario produces a substantial shift in the deployment distribution, increasing the success rate by roughly 78.2 percentage points compared with the *Reference* scenario. On average, across all combinations of CAGR and expectation assumptions, the success rate rises by about 40 percentage points. This indicates that a global diffusion of innovation across regions markedly enhances the deployment of low-carbon hydrogen relative to the *Reference* scenario. In this context, the result suggests that anticipated innovation in hydrogen production technologies stimulates investment by reducing costs and improving competitiveness sufficiently to overcome the significant barriers to deployment, thereby facilitating a least-cost pathway to carbon neutrality.

The *Combined Policies* scenario—which combines innovation with trade liberalization—produces outcomes that closely resemble those of the *Innovation* scenario. The shift in the CDF is nearly identical, indicating that trade openness generates little to no marginal effect, with the overall improvement appearing to be driven primarily by innovation. Moreover, the average success rate of the *Combined Policies* scenario across all specifications—although increasing by 40.1 percentage points relative to the *Reference* scenario—shows no meaningful difference compared to the *Innovation* scenario, as reported in Table 2.

Examining the role of the CAGR distribution assumption, Table 2 shows only small differences in the average success rate between the *No Emergency* and *Emergency* cases. In the *Reference* and *Trade Liberalization* scenarios, the average difference is about 2.6 percentage points, while in the *Innovation* and *Combined Policies* scenarios, it increases to roughly 9 percentage points. These results suggest that efforts to remove the strongest barriers to the diffusion rate of technology deployment would yield only limited improvements.

Expectations length has a consistently large and differentiated impact on the average success rate of low-carbon hydrogen deployment. The effects are again very similar in the *Reference* and *Trade Liberalization* scenarios: success rates increase from roughly 0.6–1.4% under a 5-year expectations horizon to about 71–74% when expectations ex-

Figure 4: CDFs of low-carbon hydrogen deployment in 2050



Note: This figure displays the cumulative distribution functions (CDFs) of low-carbon hydrogen production capacities deployed in 2050 for each policy scenario considered. The vertical black dashed line represents the hydrogen deployment optimal target estimated in the *Reference* scenario for 2050 using KiNESYS-IFPEN model. Note that here we assume CAGR *Emergency* and 5-year expectations on the future market size.

tend to 20 years. A comparable positive effect is observed in the *Innovation* and *Combined Policies* scenarios, where success rates rise from an average of 18–21.8% with no expectations to 94.9–95.6% under 20-year expectations. Overall, these results indicate that—even in the absence of additional policies beyond a global CO_2 cap—anchoring expectations around the energy transition pathway can yield success rates comparable to those achieved when public authorities promote innovation but fail to provide sufficiently long-term expectations.

Beyond merely achieving the 2050 target, we find that combining trade liberalization with long-term expectations substantially increases the likelihood of exceeding the *Reference* deployment level. As shown in Figure 5, and regardless of the assumed CAGR distribution or the presence of technological innovation in hydrogen production, a 20-year expectations horizon under a trade-liberalization policy raises the 2050 probability of surpassing the *Reference* target from 14% to 27%. This effect is primarily driven by the delayed global impact of trade liberalization, which strengthens the development of low-carbon hydrogen only toward 2070. Because of this delayed response, anchoring expectations plays a critical role in enabling sustained and successful technology deployment.

Table 2: Average success rate in 2050 across scenarios

	Reference (%)	***Trade Liberalization*** (%)	***Innovation*** (%)	***Combined Policies*** (%)
Overall average	29.1	27.8	69.8	69.2
CAGR				
No Emergency	27.2	26.6	65.5	64.5
Emergency	31	29	74.2	73.9
Expectations horizon				
None	0	0	18	21.8
5-year	0.6	1.4	73.8	71.3
10-year	44	36	91.8	88.8
20-year	71	74	95.6	94.9

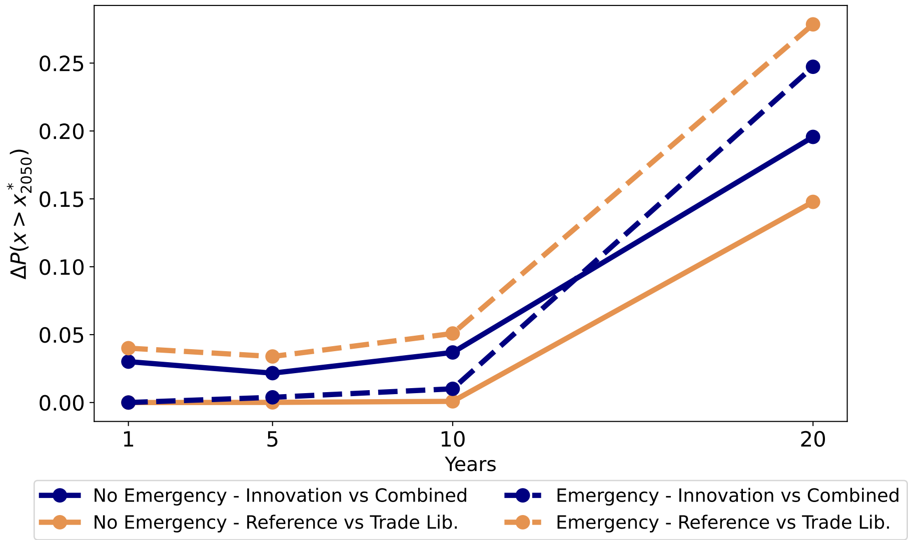
Note: This table reports all the different average success rates in 2050 for each configuration of scenarios defined in the table.

3.2 Regional heterogeneity and trade specialization

While globally the impacts of trade liberalization are limited, we investigate the effects throughout the regions covered by our study. For clarity, we aggregate the original 29 regions solely for the purpose of presenting the results, following the aggregation shown in Table A3 in Appendix A.2. Table 3 reports the distribution of low-carbon hydrogen production capacities across regions in the *Reference* scenario. By 2050, Other Asia emerges as the global leader, with an average installed capacity of 221 GW, followed by China (184 GW) and the Middle East (144 GW). North America and India reach 97 GW and 79 GW, respectively, while Latin America, Europe, Africa, and Russia display more moderate levels ranging from 59 GW to 48 GW. Saudi Arabia and Australia exhibit comparatively lower installed capacities at 21 GW and 11 GW. Taken together, these results suggest that—absent any additional policy support beyond the NZE target—Asia becomes the main hub of low-carbon hydrogen installed capacities by 2050, accounting for nearly half of global installed capacity.

Turning to the rate of success, the *Reference* scenario highlights the substantial impact of uncertainty on regional deployment outcomes. Most regions show success rates close to zero, with the notable exceptions of the Middle East, China, Other Asia, Latin America, and Australia. The Middle East achieves the highest success rate (68%), meaning that more than two-thirds of simulations meet or exceed the region's *Reference* target by 2050. China and Other Asia follow with success rates of 37% and 33%, while Latin America and Australia reach 21% and 8.8%. This stands in sharp contrast to the

Figure 5: Combined effect of trade liberalization with expectation horizons



Note: This figure shows the difference in the probability of achieving higher levels of low-carbon hydrogen deployment between scenarios with and without trade liberalization. The comparison also accounts for alternative CAGR assumptions (*No Emergency* and *Emergency*). $\Delta P(X > X^*_{2050})$ denotes the change in the probability that deployed capacities X exceed the *Reference* target X^*_{2050}.

global result, where the overall success rate is only 0.5%. The discrepancy highlights substantial regional heterogeneity, which does not translate into higher success at the global scale.

In the *Trade Liberalization* scenario, only two regions—the Middle East and North America—exhibit higher levels of low-carbon hydrogen deployment by 2050 compared to the *Reference* scenario. Both regions experience an increase in average installed capacity and in their rate of success. Specifically, the Middle East expands its deployment by 58GW, while North America increases by 33GW on average. These increases correspond to improvements in the success rate by 32.3 and 42.4 percentage points, respectively. In contrast, all other regions experience a decline in deployment, reflected by a reduction of their success rates to 0%. At the global level, the overall feasibility of low-carbon hydrogen deployment remains largely unchanged, suggesting that trade liberalization does not enhance global deployment potential. Instead, it shifts the center of gravity of the hydrogen economy toward North America and the Middle East, indicating a growing regional concentration of production. The absence of significant global differences between the *Reference* and *Trade Liberalization* scenarios, despite marked regional effects, points to the emergence of trade specialization patterns induced by market openness. In this zero-sum dynamic, the Middle East and North America emerge as the "winners" of trade liberalization, while other regions experience reduced capacity to achieve their targets, effectively becoming the "losers" of the global hydrogen trade shift.

In the *Innovation* scenario, nearly all regions exhibit higher levels of low-carbon hydrogen deployment by 2050 compared to the *Reference* scenario. Regions showing improved success rates experience increases ranging from 31 to 67 percentage points, with Other Asia and the Middle East reaching a 100% success rate, while China approaches this threshold. Furthermore, the variation in the average installed capacity by 2050 remains relatively homogeneous across regions, with increases between 40 and 60 percentage points relative to the *Reference* scenario. This consistent pattern suggests that the reduction in investment costs induced by technological innovation affects all regions in a similar manner, with the magnitude of the impact primarily determined by each region's initial deployment level. Overall, these findings indicate that all regions benefit from a global effort to lower technology costs through innovation, reinforcing its role as a key driver of widespread low-carbon hydrogen adoption.

In the *Combined Policies* scenario, the effects on regional low-carbon hydrogen deployment are more heterogeneous. This scenario combines two contrasting dynamics: the *all-winner* effect observed in the *Innovation* scenario—characterized by an overall increase in success rates across all regions—and the *winner-loser* effect inherent to the *Trade Liberalization* scenario, where only a few regions gain while others lose deployment capacity. The *all-winner* component dominates the global outcome, as all regions display an increase in their success rates similar to that observed under *Innovation*. However, the trade component introduces regional specialization effects that modify this overall trend. Specifically, the impact of trade liberalization within this scenario affects success rates positively for Latin America, but negatively for Other Asia, North America, Europe, Africa, and Australia. When comparing the *Combined Policies* scenario to the *Innovation* scenario, it appears that Africa and Europe lose most of the benefits gained from cost reductions induced by innovation. By 2050, both regions return to levels of average deployment and success rates comparable to those in the *Reference* scenario. Other Asia also experiences a loss in benefit, though to a lesser extent, maintaining an average gain of 26GW and a success rate of 53% relative to the *Reference* case. In contrast, several regions benefit from the interaction between trade liberalization and innovation. The Middle East, Latin America, and China increase their average deployment and expand the upper bound of their 95% confidence intervals, indicating a higher probability of achieving larger installed capacities by 2050. Although their success rates remain stable—with the Middle East already reaching 100%—the distribution of deployment outcomes shifts toward higher values. Notably, Latin America and China double their 95% bounds compared to the *Innovation* scenario, while the Middle East exhibits a marked rightward shift of its deployment distribution, suggesting high sensitivity to trade liberalization effects.

Table 3: Hydrogen deployment in 2050 by region

Region	**Stats**	***Reference***	***Trade Liberalization***	***Innovation***	***Combined Policies***
World	Average	958.86	-25.12	+386.30	+386.30
	[5%-95%]	[707.60;1123.05]	[-20.76;+6.11]	[+233.20;+537.09]	[+214.64;+579.90]
	% Success	0.50	+0.7	+78.2	+76.0
Asia other	Average	211.97	-60.58	+110.92	+26.28
	[5%;95%]	[188.28;227.36]	[-52.88;-66.52]	[+87.53;+124.39]	[+17.31;+28.17]
	% Success	33.30	-33.3	+66.7	+53.3
China	Average	184.77	-23.12	+70.87	+120.24
	[5%;95%]	[148.09;199.34]	[-19.83;-25.38]	[+56.48;+70.52]	[+59.04;+141.83]
	% Success	36.50	-36.5	+59.9	+59.9
Middle East	Average	144.87	+58.65	+68.73	+126.93
	[5%;95%]	[128.47;156.10]	[+65.07;+50.69]	[+50.77;+82.68]	[+121.60;+124.79]
	% Success	67.70	+32.3	+32.3	+32.3
North America	Average	97.01	+33.15	+47.45	+47.49
	[5%;95%]	[52.30;132.59]	[+1.39;+86.72]	[+7.04;+111.79]	[+3.10;+133.55]
	% Success	0.00	+42.4	+52.2	+48.8
India	Average	79.09	-2.51	+36.40	+30.44
	[5%;95%]	[54.30;102.59]	[-2.41;-1.39]	[+13.85;+65.38]	[+10.29;+58.06]
	% Success	0.30	+0.0	+51.2	+43.4
Latin America	Average	59.01	-5.45	+26.85	+55.43
	[5%;95%]	[37.62;70.20]	[-1.41;-7.97]	[+8.19;+41.85]	[+2.35;+114.77]
	% Success	21.30	-21.3	+57.4	+58.6
Europe	Average	51.65	-10.35	+10.77	+0.83
	[5%;95%]	[40.52;60.85]	[-4.06;-16.02]	[+2.36;+18.16]	[+2.16;+1.58]
	% Success	0.30	-0.3	+47.2	+1.7
Africa	Average	50.43	-7.02	+13.14	+1.81
	[5%;95%]	[40.92;58.58]	[-5.46;-8.45]	[+6.08;+18.86]	[-0.61;+3.49]
	% Success	0.30	-0.3	+60.3	+7.9
Russia	Average	47.88	-6.96	-1.62	-23.66
	[5%;95%]	[2.62;58.82]	[-0.24;-5.72]	[-0.00;-2.14]	[-0.28;-29.10]
	% Success	0.00	+0.0	+0.0	+0.0
Saudi Arabia	Average	21.39	+1.23	-0.30	-0.38
	[5%;95%]	[8.18;42.58]	[+0.37;+2.23]	[-0.24;+0.72]	[-0.18;-0.08]
	% Success	0.00	+0.0	+0.0	+0.0
Australia	Average	10.79	-2.17	+3.08	+0.88
	[5%;95%]	[6.28;14.67]	[-1.28;-2.62]	[+1.14;+4.64]	[-0.14;+2.18]
	% Success	8.80	-8.8	+41.5	+17.4

Note: This table reports the average level of low-carbon hydrogen production capacities deployed in GW, the 5%-95% interval of the distribution projected in GW, and % success rate. All the statistics for *Trade Liberalization*, *Innovation* and *Combined Policies* scenarios are expressed in deviation from the *Reference* scenario. Note that these results are extracted from the scenario with CAGR *Emergency* assumptions and 5-year expectations on the future market size.

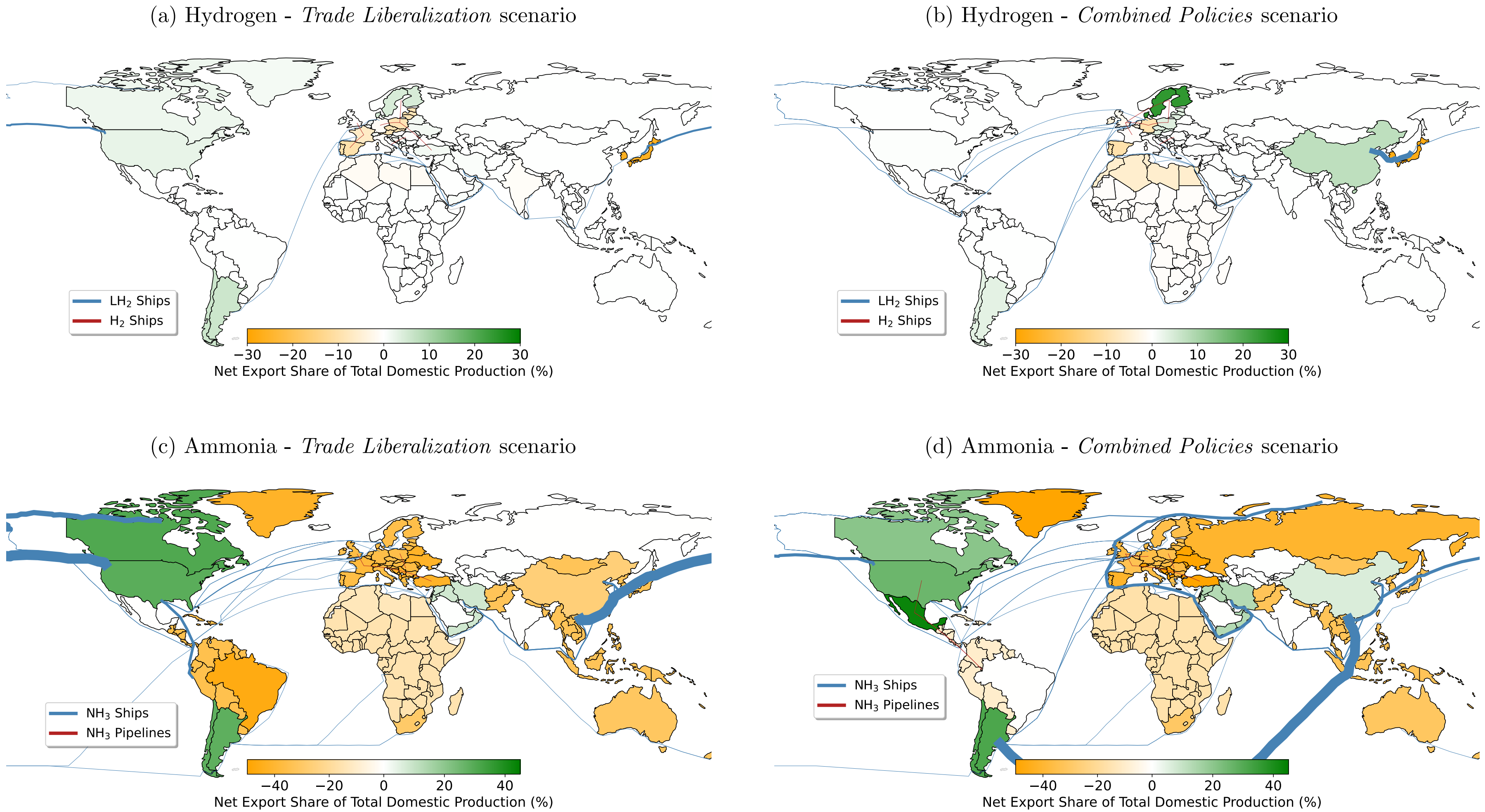
Taken together, these dynamics under trade liberalization with and without innovation indicate that, although the absolute level of deployed capacity remains relatively modest, strong specialization patterns emerge, reallocating low-carbon hydrogen production across regions. As shown in Figure 6, the *Trade Liberalization* and *Combined Policies* scenarios both generate extensive international trade in hydrogen and ammonia, reflected in the deployment of large-scale pipelines in Europe and dense maritime shipping routes worldwide. Overall, 1.7% of global hydrogen demand is met through international trade in the *Trade Liberalization* scenario, rising to 3.7% in the *Combined Policies* scenario—an increase corresponding to a 150% growth in traded volumes between the two cases. By contrast, ammonia is far more extensively traded, with nearly 43% of global demand satisfied through international trade in both scenarios.

This expansion in cross-border trade is accompanied by pronounced regional specialization, with some regions emerging as net exporters and others as net importers. Figure 6 shows that regions increasing their low-carbon hydrogen deployment in response to trade liberalization—most notably North America, the Middle East, and Argentina–Chile—also become net exporters of hydrogen and ammonia in the *Trade Liberalization* scenario. Most other regions move into a net import position for ammonia, while Europe and East Asian regions also become net importers of hydrogen. In the *Combined Policies* scenario, the overall specialization pattern is similar, but China additionally emerges as a net exporter relative to the *Trade Liberalization* case.

These specialization patterns also translate into a high degree of concentration in international hydrogen and ammonia markets on both the export and import sides. Figure 7 illustrates the combined trade flows of ammonia and hydrogen, expressed in $Mt_{H2_{eq}}$. In the *Trade Liberalization* scenario, the export market is highly concentrated: North America accounts for 85% of global exports, followed by the Middle East with 10.6%. Table B3 confirms this—measuring global supply concentration through Herfindahl-Hirschman Index (HHI)—where *Trade Liberalization* scenario leads to the highest HHIs for both hydrogen and ammonia global supply. On the import side, Other Asia dominates with a 67.3% market share, sourcing nearly all of its hydrogen and ammonia from North America. China, Europe, and Latin America also import significant volumes—each capturing between 7.9% and 11% of the import market—and rely primarily on North America and, to a lesser extent, the Middle East.

In the *Combined Policies* scenario, the structure of the international market shifts considerably. The export side becomes more competitive, with four major exporters—Latin America, North America, China, and the Middle East—holding 34%, 22.8%, 25.2%, and 16.6% of the market, respectively. This indicates that the introduction of innovation alongside trade liberalization reshapes global competitiveness, yielding a less concentrated export landscape. This is confirmed by Table B3 reporting a reduction in HHIs for both global hydrogen and ammonia supply within *Combined Policies* scenario compared to *Trade Liberalization* scenario.

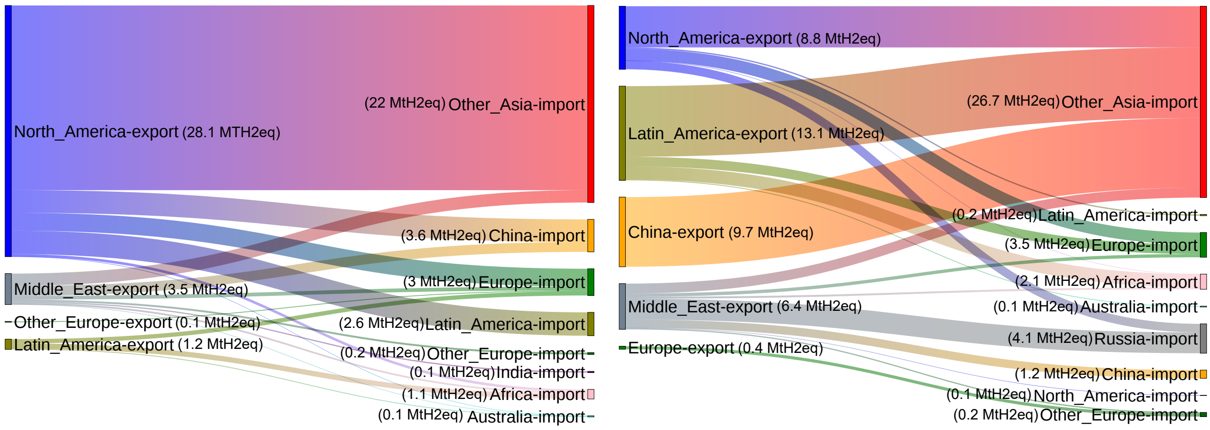
Figure 6: Hydrogen and ammonia international trade in 2050



Note: The trade volumes are estimated using the KiNESYS-IFPEN model under both *Trade Liberalization* (left side) and *Combined Policies* (right side) scenarios in 2050. The trade routes are determined using the `searoute` Python package finding the shortest existing maritime route between two regions. All flows are expressed in PJ_{H_2eq}, applying a 0.9 conversion factor to traded ammonia volumes to reflect the energy volume based on their hydrogen content. The width of the red and blue lines are proportional to the amount of hydrogen and ammonia traded.

Conversely, the import market becomes more concentrated. Other Asia increases its import share by 3 percentage points and diversifies its supply sources to include Latin America, China, North America, and the Middle East. Europe and Russia follow as the next largest importers.

Figure 7: Global hydrogen and ammonia trade flows in 2050



(a) *Trade Liberalization* scenario (b) *Combined Policies* scenario

Note: This figure draws the net flows between the regions in KiNESYS-IFPEN in both *Trade Liberalization* and *Combined Policies* scenarios in 2050. All the volumes are expressed in $\mathrm{Mt}_{\mathrm{H_2eq}}$, applying a 0.9 conversion factor to traded ammonia volumes to reflect their hydrogen content.

3.3 Technological disparities

In this section, we investigate the heterogeneous effect of trade liberalization on different low-carbon hydrogen production technologies. We separate low-carbon hydrogen production in two different types of production technologies: natural-gas-based hydrogen ans electrolyzers technologies. We define natural-gas-based hydrogen as hydrogen production technologies relying on natural gas with carbon capture, and we include Alkaline and Proton Exchange Membrane electrolyzers, both on-grid and off-grid.

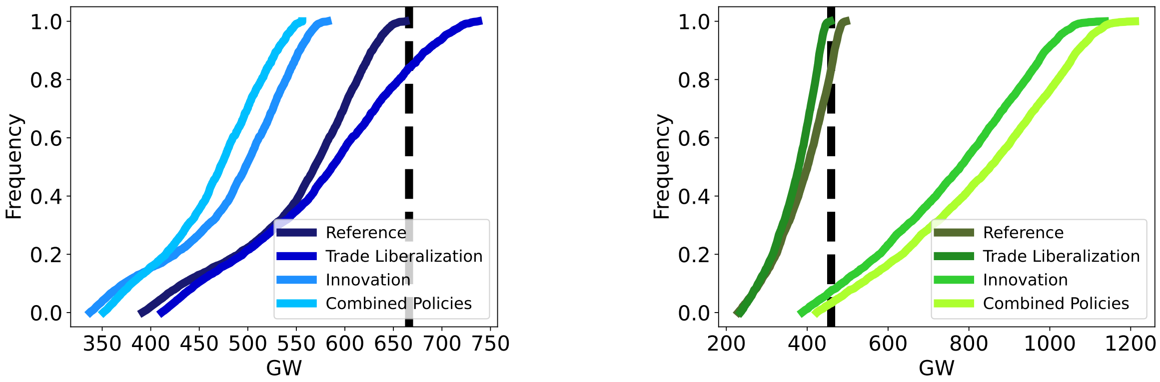
In the *Reference* scenario, as Figure 8 shows, no projection natural-gas-based hydrogen reach effectively the *Reference* target in 2050. By contrast, electrolyzers shows a 19.1% success rate in 2050. This indicates that electrolyzer deployment is globally more likely to reach the *Reference* target in 2050 than natural-gas-based hydrogen.

In the *Trade Liberalization* scenario, Figure 8 shows that global deployment of natural-gas-based hydrogen increases by an average of 25.5 GW, accompanied by a 17-percentage-point rise in its success rate. In contrast, global electrolyzer deployment declines by an average of 20 GW, resulting in a 19-percentage-point reduction in its success rate, which falls to 0%. These findings indicate that trade liberalization in the absence of technological change disproportionately benefits natural-gas-based hydrogen while adversely affecting electrolyzer deployment. This differentiated impact arises from heterogeneous regional responses. As reported in Table B1, the Middle East and North America are the only regions where natural-gas-based hydrogen deployment improves, with success rates increasing by 50.7 and 42 percentage points, respectively. On the electrolyzer side, some regions—notably the Middle East, India, Latin America, and North America—experience gains, but these are more than offset by declines elsewhere. Overall, the *Trade Liberalization* scenario leads to an expansion of natural-gas-based hydrogen at the expense of electrolyzers, driven by strong adjustments in the Middle East and North America, which shift toward specialization in natural-gas-based production and export hydrogen to other regions.

In the *Innovation* scenario, global electrolyzer deployment increases sharply, rising by an average of 371 GW and raising the associated success rate by 73.9 percentage points. In contrast, natural-gas-based hydrogen deployment declines by an average of 69 GW. These effects are mainly driven by increases in electrolyzer deployment across all regions, as reported in Table B2, reflecting a substitution away from natural-gas-based hydrogen toward electrolyzers due to their sharply reduced investment costs as illustrated by Figure B1.

In the *Combined Policies* scenario, global electrolyzer deployment increases by an average of 440 GW, corresponding to a 78-percentage-point rise in the success rate—4 percentage points higher than in the *Innovation* scenario. In contrast, the negative effect on natural-gas-based hydrogen deployment intensifies relative to the *Innovation* scenario, with its global success rate remaining at 0%. As in the *Innovation* scenario, electrolyzer deployment improves relative to the *Reference* scenario in all regions, but the marginal effect of trade liberalization compared with *Innovation* is heterogeneous. As shown in Table B2, China, Latin America, the Middle East, and North America experience additional gains in electrolyzer deployment compared with the *Innovation* scenario, while other regions lose ground. For natural-gas-based hydrogen, Table B1 indicates that the Middle East and North America continue to expand deployment when trade is liberalized, even though natural-gas-based technologies become less competitive globally, as illustrated in Figure B1. This underscores the high sensitivity of natural-gas-based hydrogen production in these regions to trade openness. Overall, these results show that the trade specialization effects observed in the *Combined Policies* scenario stem from heterogeneous regional responses in electrolyzer deployment, driven by the competitiveness gains associated with strong innovation in these technologies.

Figure 8: CDFs of global low-carbon hydrogen deployment in 2050 by technology



(a) Natural-gas-based (b) Electrolyzer

Note: This figure displays the cumulative distribution functions (CDFs) of hydrogen production capacities deployed in 2050 for each policy scenario considered. The vertical black dashed line represents the hydrogen deployment optimal target estimated in the *Reference* scenario for 2050 using KiNESYS-IFPEN model. Note that here we assume CAGR *Emergency* and 5-year expectations on the future market size.

3.4 Mechanism

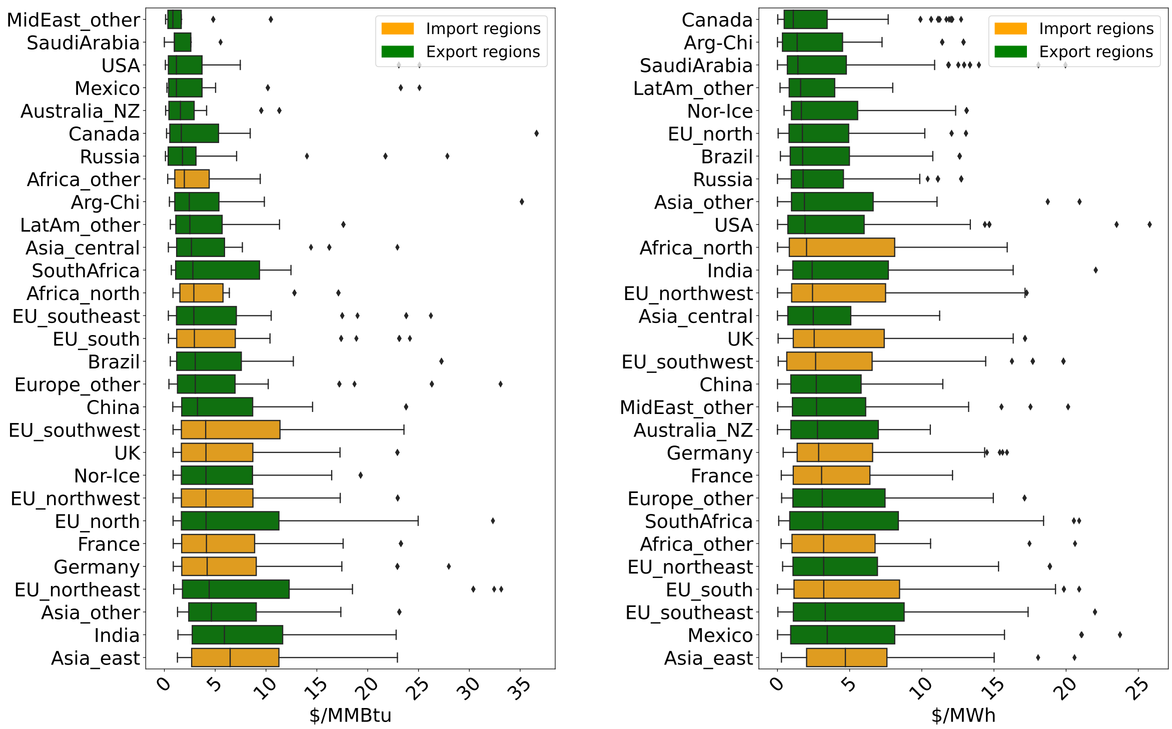
In the previous section, we showed that trade liberalization policies triggered specialization across regions, and this mainly influenced by the ability of each region to deploy either natural-gas-based or electrolysis technologies. We find that this responsiveness is explained by two factors: first, the competitive advantage of a region to produce low-cost hydrogen, and its ability either to substitute the inputs for hydrogen production or to mobilize unused resources to expand hydrogen production.

3.4.1 Production costs differential

As shown in Figure C1, over 99% of trade flows in 2050 occur when the marginal production cost differential between exporting and importing regions is negative, indicating that competitiveness plays a central role in driving hydrogen trade.

According to traditional international trade theory (Dornbusch et al., 1977; Costinot and Rodríguez-Clare, 2014), comparative advantages can arise from differences in resource endowments or technological capabilities (Eaton and Kortum, 2002), and then creates competitiveness. In our framework, technology characteristics are assumed to be homogeneous across regions (see Section 2.4), which rules out technological heterogeneity as a source of trade. Consequently, the only remaining driver is resource endowment costs. In the context of hydrogen production, resource endowment costs matter indirectly because natural resources (e.g., natural gas, renewable energy) are the key inputs into the hydrogen production process. Table C1 illustrates that, throughout all scenarios, input cost represents between 48.6% and 61.4% of the levelized cost of hydrogen (LCOH). This highlights the central role of input marginal cost in leading the hydrogen production cost differential between regions. As shown by Figure 9, which ranks regions by the median marginal cost of natural gas and electricity, we observe that major exporters of natural-gas-based hydrogen are those with the lowest natural gas production costs, such as the Middle East, the USA and Canada that are those benefiting the most from trade openness under the *Trade Liberalization* scenario. Conversely, under the *Combined Policies* scenario, where electricity-based hydrogen becomes more competitive, the principal exporters are regions with the lowest renewable electricity costs, including Canada, Argentina–Chile, Saudi Arabia, and Latin America. This demonstrates that resources endowment costs explain a significant part of regions trade specialization, and foster low-carbon hydrogen deployment in these regions. Nevertheless, resource input costs do not fully explain trade patterns. For example, China emerges as a significant exporter despite exhibiting relatively high median marginal costs for both natural gas and electricity. The potential to explore new resources or

Figure 9: Marginal cost of production



(a) Natural gas

(b) Electricity

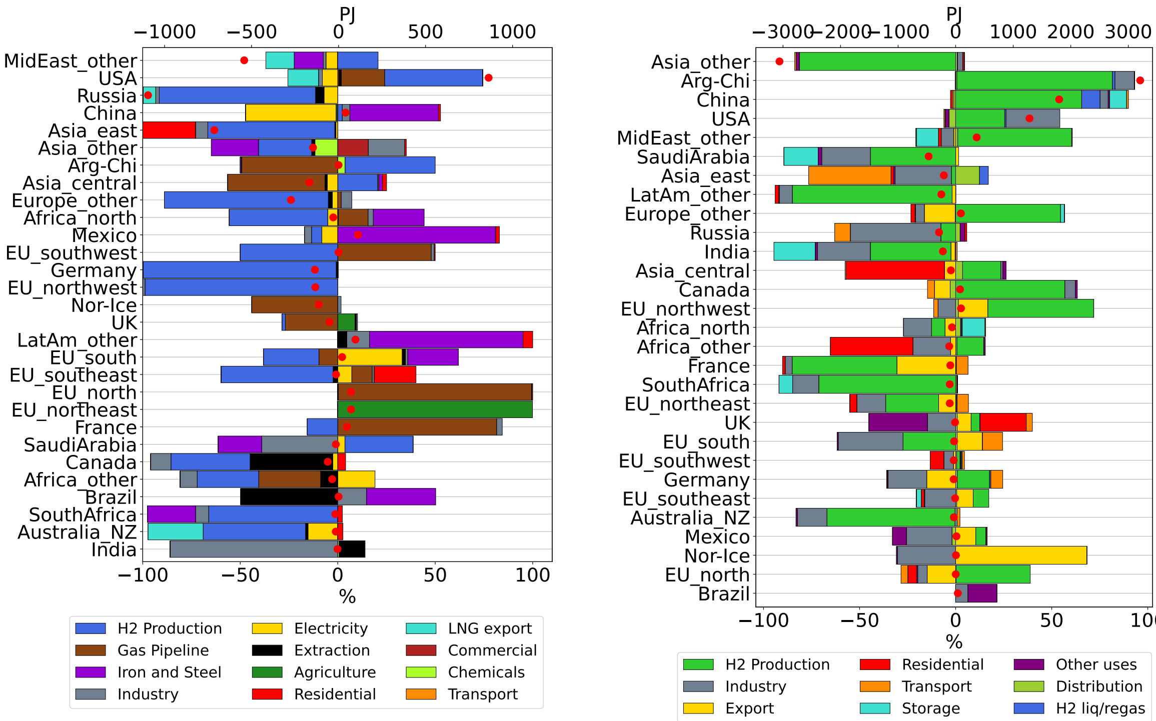
Note: The figures show the boxplot of marginal cost of production of natural gas (left side) and electricity (right side) in 2050 represented by the shadow price of the commodity in the *Combined Policies* scenario from KiNESYS-IFPEN. Export (and import) regions are determined by the share of export (and import) over the total domestic production in 2050.

to substitute existing natural gas or electricity consumption with hydrogen production plays also a role.

3.4.2 Input resources management

We analyze how regions manage input resources when they specialize themselves in hydrogen and ammonia production. Figure 10 highlights two distinct responses: level effects, where regions adjust overall resource use by increasing or decreasing consumption of electricity or natural gas without reallocating it elsewhere, and substitution effects, where resources are redirected from one use, such as exports or industry, to hydrogen production. For natural gas (Figure 10a), most regions expanding hydrogen production substitute natural gas away from exports or industry. The Middle East, for instance, increases natural gas use for hydrogen by reducing LNG exports and steel sector demand. Argentina–Chile and Central Asia follow a similar pattern, diverting pipeline exports toward hydrogen. The United States, by contrast, illustrates a level effect, raising total gas consumption by nearly 900 petajoules (PJ) while partly off-

Figure 10: Commodity use change in 2050



(a) Natural gas

(b) Electricity

Note: The red points are the absolute changes in the consumption (in petajoules) of natural gas and electricity commodities in 2050 in the *Combined Policies* scenario from KiNESYS-IFPEN. The bars represent the decomposed relative changes (in percentages).

setting this through lower LNG exports. Regions reducing hydrogen output, such as Russia, East Asia, Germany, and Northwest Europe, also rely mainly on level effects, cutting gas use outright without reallocating it. Net hydrogen and ammonia importers thus tend to contract their gas use in hydrogen production via level effects, whereas exporters substitute away from trade or industrial uses to expand production. For electricity (Figure 10b), level effects dominate. Argentina–Chile, China, the United States, and the Middle East all increase electricity use in hydrogen production alongside higher overall electricity consumption, reflecting large-scale deployment of solar and wind enabled by abundant resources and land availability.

Overall, natural gas use adjusts through a mix of substitution and level effects that varies with a region's trade position, whereas electricity inputs to hydrogen production are driven almost exclusively by level effects via the expansion of renewable generation.

4 Discussion

Our findings highlight several mechanisms shaping the global deployment of low-carbon hydrogen, with trade-driven ammonia demand emerging as a central driver of regional specialization. As shown earlier, trade liberalization disproportionately affects the ammonia sector, where 43% of global demand is internationally traded. Because ammonia production is one of the largest hydrogen-consuming sectors, expanding cross-border ammonia flows creates a powerful demand pull for hydrogen in export-oriented regions. In our scenarios, ammonia consistently increases its share of total hydrogen consumption when trade is liberalized—by 6.1 percentage points in the *Trade Liberalization* scenario and 1.7 percentage points in the *Innovation* scenario (see Table D1). These shifts underscore the strong coupling between ammonia markets and hydrogen deployment, reinforcing the idea that ammonia may function as an early anchor market that facilitates scale-up in regions positioned to export (IRENA, 2022).

While these results demonstrate that trade policies can significantly amplify the ammonia-driven pull on global hydrogen production, the realization of such trade-induced deployment patterns ultimately depends on the establishment of harmonized international governance frameworks. For ammonia, which is increasingly envisioned as a traded energy carrier, the absence of globally aligned safety, handling, and environmental standards—particularly concerning fuel toxicity, bunkering operations, and permissible emission levels—poses substantial barriers to the emergence of reliable cross-border supply chains (The Royal Society, 2020; ABS, 2023; EMSA, 2024; UNECE, 2025). Similar issues arise in hydrogen markets more broadly. Today, the lack of unified carbon-intensity thresholds, certification systems, and mutually recognized accounting methodologies continues to impede the formation of long-term hydrogen trade contracts

(IRENA, 2021; IPHE, 2022). These regulatory gaps create significant uncertainty for infrastructure investment, market development, and contracting practices, underscoring that robust and internationally coordinated regulatory harmonization will be essential for enabling the large-scale international trade of both hydrogen and ammonia.

Moreover, as demonstrated in this study, the emerging hydrogen market is likely to take the form of an oligopsony, with Europe and East Asia dominating import demand and exerting disproportionate influence in setting global rules (IRENA, 2021). Targeted regulatory cooperation with these major importing regions—similar to early coordination processes observed in LNG or electricity market coupling—could accelerate the establishment of global norms. Harmonized rules would also improve firms' ability to form expectations about future demand and reduce regulatory uncertainty, thereby enhancing the effectiveness of trade-supporting policies.

Despite the relevance of trade dynamics, our results demonstrate that innovation support has far greater potential to drive global hydrogen deployment. Strong innovation efforts—reflected in accelerated cost reductions and performance improvements—produce the most substantial increases in electrolyzer capacity across all regions. This aligns with broader empirical evidence showing that endogenous technological progress, supported by R&D investment and deployment incentives, is a dominant determinant of cost trajectories for clean energy technologies (Nemet, 2006). Policies that incentivize early deployment—even of initially inefficient technologies—can amplify learning-by-doing effects, lowering long-term costs and facilitating deeper market penetration (Bollinger and Gillingham, 2012). Our results therefore suggest that innovation-first strategies are critical for achieving large-scale diffusion of low-carbon hydrogen, while trade policies play a secondary but complementary role.

Innovation also has important implications for the structure and concentration of international hydrogen markets. In scenarios where trade liberalization occurs without substantial technological progress, global hydrogen trade becomes highly concentrated around regions with abundant and inexpensive natural gas—namely North America and the Middle East. These patterns reflect the risk that early hydrogen markets may mirror the geopolitical structures of existing fossil fuel markets, with a small set of dominant exporters shaping international supply chains. Indeed, our results indicate a level of market concentration comparable to that observed in the oil market since the 1990s, when OPEC (Organization of the Petroleum Exporting Countries) has often been characterized as a cartel (Hughes and Long, 2014). However, when innovation significantly reduces electrolyzer costs, a wider range of regions becomes cost-competitive, leading to a more diversified export landscape. This diversification loosens the potential formation of an international oligopoly and reduces the likelihood that hydrogen markets replicate historical dependencies associated with fossil energy systems. In this sense, innovation not only accelerates deployment but also contributes to a more equitable and resilient global hydrogen and ammonia market architecture.

Finally, the implications of hydrogen trade for emerging economies warrant careful consideration. Our findings deviate from existing analyses that often portray Africa and other emerging regions as major hydrogen exporters (Franzmann et al., 2023; IRENA, 2025). Most of these studies evaluate bilateral trade potential or resource endowment in isolation, without accounting for global competition or the broader economic constraints facing emerging economies. By incorporating resource competition and welfare maximization within each region, our results reveal that large-scale export strategies may not always be economically viable or aligned with domestic development needs. This nuance is frequently absent from policy narratives that frame hydrogen primarily as an export commodity for the Global South and an import decarbonization vector for the Global North—narratives that risk reproducing unequal exchange or even "green extractivism" (Hornborg, 1998; Tunn et al., 2024). Our findings underscore the necessity of integrating development considerations into hydrogen trade agreements to avoid reinforcing historical patterns of resource dependency and to ensure that emerging economies retain the capacity to decarbonize their own industries.

Taken together, these results point toward a global hydrogen landscape in which innovation support, regulatory harmonization, and development-sensitive trade policy emerge as the key pillars for scaling low-carbon hydrogen in an economically and geopolitically sustainable manner.

5 Conclusion

This paper investigates whether global hydrogen and ammonia trade liberalization can accelerate the deployment of low-carbon hydrogen required to meet Net-Zero Emissions by 2050. Using a hybrid framework that integrates a least-cost energy-system model with a probabilistic logistic diffusion model, we show that trade openness alone does not substantially enhance global deployment prospects. Although it enables international specialization, its effects are primarily redistributive: production shifts toward regions with low-cost natural gas—most notably the Middle East and North America—while many other regions experience declines in domestic deployment. Trade thus reshapes the geography of production without increasing the global probability of reaching optimal deployment levels. In contrast, innovation-driven cost reductions in electrolyzer technologies emerge as the strongest determinant of large-scale diffusion, raising global success rates by nearly 80 percentage points. Innovation triggers widespread increases in deployment across almost all regions, shifts production toward green hydrogen, and reduces the concentration of export power that arises when trade liberalization occurs without technological progress. A third key finding is the central role of expectation horizons. Extending expectations from short to long time frames significantly boosts deployment probabilities—even in the absence of innovation—and strongly amplifies the effects of both innovation and trade. Anchored expectations thus operate as a coordination device, mitigating uncertainty and enabling investment dynamics consistent with Net-Zero trajectories. Finally, our results highlight important geopolitical and developmental implications. Without innovation, trade liberalization risks reinforcing fossil-like concentration patterns, whereas innovation promotes a more diversified export landscape. Moreover, when domestic welfare constraints are accounted for, many emerging economies do not appear as large-scale exporters, cautioning against development-blind hydrogen trade narratives. Taken together, these findings indicate that innovation, credible long-term policy signals, and international regulatory harmonization—rather than trade liberalization alone—constitute the critical pillars for scaling low-carbon hydrogen in an economically viable and geopolitically sustainable manner.

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A Appendix

A.1 Details on KiNESYS-IFPEN

This section provides additional details on the KiNESYS-IFPEN model, including the data used to calibrate the upstream sector, the representation of the hydrogen value chain, and the calibration of exogenous demand drivers.

A.1.1 Upstream sector

The upstream sector includes all the primary energy sources needed to produce different types of hydrogen. It goes from biomass, crude oil, coal, natural gas extractions with their refining into a usable input energy source for hydrogen production. Another energy carrier is the electricity from the grid to produce on-grid hydrogen and off-grid for off-grid hydrogen production. Regions' primary energy resources are calibrated according to IEA energy balances database in 2019. Fossil fuel supply cost curves are sourced from Rystad Energy. Hourly solar and wind generation profiles are derived from the PVGIS Typical Meteorological Year (TMY) dataset,[6] aggregated at the regional level. The methodology behind the TMY construction is detailed in Huld et al. (2018). Techno-economic parameters for renewable electricity technologies are obtained from the REZoning database provided by the World Bank's ESMAP program.[7] Assumptions on hourly electricity load profiles are based on data from ENTSO-e[8] and KAPSARC. Historical data on installed renewable electricity capacity and generation are collected from both PLATTS and IRENASTAT,[9] while assumptions on future renewable electricity technologies are based on the World Energy Outlook 2022.[10]

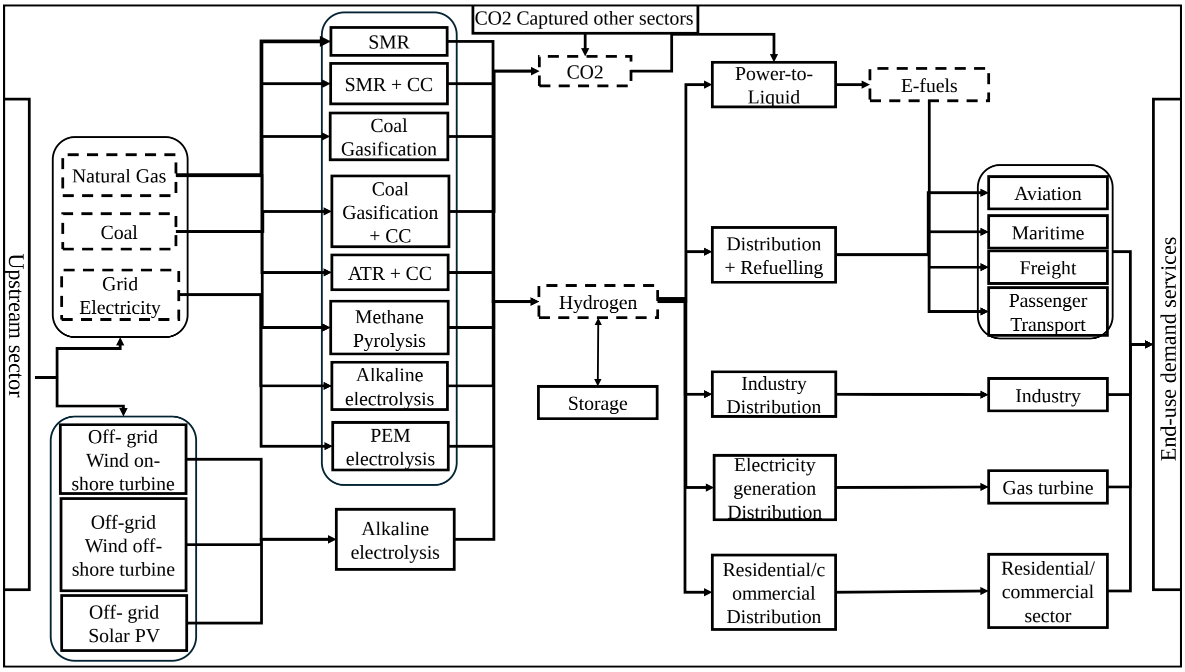
A.1.2 Hydrogen sector

The TIMES-family models have been widely applied to assess the impact of various scenarios on future hydrogen deployment (Brändle et al., 2021; Seck et al., 2022; Shirizadeh et al., 2023). Building on this body of work, we develop a detailed representation of the hydrogen value chain that reflects key sector-specific characteristics. Figure A1 illustrates the reference energy system (RES) for the hydrogen sector as implemented in the KiNESYS-IFPEN model. The value chain is decomposed into four main components:

[6] For more information, see PVGIS – Photovoltaic Geographical Information System.
[7] For more information, see REZoning data page.
[8] For more details, see ENTSO-e Transparency Platform
[9] For more information, see IRENASTAT.
[10] See World Energy Outlook 2022.

(i) primary energy sources, (ii) hydrogen-specific upstream activities, (iii) production, transmission, and distribution, and (iv) end-use consumption.

Figure A1: Hydrogen Reference Energy System



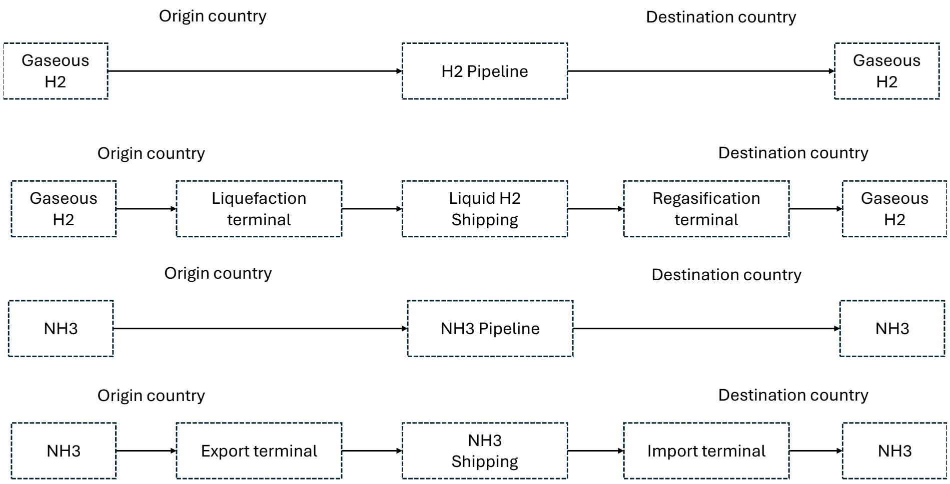
Note: This represents the Reference Energy System (RES) in the KiNESYS-IFPEN model specific to the hydrogen sector ranging from the upstream to the downstream sector. The rectangles in solid lines define processes converting an input commodity into another. Rectangles in dashed lines define commodities. The arrows are expressing the flows direction. Note that this is an illustrative RES with simplification for better understanding.

Table A1: Hydrogen production: techno-economic assumptions

Technology Description	Efficiency (%)	Availability factor (%)	Capital expenditure ($/kW)	Fixed cost ($/kW)	Variable cost ($/GJ)	Lifetime (years)
Coal Gasification	0.60	0.95	2770.67	138.53	0.1911	25
Coal Gasification + Carbon Capture	0.58	0.95	2884.81	144.24	0.3049	25
Methane Steam Reforming	0.76	0.95	944.31	44.38	0.0903	25
Methane Steam Reforming + Carbon Capture	0.72	0.95	1743.34	52.30	0.6211	25
ATR + Carbon Capture	0.74	0.95	924.02	27.72	0.6122	25
GHR/ATR + Carbon Capture	0.78	0.95	958.67	28.76	0.6122	25
Molten Media Methane Pyrolysis	0.49	0.95	898.38	74.96	0.0890	20
PEM Electrolyzer on-grid	0.63	0.95	2021.29	60.64	0.1780	15
Alkaline Electrolyser on-grid	0.65	0.90	1443.78	21.66	0.1780	20
Alkaline Electrolyser, onshore Wind offgrid	0.65	0.90	1443.78	21.66	0.1780	20
Alkaline Electrolyser, PV offgrid	0.65	0.90	1443.78	21.66	0.1780	20

Note: The assumptions regarding the production are drawn from Seck et al. (2022). All technologies are centralized and we assume their size as large. The efficiency parameter is only based on the amount of the main input needed to produce hydrogen, but technology with carbon capture also consume electricity from the grid to power it.

Figure A2: International transport value chain



Note: This figure represents the international transport value chain of both hydrogen and ammonia. At each step, each technology is modeled with techno-economic parameters such as capital expenditure, fixed operation and maintenance costs, efficiency and lifetime.

A.1.3 Demand drivers calibration

As specified previously, the model is driven by the evolution of socio-economic characteristics summarized in Table A2. These projections are drawn from Cuaresma (2017) and represent the evolution of the Shared SocioEconomic pathway 2 (SSP2) that considers the medium case from IIASA projections.[11]

Table A2: Demand Drivers

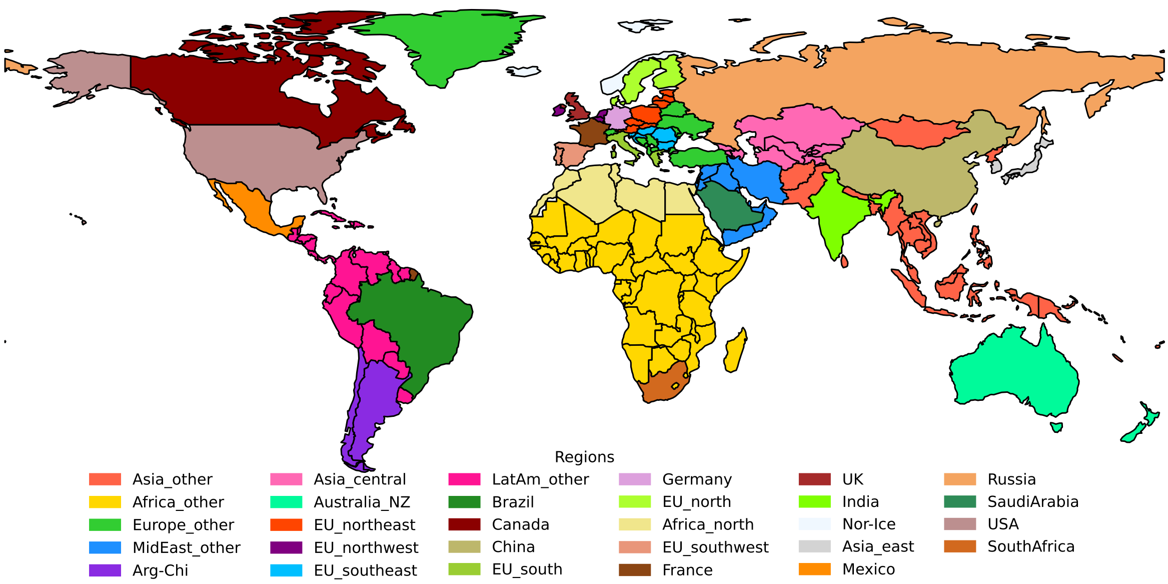
Category	**Subcategory**	**2019**	**2020**	**2025**	**2030**	**2035**	**2040**	**2045**	**2050**	**CAGR(%)**
GDP Total (Trillion)		122.9	125.5	143.7	158.5	174.4	193.7	214.3	236.3	2.1
	Agriculture	7.2	7.5	8.7	9.8	11	12.5	14	15.5	2.5
	Industry	37.2	38.1	43.7	48.6	53.9	60.3	67.3	74.5	2.3
	Services	76.6	78	90.3	98.7	107.7	118.6	130.4	142.5	2
Households (Billion)		2.22	2.24	2.34	2.45	2.54	2.61	2.68	2.72	0.7
Population (Billion)		7.7	7.8	8.1	8.5	8.8	9.1	9.4	9.6	0.6

Note: The demand drivers projections are based on the Shared Socioeconomic Pathways 2 (SSP2) from Cuaresma (2017).

[11]For more details, see IIASA SSP Database visualization tool

A.2 Regional decomposition

Figure A3: KiNESYS-IFPEN regions



Note: The regional mapping in KiNESYS-IFPEN is specifically designed to balance detail and computational efficiency by capturing key regional characteristics while maintaining an intermediate level of aggregation. We keep the same regional mapping to project the evolution of low-carbon installed capacities.

Table A3: Results regional mapping

KiNESYS Region		Results' Region
Africa_other Africa_north SouthAfrica	→	Africa
Australia_NZ	→	Australia
China	→	China
UK EU_southwest France EU_south Nor-Ice Germany EU_northeast EU_northwest EU_southeast EU_north Europe_other	→	Europe
India	→	India
LatAm_other Brazil Arg-Chi Mexico	→	Latin America
MidEast_other	→	Middle East
USA Canada	→	North America
Asia_east Asia_other Asia_central	→	Other Asia
Russia	→	Russia
Saudi Arabia	→	Saudi Arabia

Note: This table reports the regional aggregation made to show the regional breakdown results in the results section. Note that the regions are aggregated based on their geographical and economic relevance.

A.3 Diffusion model calibration details

A.3.1 Initial capacity distribution

Consistent with our 29-region decomposition, we filter the database to include only projects currently in operation and aggregate the data at the regional level. For regions with no reported operational capacity, we assign a minimal non-zero initialization value to allow capacity evolution within the diffusion model. The resulting spatial distribution of initial capacities is shown in Figure A4 in the Appendix.

A.3.2 Compound annual growth rate distribution

Following Odenweller et al. (2022), we set the baseline assumption that the CAGR of low-carbon hydrogen production capacity could be equal to historical solar and wind power capacity one because they are the most recent example of low-carbon technology widely developed. Solar and wind power capacity showed historically an exponential deployment shape (Hansen et al., 2017). We estimate the CAGR with the non-linear least squares (NLS) considering renewable electricity generation capacity amount per region as an endogenous variable and time as an exogenous variable (Equation 9). Using annual data from 1997 to 2022 (Energy Institute Statistical Review of World Energy, 2023[12]), we draw the CAGR distribution estimating 1,000 rolling windows of 10-year CAGR:

$$C_{r,t} = \alpha_i * e^{\beta^r (t-t_0)} + \epsilon_{r,t} \tag{9}$$

where $C_{r,t}$ is the installed capacity in region r at year t, α the initial capacity estimated, β^r the CAGR for the region r, t_0 the initial period, and $\epsilon_{r,t}$ the error term.

Then, we simulate truncated-normal distribution based on the in-sample mean $\hat{\mu_r}$ and standard deviation $\hat{\sigma_r}$ of the estimated set of CAGR for each region:

$$\begin{aligned} f_r(x; \hat{\mu_r}, \hat{\sigma_r}, \mathbf{a}, \mathbf{b}) &= \frac{1}{\hat{\sigma_r}} \times \frac{\phi(\frac{x-\hat{\mu_r}}{\hat{\sigma_r}})}{\Phi(\frac{b-\hat{\mu_r}}{\hat{\sigma_r}}) - \Phi(\frac{a-\hat{\mu_r}}{\hat{\sigma_r}})} \\ \text{with:} \quad \phi(z) &= \frac{1}{\sqrt{2\pi}} e^{-\frac{1}{2}z_r^2} \text{ and } z_r = \frac{x-\hat{\mu_r}}{\hat{\sigma_r}} \end{aligned} \tag{10}$$

where $f_r(.)$ represents the normal probability density function for the region r with a and b truncation parameters for the random variable x, and $\Phi(.)$ is the normal cumulative distribution function.

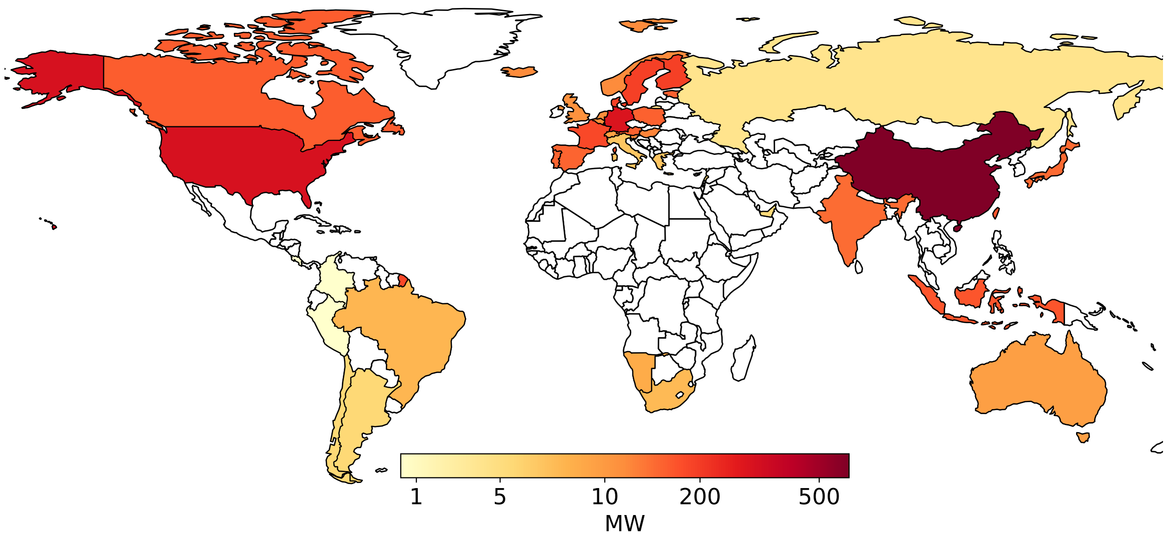
We examine two case scenarios regarding the distribution of the CAGR: *CAGR No*

[12]See https://www.energyinst.org/statistical-review

Emergency and *CAGR Emergency*. The *CAGR No Emergency* scenario applies no assumptions on the truncation parameters, and reflects all the CAGR values likely to occur. The *CAGR Emergency* scenario imposes a lower truncation on the CAGR distribution. We choose the truncation parameters a and b according to Odenweller et al. (2022)'s emergency growth rate definition and mathematical constraints. We set a equal to 0.15 in the deployment emergency case and 0 when it was unrestricted. We set b equal to 1.5 to avoid bound issues in the projection.

A.3.3 Parameters values

Figure A4: Initial low-carbon capacity installed



Note: This figure represents the geographical distribution of the low-carbon hydrogen installed capacity that are operational in 2024. In this figure, the data are aggregated at a country-level but we aggregate them at a regional-level (based on KiNESYS-IFPEN regional decomposition) in the study.

Table A4: CAGR distribution by region

Region	*No Emergency*							*Emergency*						
	Mean	Std.	Min	25%	50%	75%	Max	Mean	Std.	Min	25%	50%	75%	Max
EU_southeast	0.59	0.33	0	0.34	0.56	0.81	1.49	0.63	0.3	0.13	0.4	0.6	0.84	1.47
Brazil	0.51	0.3	0	0.28	0.48	0.71	1.41	0.54	0.29	0.06	0.32	0.5	0.73	1.46
Russia	0.48	0.3	0	0.25	0.44	0.67	1.48	0.45	0.29	0.02	0.22	0.42	0.64	1.49
SouthAfrica	0.43	0.24	0	0.24	0.41	0.59	1.43	0.42	0.22	0.07	0.26	0.39	0.56	1.27
China	0.4	0.15	0.01	0.3	0.39	0.5	0.93	0.45	0.13	0.24	0.35	0.44	0.53	1
Asia_other	0.4	0.1	0.11	0.34	0.4	0.47	0.71	0.44	0.08	0.31	0.38	0.43	0.49	0.72
Asia_central	0.4	0.19	0	0.27	0.4	0.53	0.99	0.43	0.16	0.17	0.31	0.41	0.54	0.92
Arg-Chi	0.36	0.16	0	0.25	0.36	0.48	0.86	0.4	0.13	0.17	0.3	0.38	0.49	0.84
Mexico	0.35	0.15	0	0.25	0.35	0.46	0.81	0.39	0.13	0.17	0.29	0.37	0.47	0.84
Africa_other	0.34	0.08	0.11	0.28	0.34	0.39	0.61	0.36	0.06	0.25	0.31	0.35	0.4	0.61
MidEast_other	0.33	0.06	0.13	0.29	0.33	0.37	0.53	0.35	0.05	0.27	0.31	0.34	0.38	0.57
France	0.32	0.16	0	0.2	0.31	0.43	0.91	0.36	0.14	0.13	0.25	0.35	0.46	0.85
Europe_other	0.31	0.07	0.11	0.26	0.31	0.35	0.5	0.32	0.05	0.23	0.28	0.32	0.36	0.52
EU_northeast	0.28	0.14	0	0.17	0.27	0.37	0.71	0.31	0.11	0.12	0.22	0.29	0.38	0.86
Australia_NZ	0.28	0.11	0	0.21	0.28	0.35	0.64	0.31	0.09	0.16	0.25	0.31	0.37	0.68
Asia_east	0.27	0.08	0.03	0.22	0.27	0.32	0.51	0.29	0.06	0.19	0.25	0.29	0.33	0.49
Canada	0.27	0.12	0	0.19	0.28	0.35	0.68	0.29	0.1	0.13	0.21	0.28	0.36	0.66
LatAm_other	0.25	0.09	0	0.19	0.25	0.31	0.62	0.28	0.07	0.16	0.22	0.27	0.32	0.6
UK	0.25	0.06	0.04	0.2	0.25	0.29	0.45	0.26	0.05	0.18	0.22	0.25	0.29	0.48
EU_south	0.24	0.12	0	0.15	0.23	0.31	0.65	0.25	0.11	0.09	0.17	0.24	0.32	0.62
India	0.21	0.04	0.09	0.18	0.21	0.24	0.35	0.23	0.04	0.17	0.2	0.22	0.25	0.38
USA	0.21	0.06	0	0.17	0.21	0.25	0.47	0.23	0.05	0.15	0.19	0.22	0.26	0.38
EU_northwest	0.2	0.03	0.09	0.17	0.2	0.22	0.3	0.21	0.03	0.16	0.18	0.2	0.22	0.29
Africa_north	0.2	0.03	0.12	0.19	0.2	0.22	0.29	0.21	0.02	0.18	0.19	0.21	0.23	0.28
EU_southwest	0.16	0.09	0	0.08	0.15	0.22	0.45	0.16	0.08	0.03	0.1	0.16	0.22	0.45
SaudiArabia	0.15	0.05	0.01	0.11	0.15	0.18	0.33	0.16	0.04	0.09	0.13	0.16	0.19	0.31
Germany	0.15	0.05	0.01	0.11	0.15	0.18	0.3	0.16	0.04	0.09	0.13	0.16	0.19	0.32
EU_north	0.11	0.03	0	0.08	0.11	0.13	0.22	0.12	0.03	0.07	0.1	0.11	0.13	0.21

Note: This table reports summary statistics for the regional CAGR distributions under the *CAGR No Emergency* and *Emergency* cases. The regional decomposition follows the structure used in KiNESYS-IFPEN. Regions are ranked by their mean values.

B Technological deployment by region

Table B1: Natural-gas-based hydrogen deployment by region

Region	Stats	*Reference*	*Trade Liberalization*	*Innovation*	*Combined*
World	Average	552.08	+25.54	-69.63	-87.49
	[5%-95%]	[412.37;637.90]	[+17.67;+65.03]	[-58.43;-75.91]	[-46.45;-98.08]
	% Success	0.00	+17.1	+0.0	+0.0
Middle East	Average	137.46	+42.12	+1.87	+30.19
	[5%-95%]	[123.34;146.65]	[+50.31;+34.62]	[+2.56;+1.31]	[+40.59;+22.35]
	% Success	49.30	+50.7	+9.2	+50.7
North America	Average	94.26	+31.58	+9.51	+9.65
	[5%-95%]	[51.64;127.22]	[+0.89;+82.98]	[+1.75;+18.27]	[-2.45;+31.56]
	% Success	0.00	+42.0	+19.4	+23.3
Other Asia	Average	55.74	-11.07	-19.93	-28.80
	[5%-95%]	[54.34;56.83]	[-10.79;-11.48]	[-20.20;-19.50]	[-29.28;-29.00]
	% Success	100.00	-100.0	-100.0	-100.0
Russia	Average	47.88	-6.96	-1.62	-23.66
	[5%-95%]	[2.62;58.82]	[-0.24;-5.72]	[-0.00;-2.14]	[-0.28;-29.10]
	% Success	0.00	+0.0	+0.0	+0.0
Europe	Average	42.90	-9.26	-8.49	-22.96
	[5%-95%]	[35.76;47.77]	[-4.65;-12.03]	[-6.88;-8.90]	[-17.34;-26.49]
	% Success	0.00	+0.0	+0.0	+0.0
China	Average	42.51	+0.41	-12.35	-12.79
	[5%-95%]	[42.24;42.91]	[+0.41;+0.24]	[-12.40;-12.07]	[-12.67;-13.14]
	% Success	84.70	+12.3	-84.7	-84.7
Africa	Average	40.81	-7.10	-9.76	-18.77
	[5%-95%]	[34.74;45.25]	[-5.90;-7.95]	[-6.47;-11.83]	[-14.05;-22.09]
	% Success	0.00	+0.0	+0.0	+0.0
India	Average	34.62	-7.72	-8.80	-8.12
	[5%-95%]	[30.05;37.78]	[-5.79;-9.18]	[-6.35;-10.75]	[-6.06;-9.71]
	% Success	55.90	-55.9	-55.9	-55.9
Latin America	Average	29.26	-6.25	-12.68	-4.02
	[5%-95%]	[23.75;31.90]	[-5.33;-6.91]	[-8.83;-14.81]	[-1.53;-5.45]
	% Success	5.80	-5.8	-5.8	-5.8
Saudi Arabia	Average	18.36	+0.84	-6.64	-6.67
	[5%-95%]	[7.77;33.90]	[+0.32;+1.27]	[-1.69;-14.27]	[-1.71;-14.30]
	% Success	0.00	+0.0	+0.0	+0.0
Australia	Average	8.28	-1.06	-0.74	-1.54
	[5%-95%]	[5.51;10.18]	[-0.96;-0.76]	[-0.31;-1.11]	[-1.13;-1.59]
	% Success	0.00	+0.0	+0.0	+0.0

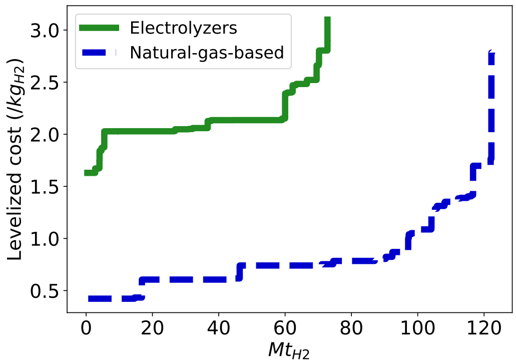
Note: This table reports the average level of natural-gas-based hydrogen production capacities deployed in GW, the 5%-95% interval of the distribution projected in GW, and % success rate. All the statistics for *Trade Liberalization*, *Innovation* and *Combined Policies* scenarios are expressed in deviation from the *Reference* scenario. Note that these results are extracted from the scenario with CAGR *Emergency* assumptions and 5-year expectations on the future market size.

Table B2: Electrolyzer deployment by region

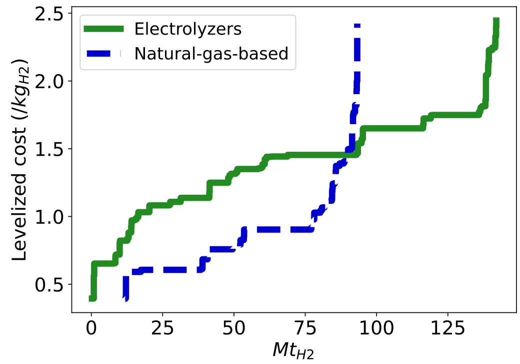
Region	Stats	*Reference*	*Trade Liberalization*	*Innovation*	*Combined*
World	Average	387.32	-20.11	+371.72	+439.85
	[5%-95%]	[258.39;475.90]	[+0.84;-37.61]	[+180.23;+548.65]	[+221.84;+626.51]
	% Success	19.10	-19.0	+73.9	+78.0
Other Asia	Average	130.34	-33.40	+89.27	+46.82
	[5%-95%]	[87.11;160.56]	[-15.07;-46.97]	[+34.06;+140.81]	[+22.23;+63.67]
	% Success	11.60	-11.6	+71.8	+58.0
China	Average	104.18	-13.23	+78.33	+115.32
	[5%-95%]	[52.98;134.28]	[-2.85;-21.90]	[+24.34;+105.30]	[+27.84;+175.91]
	% Success	18.00	-18.0	+61.6	+64.1
India	Average	62.92	+4.62	-14.86	-22.21
	[5%-95%]	[48.76;74.06]	[+1.63;+8.17]	[-22.11;+5.80]	[-26.28;-5.54]
	% Success	0.50	+20.2	+6.6	+1.9
Latin America	Average	32.18	+3.49	+35.13	+90.35
	[5%-95%]	[23.97;38.69]	[+0.33;+3.35]	[+15.83;+51.72]	[+45.33;+120.00]
	% Success	21.40	+37.1	+76.8	+78.6
Europe	Average	16.06	-0.42	+12.48	+11.05
	[5%-95%]	[13.79;17.37]	[-0.48;-0.48]	[+10.26;+14.86]	[+8.68;+13.86]
	% Success	100.00	+0.0	+0.0	+0.0
Saudi Arabia	Average	15.57	+0.52	+18.65	+13.41
	[5%-95%]	[8.92;21.48]	[+0.38;+0.26]	[+5.39;+31.11]	[+4.30;+21.39]
	% Success	0.00	+0.0	+72.8	+66.3
Africa	Average	10.15	+0.40	+23.98	+19.62
	[5%-95%]	[8.80;11.59]	[+0.51;+0.51]	[+15.14;+32.15]	[+12.87;+25.72]
	% Success	0.00	+0.0	+100.0	+100.0
North America	Average	5.89	+2.78	+45.63	+62.13
	[5%-95%]	[5.28;6.53]	[+2.13;+3.51]	[+22.14;+76.66]	[+29.45;+103.50]
	% Success	100.00	+0.0	+0.0	+0.0
Middle East	Average	5.61	+17.15	+79.45	+101.02
	[5%-95%]	[4.88;6.51]	[+16.10;+18.03]	[+73.32;+85.04]	[+96.57;+104.40]
	% Success	100.00	+0.0	+0.0	+0.0
Australia	Average	4.40	-2.02	+3.68	+2.33
	[5%-95%]	[3.89;4.84]	[-1.85;-2.10]	[+1.86;+5.20]	[+0.87;+3.60]
	% Success	100.00	-100.0	+0.0	+0.0

Note: This table reports the average level of natural-gas-based hydrogen production capacities deployed in GW, the 5%-95% interval of the distribution projected in GW, and % success rate. All the statistics for *Trade Liberalization*, *Innovation* and *Combined Policies* scenarios are expressed in deviation from the *Reference* scenario. Note that these results are extracted from the scenario with CAGR *Emergency* assumptions and 5-year expectations on the future market size.

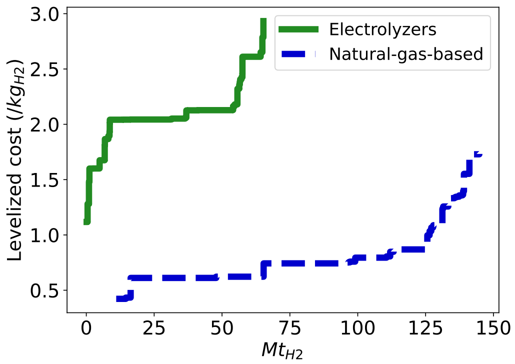
Figure B1: Low-carbon hydrogen supply curve in 2050



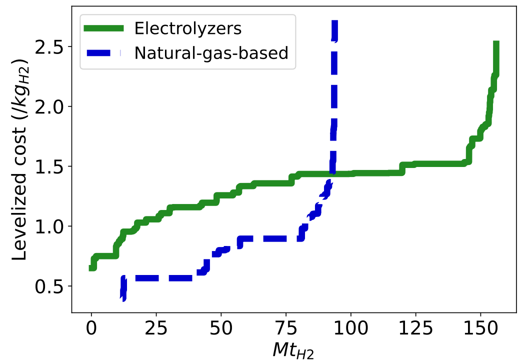
(a) *Reference* scenario



(c) *Innovation* scenario



(b) *Trade Liberalization* scenario



(d) *Combined Policies* scenario

Note: These figures represent the supply curves comparison between hydrogen produced from electrolyzer and natural-gas-based technologies for each policy scenario in 2050 from KiNESYS-IFPEN.

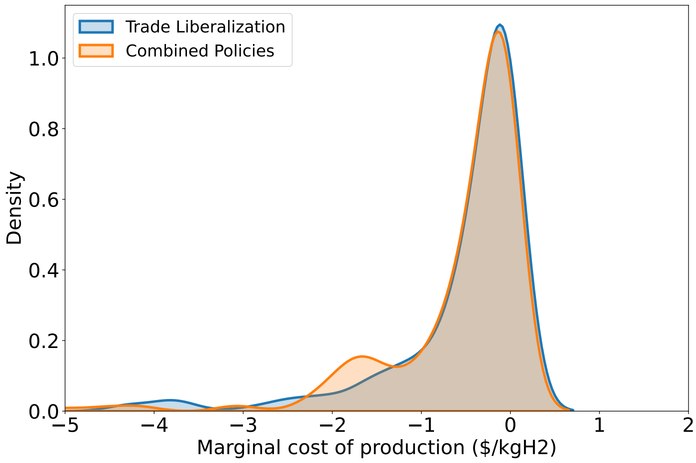
Table B3: Herfindahl-Hirschman Index by commodity in 2050

Commodity	**Production type**	***Reference***	***Trade Liberalization*** (Δ)	***Innovation*** (Δ)	***Combined Policies*** (Δ)
Hydrogen	-	974.6	+142.2	+63.2	+118.8
	Natural-gas-based	1137.8	+321.4	+243.2	+553.0
	Electrolysis	2287.8	-260.0	-675.6	-940.5
Ammonia	-	1188.9	+561.5	+173.1	+332.6

Note: This table reports the values for the Herfindahl-Hirschman Index (HHI) for hydrogen and ammonia for each policy scenario. The HHI here is expressed as the sum of the squared supply share throughout the 29 regions within KiNESYS-IFPEN: $\sum_{i=1}^{N}(S_{i,c})^2$, where $S_{i,c}$ represents the share of region i in the global supply of the commodity c.

C Low-carbon hydrogen cost

Figure C1: Hydrogen marginal cost of production differential



Note: This figure displays the distribution density of the hydrogen marginal cost of production differential between the regions that actually trade in the *Trade Liberalization* and *Combined Policies* scenarios. 99% of the trade volume are made when marginal cost differential is negative.

Table C1: Levelized Cost of Hydrogen in 2050

Scenario	**Average LCOH**	**% Investment Cost**	**% Fixed O&M Cost**	**% Input Cost**	**% Activity Cost**
Reference	1.33	37.25	11.58	50.18	0.99
Trade Liberalization	1.20	38.27	12.06	48.60	1.07
Innovation	1.18	29.57	9.15	60.33	0.95
Combined Policies	1.13	28.91	8.74	61.38	0.97

Note: This table reports the average Levelized Cost of Hydrogen in 2050 from KiNESYS-IFPEN ouputs, and its decomposition by policy scenario.

D Sectoral decomposition

Table D1: Hydrogen sector decomposition

		Reference	***Trade*** **Liberalization**	***Innovation***	***Combined Policies***
Global production (Mt/year)	-	235.54	+9.98 (+4.24%)	+35.79 (15.19%)	+45.83 (+19.46%)
Production (%) (by process)	SMR w/ CC	52.8	+8.4	-17.1	-18.5
	Alkaline	25.3	-2.8	+19.3	+22.5
	NH3-Integ.	13.1	-2.8	-3	-4.5
	PEM	6	-0.9	+2.9	+3.3
	SMR	2.8	-1.9	-1.5	-2.8
Consumption (%) (by sector)	Industry	40.3	-1.7	-2.7	-4.7
	Ammonia	30	+6.1	+0.2	+1.7
	Transport	15.2	-1.9	-1.9	-2.6
	DRI	8.9	-0.2	+0.9	+0.6
	Res. & Com.	3.7	-2	+2.5	+3.8

Note: This table reports the key results from the 4 scenarios ran in KiNESYS-IFPEN. It is important to note that the first column report the results for the *Reference* scenario, and the other column all the results relative to this *Reference* case. The value reported are these for the year 2050 in KiNESYS-IFPEN.