Work Package 2 - Key Results

CARTIF: Analysis of hydrogen-related policies ad targets

Introduction & Overview of Activities

Hydrogen has moved from an industrial feedstock to a central pillar of decarbonisation policy. Across Europe and internationally: targets are being set, instruments are proliferating, and sectoral roadmaps increasingly converge on hydrogen for hard-to-abate uses. HYDRA designed a task (T2.1, led by CARTIF) to bring this policy diversity onto common ground so that objectives, instruments, and timelines can be compared on equal terms and represented quantitatively in integrated assessment models (IAMs).

IAMs are powerful tools that simulate the complex interplay between the economy, energy systems, the environment, and climate. Accurately representing policies within these models is essential, as policies directly shape the decisions of economic actors and drive systemic change. By embedding policy mechanisms, IAMs can reveal how policy interventions can impact energy demand, economic performance, and emissions trajectories. This makes IAMs indispensable for evaluating the real-world impact of climate and energy strategies—one of the key reasons why the WILIAM IAM model was chosen for the HYDRA project, where our goal is to explore the implications of a future hydrogen-based economy.

For this reason, HYDRA deliverable (D2.1) presents a consolidated review of hydrogen-related policies at EU, national, and global levels; a harmonised classification by sector, value-chain stage, and instrument; and a first mapping to Key Performance Indicators (KPIs) suitable for their integration into WILIAM. In essence, the policy landscape is translated into model-ready evidence while preserving legal references and measurable targets.

To anchor the analysis, headline European initiatives and regulations are compiled together with their most policy-salient metrics—electrolyser capacity, Renewable Fuel of Non-Biological Origin (RFNBO) shares, import and domestic production targets, infrastructure build-out, and sustainable fuels mandates—so that stated intentions can be traced to operational requirements.

Methodology

To make sure policies could be compared clearly, it was important to use consistent language, especially since policy documents often mix up terms like targets, objectives, and instruments. That is why a short glossary and a tagging system were created, as a start. For each policy, the specific goal and the tool used to achieve it were clearly recorded. Then, each policy was sorted using three practical categories: the sector it applies to (like transport, buildings, or electricity), the part of the value chain it affects (such as production, transport, or storage), and the type of policy tool (for example, rules, financial incentives, awareness campaigns, or research support).

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This framing keeps the review consistent when policies cut across sectors or when a single regulation affects several value-chain stages.

The process of gathering evidence started from the top, beginning with major European strategies and regulations. These include key documents like the EU Hydrogen Strategy, REPowerEU, the Renewable Energy Directive (REDIII), ReFuelEU Aviation, the Alternative Fuels Infrastructure Regulation (AFIR), the European Hydrogen Backbone (EHB), the Net-Zero Industry Act (NZIA), and the Hydrogen & Decarbonised Gas Market Package. These documents were prioritized because they define both quantitative end-points and many enabling conditions. For each document, a standard framework was used to record important details, such as the source, its focus, the year it was published, any specific targets it sets, and how the policy works.

After organizing the main EU policies, national strategies were collected to allow comparisons between countries, looking at the 2030 horizon and beyond. These records include details like commitments to build electrolyser capacity, planned investments, rules for blending hydrogen with other gases, and sector-specific development plans. Where possible, the latest update year and a link to the official document were also included, so the information can be tracked and updated over time. A separate table was set up to expand the comparison to countries outside the EU—such as Chile, India, Japan, the United States, and the United Kingdom—highlighting the most relevant targets for international trade and standard setting.

Instruments were classified by type and sub-type, and the number of policies in each category was recorded. This step is essential for IAM scenario design, since the mix of instruments hints to how quickly changes might happen and where there could be risks of falling short. The resulting summary table reports counts for regulatory instruments (codes and standards; quotas/obligations), economic instruments (direct investment, fiscal incentives, market-based tools), soft instruments (information/education, voluntary agreements), and R&D instruments.

Finally, a KPI framework was developed so that the policy review can be translated into model inputs and tracked outputs. The indicators span techno-economic, energy, materials, social, and environmental sectors and specify availability and representation in the WILIAM modelling environment. Indicators include, among others, electrolysis capacity by sub-technology, hydrogen pipeline kilometres, stored quantities, refuelling station counts and specifications, and the GHG intensity of hydrogen production.

To ensure accuracy, quality checks were built into every step. Values were made consistent—for example, using the same units, dates, and timeframes—and unclear terms (like the difference between "renewable" and "low-carbon" hydrogen) were flagged.

Figure 1. Process review scheme

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Key Results

The EU summary shows increasing ambition supported by concrete targets. The EU Hydrogen Strategy sets a pathway to install 40 GW of electrolysers in the Union by 2030, with stepping-stone milestones (≥6 GW and up to ~1 Mt H_2 by 2024; up to ~10 Mt by 2030) and an indicative long-term role for hydrogen in final energy. REPowerEU complements this with a combined 10 Mt domestic plus 10 Mt import target by 2030, together with delegated acts on RFNBOs, tracking standards, and funding channels. Manufacturing ramp-up is explicitly recognised, with guidance indicating electrolyser manufacturing capacity on the order of ~17.5 GW per year by 2025—up from roughly 3 GW/yr in 2021 and ~6.8 GW/yr in 2023.

On the demand side, REDIII establishes binding shares for RFNBOs across industry and transport—≥42% in industry by 2030 and 60% by 2035, with at least 1% RFNBOs in transport by 2030 within broader clean-fuel shares—coupled with guarantees of origin and Member State implementation flexibility. ReFuelEU Aviation sets a sustainable aviation fuel (SAF) curve (5% in 2030 rising to 63% in 2050), which indirectly conditions hydrogen-derived e-fuel markets and supply chains.

Infrastructure rules and roadmaps round out feasibility. AFIR requires that hydrogen refuelling stations serve at least gaseous H_2 at 700 bar, creating a minimum service level for mobility corridors. In parallel, the European Hydrogen Backbone charts approximately 28,000 km of hydrogen pipelines by 2030, expanding to around 53,000 km by 2040, with investment needs estimated at €80–150 billion and annual operating costs in the range of €1.6–3.2 billion. Early-stage projects are anticipated to come online in the 2029–2031 window.

The instrument mix observed in the EU catalogue signals the chosen path to implementation: eight regulatory entries (dominated by codes and standards), fourteen economic instruments (nine direct-investment mechanisms, two fiscal incentives, three market-based tools), seven soft instruments (information/education and voluntary agreements), and two R&D instruments. This distribution reflects an early-market phase that relies on rules to reduce uncertainty and public finance to de-risk scale-up, while alliances, guidance, and research address capability gaps.

Country-level targets show a rapidly filling 2030 pipeline inside and outside the EU. Within the Union, national strategies report multi-gigawatt electrolyser capacity objectives and specific investment envelopes; outside the EU, examples include Chile's 25 GW of electrolysers by 2030, India's 5 Mt H_2 per year by 2030, Japan's 3 Mt H_2 per year and 15 GW of electrolysers by 2030, and the United Kingdom's 10 GW hydrogen production by 2030. These commitments shape potential trade corridors, price formation, and standards alignment.

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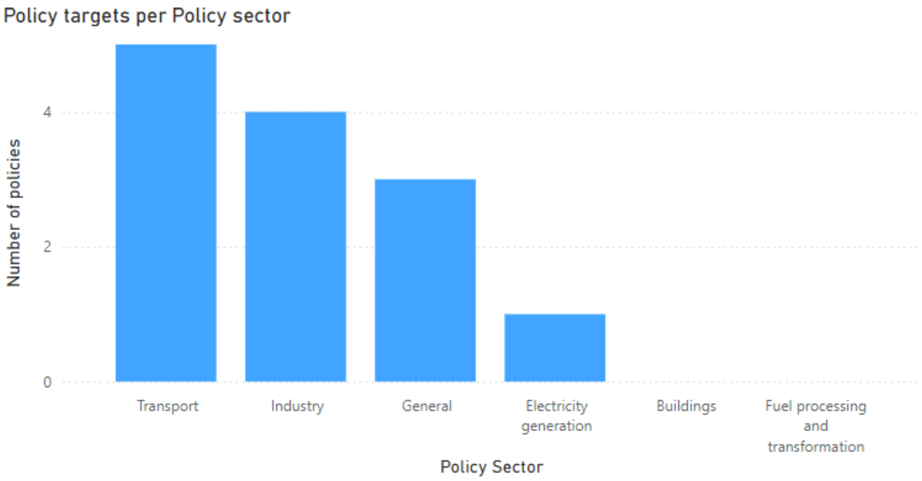

Figure 2. Number of hydrogen policies by sector in EU

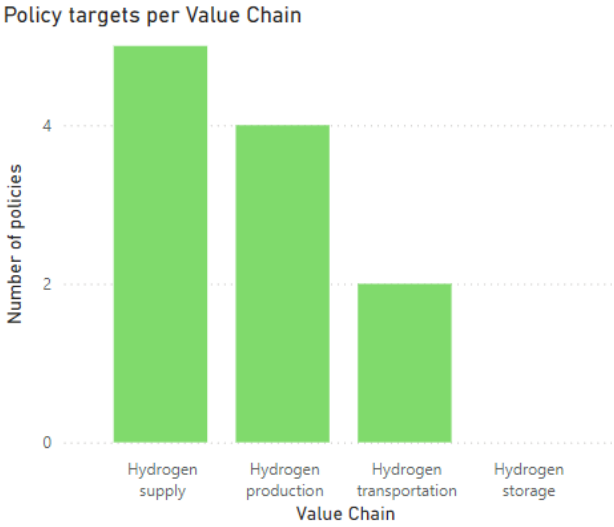

Figure 3. Number of hydrogen policies by part of the value chain in EU

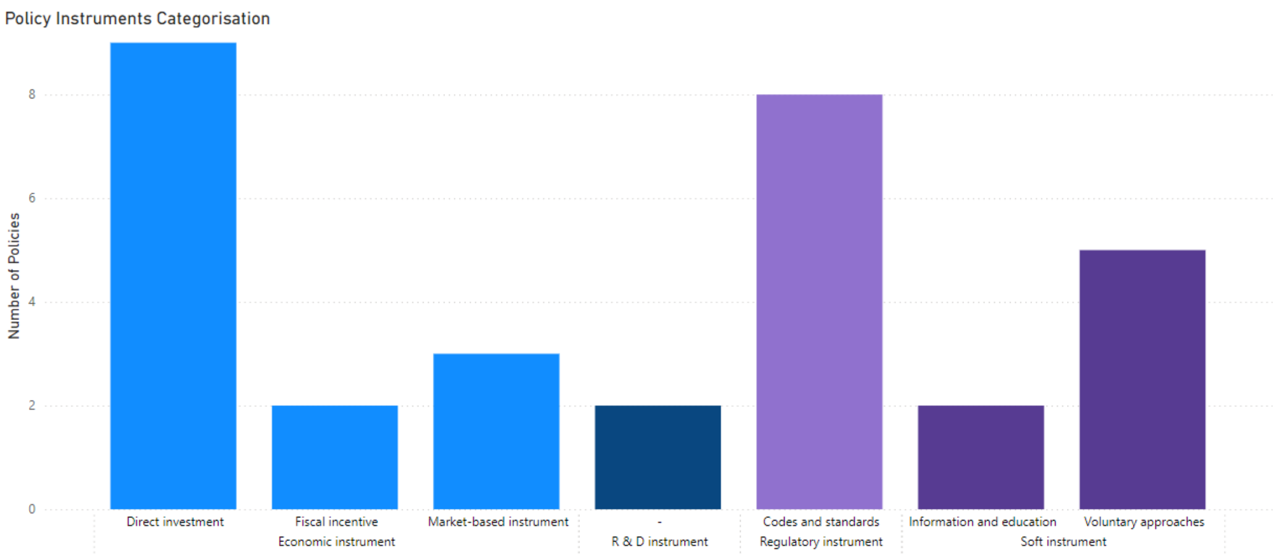

Figure 4. Number of policies by policy instrument category in EU

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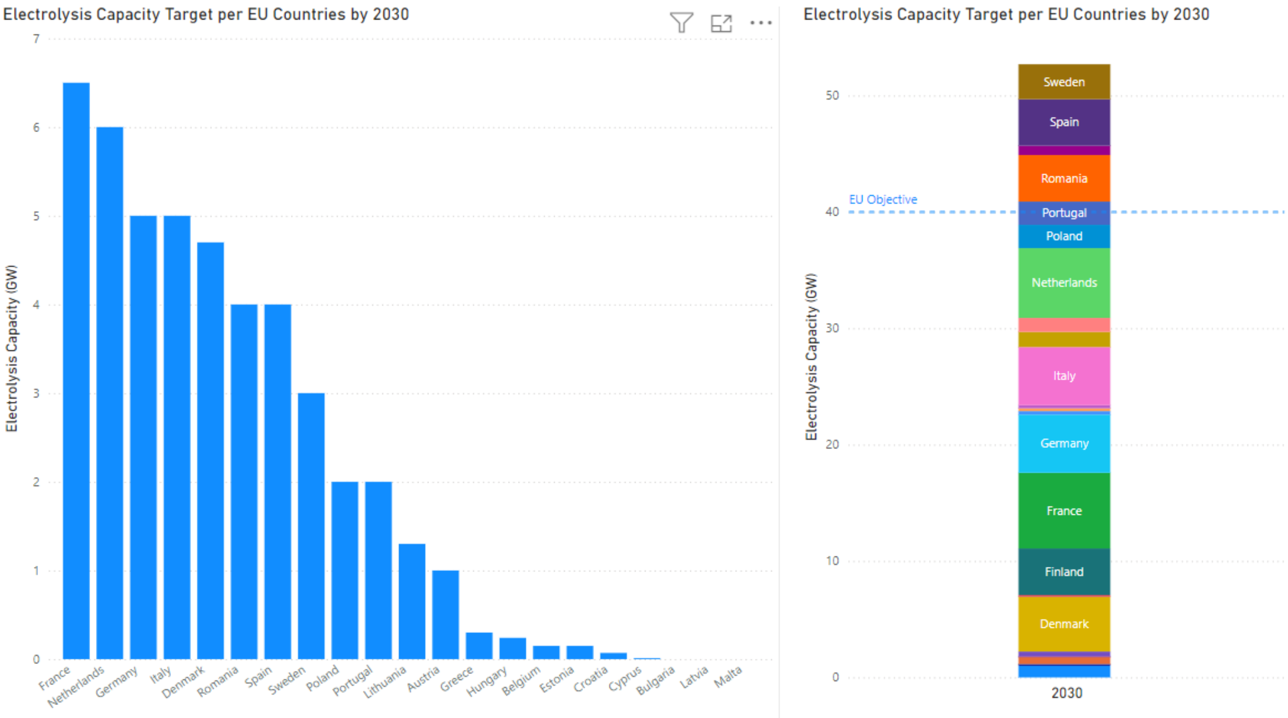

Figure 5. Electrolysis capacity target per EU country by 2030

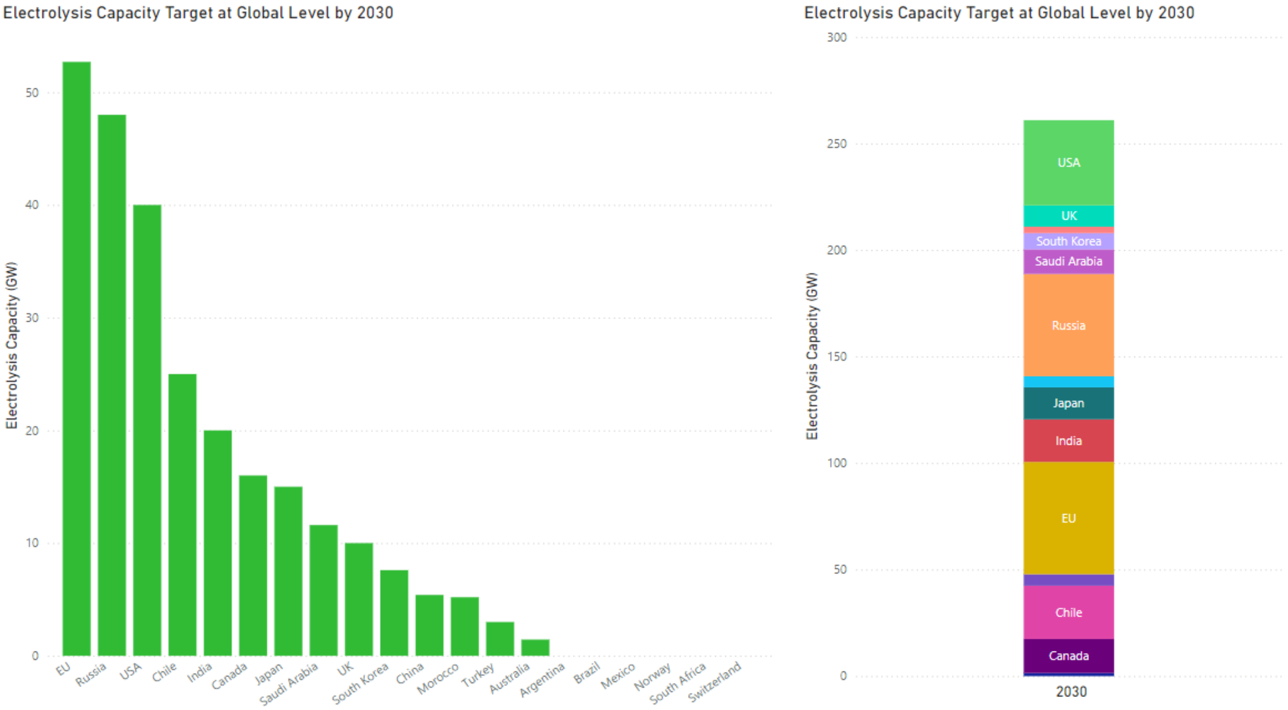

Figure 6. Electrolysis capacity target at global level by 2030

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Discussion & Interpretation

Read across instruments and timelines, the policy set shows a clear link between ambition and delivery. Demand is created through binding shares and sectoral mandates. Feasibility is supported by infrastructure rules, network planning, and manufacturing policy. Funding comes through direct investment, auctions, and market-based tools to manage early costs and risks. Skills, permitting, and information are treated as practical enablers, with sandboxes, streamlined procedures, and training programmes used to shorten lead times. In combination, this forms a straightforward path from targets, to capability, to funded projects.

This design also relies on a clear order of steps. Demand-side rules work best when minimum infrastructure and common technical specifications are in place. Manufacturing policy and public procurement give suppliers visibility on volumes and timing, which stabilises costs. Where auctions or contracts-for-difference are used, multi-year pipelines and budget ranges help bidders price risk more accurately. Consistent terminology—renewable vs low-carbon hydrogen, RFNBO rules, guarantees of origin—keeps eligibility and reporting aligned across borders.

Two limitations should be noted when interpreting scenarios on this baseline. First, definitions matter. Differences in how “renewable” and “low-carbon” are set, how upstream emissions are counted, or how temporal and geographic correlation for RFNBO electricity is applied can change who qualifies for support and how results compare. This affects investor risk and model outputs. Second, timing matters. End-use mandates depend on refuelling coverage, transmission and storage capacity, and steady equipment supply. AFIR minimums and the staged build-out of the hydrogen backbone act as practical gates on what can be achieved in the near term. A few additional points follow from this. Permitting and grid connection times often dominate delivery, so simple procedures can be as important as funding. Supply-chain depth for key components (electrolyser stacks, compression, storage, fittings) influences delivery risk and should be tracked. Power-system links are also relevant: large electrolysis programmes drive extra renewable build-out, grid upgrades, and water needs in specific places. Stable rules and mutually recognised certificates reduce the chance of stranded assets and make cross-border trade easier.

Implications for monitoring are immediate. A balanced KPI set should track not only installed capacity and annual tonnes, but also the conditions that allow projects to operate: kilometres of hydrogen pipeline in service, number and specification of refuelling stations (including pressure and throughput), storage and interconnection availability, average permitting time, and actual manufacturing throughput compared with nameplate. Financial indicators—auction volumes awarded, average support levels, and contract realisation rates—help test bankability. Sustainability metrics should run in parallel: GHG intensity by pathway, electricity demand for hydrogen versus renewable additions, and location-specific land and water indicators. Where official statistics are not yet standard, proxy measures can be used with clear notes and periodic updates. The KPI structure prepared in HYDRA is ready to host these items so that scenario results can be read against the maturity of enabling conditions.

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POLITO: Analysis of the H2 value-chain, development scenarios, and leakage estimations

Introduction & Overview of Activities

To explore how the hydrogen economy might develop—and what that could mean for hydrogen emissions—HYDRA built a detailed and structured understanding of the hydrogen value chain, its market dynamics, and the potential environmental impacts of gaseous emissions along the supply chain. The main activities under Tasks 2.2 and 2.3, led by POLITO, are as follows:

Task 2.2 focused on conducting a comprehensive assessment of the hydrogen supply chain and its technologies, including production, transportation, storage, and end-use applications. It included the collection of technical and operational parameters—such as energy requirements, water usage, and system efficiencies—across various hydrogen technologies with Technology Readiness Levels (TRL) generally above 5. Alongside, a market study was performed at the global and regional levels to map current hydrogen production and demand patterns and to project future developments under multiple international scenarios. The analysis also incorporated hydrogen-derived products (e.g., ammonia, methanol), recognizing their growing relevance in hydrogen trade and decarbonization.

Task 2.3 addressed hydrogen emissions by quantifying leakage rates along the entire hydrogen value chain. A process-level breakdown was developed to assess emissions from production routes (e.g., SMR, electrolysis), handling and storage (compression, liquefaction), transportation (pipeline, truck), and end-uses (industry, mobility, power, residential). A dataset of average, minimum, and maximum hydrogen leakage rates was provided. The main goal was then to quantify overall hydrogen emissions under both current and future scenarios. Additionally, the task evaluated emissions of other relevant gases (methane, ammonia, methanol) and reviewed the performance of current hydrogen leakage detection technologies. This information provides a baseline for future experimental validation and sensor development in WP3.

These results directly informed subsequent modeling in WILIAM, ensuring that future scenario development and risk mitigation strategies are grounded in a robust techno-economic and environmental understanding of the hydrogen landscape.

Methodology

The methodology adopted was designed to generate a detailed and coherent understanding of hydrogen technologies, market dynamics, and emission patterns. The approach integrated process-level technology assessments with international scenario analysis to inform subsequent work packages.

In Task 2.2, the analysis began with a structured evaluation of the hydrogen value chain, covering production, transport, storage, and end-use applications. Technologies were selected based on their maturity (TRL above 5) to ensure relevance for medium- and long-term

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deployment. Each technology was assessed using a harmonized framework that captured energy and material inputs, operating conditions, and performance characteristics. The evaluation also included sector-specific end uses, notably transport, industry, power generation, and residential heating, to assess decarbonization potential across different application domains.

In parallel, a global hydrogen market analysis was conducted to map current production, demand, and trade flows. Data were collected and disaggregated by region, country, production method, and sectoral end use. The study distinguished between captive hydrogen (used on-site) and merchant hydrogen (traded commercially), and accounted for hydrogen produced as a by-product from industrial processes. Future supply and demand trajectories were examined using projections from major institutions including the International Energy Agency (IEA), the International Renewable Energy Agency (IRENA), and the Hydrogen Council. Key scenarios—such as IEA's Net Zero Emissions by 2050 (NZE), Announced Pledges Scenario (APS), and Stated Policies Scenario (STEPS)—were compared to assess alternative futures based on varying policy ambitions. The market analysis also included a deep dive into hydrogen-derived products like ammonia and methanol, evaluating their role in enabling long-distance trade and sector coupling.

Task 2.3 focused on the estimation of hydrogen leakages and associated gaseous emissions across the supply chain. A process-based decomposition approach was used to assess leakage rates at each stage—from production (e.g., SMR, electrolysis, coal gasification) to handling (compression, liquefaction), transport (pipelines, trucks), storage, and final use (industry, mobility, power, residential). Leakage rates were compiled from peer-reviewed literature and technical reports, and included average values as well as minimum and maximum bounds to capture the uncertainty range. These values were then used to define three distinct emission scenarios—pessimistic, plausible, and optimistic.

The hydrogen leakage dataset was applied to future supply chain projections using the same IEA, IRENA, and Hydrogen Council scenarios explored in Task 2.2. This allowed for the quantification of absolute hydrogen losses under different production and consumption patterns, and the identification of stages most prone to emissions. Additionally, leakage rates of other gases—such as methane, ammonia, and methanol—were collected and evaluated for their environmental relevance. A preliminary assessment of the impacts of these emissions on the biosphere was also carried out.

Finally, the task included a review of state-of-the-art hydrogen detection systems. This covered available sensor types, detection thresholds, selectivity, and deployment challenges in real-world infrastructure. The review provides an essential reference point for the design and testing of improved leakage monitoring solutions in Work Package 3 (WP3).

Overall, the methodology ensured that WP2 results are comprehensive, consistent across technologies and scenarios, and directly usable in subsequent modeling and policy guidelines development tasks.

Key Results

A major outcome of T2.2 task was the development of a comprehensive database of hydrogen supply chain technologies, filtered by TRL, and covering parameters relevant for integrated assessment modelling. The study also produced a clear overview of hydrogen applications in the transport, industrial, and power sectors, identifying how deployment pathways differ depending on context and end-use demands.

The accompanying market analysis provided a country- and region-level picture of hydrogen production and consumption, both for current conditions and future scenarios. Production was disaggregated by technology, with distinctions made between fossil-based, electrolysis-based, and by-product hydrogen. Demand was broken down by sector—including refining, ammonia and methanol production, steelmaking, and transport—and analysed over time. In addition to mapping today's landscape, the study explored alternative futures through scenario comparisons using the IEA (NZE, APS, STEPS), IRENA, and Hydrogen Council projections. This allowed for the identification of key uncertainties and trends in global hydrogen uptake.

In Task 2.3, using a process-level breakdown, leakage rate estimates were provided for each stage of the hydrogen supply chain—production, handling, storage, transport, and end-use— The dataset included average leakage values, as well as minimum and maximum bounds, accounting for technical and operational variability. This information was used to define three leakage scenarios (pessimistic, plausible, and optimistic), which were then applied to the future supply chain projections from Task 2.2. As a result, it was possible to estimate total hydrogen losses under present, 2030 and 2050 conditions, and to identify the most emission-intensive phases of the chain, such as liquefaction, distribution pipelines, and some end-use applications.

Beyond hydrogen, leakage rates for other gases commonly associated with hydrogen infrastructure—such as methane, ammonia, and methanol—were also estimated. A preliminary review of their potential impacts on the biosphere was also included, emphasizing interactions with atmospheric chemistry and climate-relevant feedbacks.

Another important result from Task 2.3 was the assessment of current hydrogen detection technologies. A qualitative and quantitative review was conducted to evaluate the sensitivity, selectivity, and operational challenges of available sensor types. This provides a reference baseline for WP3, which will focus on developing and validating improved hydrogen leakage monitoring systems.

Comparison of hydrogen leakages in the different scenarios (D. Trapani, P. Marocco, M. Gandiglio, and M. Santarelli, "Hydrogen leakages across the supply chain: Current estimates and future scenarios," Int J Hydrogen Energy, vol. 145, pp. 1084–1095, Jul. 2025, doi: 10.1016/j.ijhydene.2025.06.103.):

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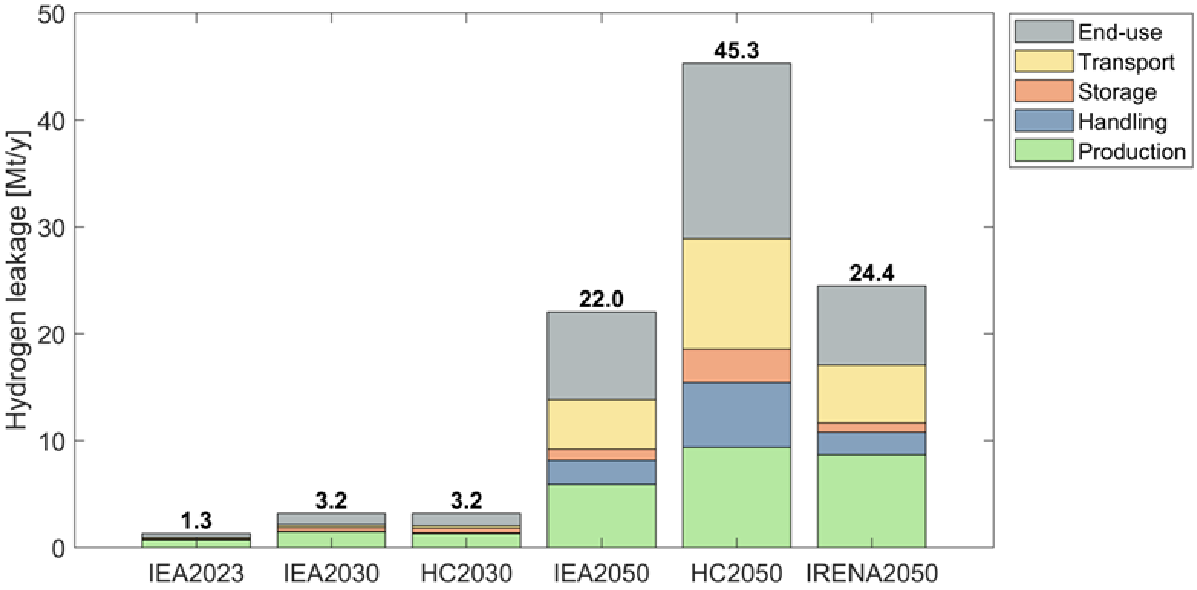
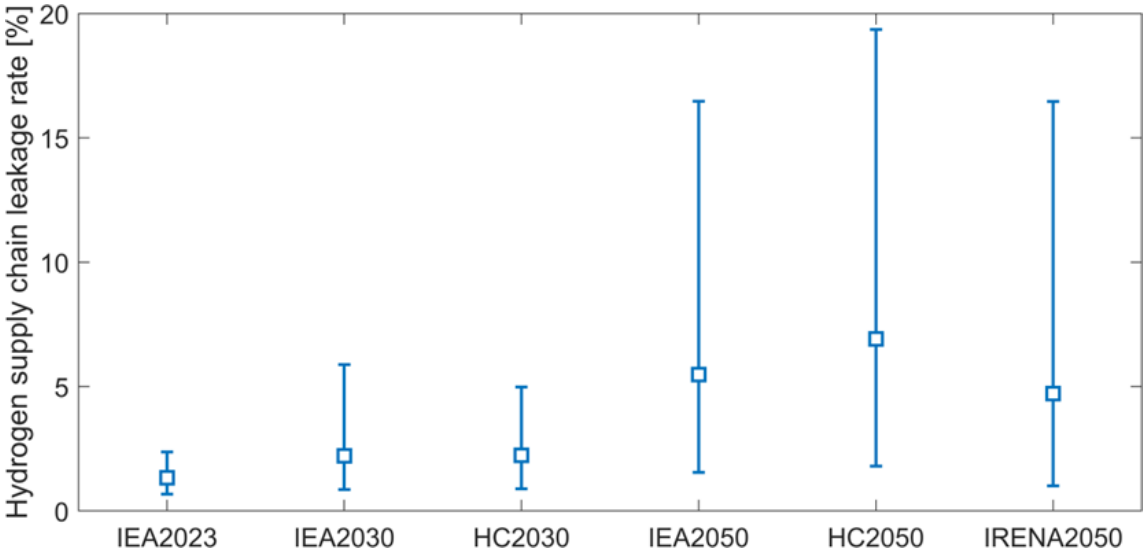


Minimum-maximum variation in the leakage rates of the hydrogen supply chain (D. Trapani, P. Marocco, M. Gandiglio, and M. Santarelli, "Hydrogen leakages across the supply chain: Current estimates and future scenarios," Int J Hydrogen Energy, vol. 145, pp. 1084–1095, Jul. 2025, doi: 10.1016/j.ijhydene.2025.06.103.):



Discussion & Interpretation

The findings of WP2 offer a robust and multi-dimensional understanding of the hydrogen sector, combining technological, market, and environmental perspectives. The integrated analysis provides a strong platform for supporting modelling and policy design activities in subsequent work packages. By bringing together technology-specific data and scenario-based projections, WP2 highlights both the potential and the challenges of scaling a hydrogen economy in a sustainable and efficient manner. One of the key strengths of the work lies in its structured treatment of the hydrogen value chain. Task 2.2 succeeded in translating a complex set of technologies and processes into a consistent, comparable dataset that can be used for scenario building and impact assessment. The inclusion of detailed energy and material

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requirements, operational conditions, and technology readiness levels ensures that the modelling work in WP4 will be based on grounded, up-to-date information. Furthermore, the market analysis contributes essential context, showing how hydrogen production and consumption patterns are evolving globally, and how policy, economics, and infrastructure are shaping future deployment pathways.

The cross-comparison of international scenarios was particularly valuable in highlighting uncertainties and sensitivities. For instance, projections from IEA, IRENA, and the Hydrogen Council differ significantly in terms of hydrogen uptake by sector and region. By mapping WP2 outputs onto these scenarios, the project is better positioned to evaluate a range of futures, from conservative to highly ambitious. The analysis of hydrogen-derived products such as ammonia and methanol also provides important insights into the role of chemical carriers in enabling long-distance hydrogen trade—an increasingly relevant issue in global energy system planning.

In Task 2.3, the quantification of hydrogen leakages represents a critical contribution, as this aspect is often overlooked in strategic planning. The process-level breakdown of leakage rates adds depth and specificity to our understanding of where emissions are most likely to occur. This is especially relevant when considering the climate implications of hydrogen leakage, which, through indirect effects, may contribute to global warming despite hydrogen itself being non-greenhouse gas. The ability to estimate total hydrogen losses under future scenarios strengthens the predictive capacity of the overall assessment framework.

Moreover, the inclusion of leakage rates for other gases—particularly methane and ammonia—expands the environmental lens of the project. While the main focus remains on hydrogen, these additional emissions could pose significant risks if not properly managed. The preliminary assessment of their potential biospheric impacts helps lay the groundwork for more comprehensive environmental evaluations in future phases. The review of existing hydrogen sensors further enhances the operational relevance of the WP2 findings. It reveals current technological gaps, particularly in terms of sensor sensitivity, selectivity, and reliability under different operating conditions. This input is essential for the development of improved detection systems in WP3 and for informing broader policy discussions around safety standards and monitoring requirements in hydrogen infrastructure.

While WP2 provided a structured assessment of the hydrogen value chain, some limitations remain. In particular, several leakage estimates are based on data from the literature, as large-scale deployment of many technologies is still limited. Although scenario ranges were used to reflect uncertainty, additional validation through real-world measurements will be useful in future work. Overall, WP2 has contributed a set of technical and environmental data and analyses that will support the next stages of the project. It offers a consistent starting point for further exploration of hydrogen-related scenarios and potential mitigation strategies.

Further information on this work can be found in the scientific paper written by POLITO: *D. Trapani, P. Marocco, M. Gandiglio, and M. Santarelli, "Hydrogen leakages across the supply chain: Current estimates and future scenarios," Int J Hydrogen Energy, vol. 145, pp. 1084–1095, Jul. 2025, doi: 10.1016/j.ijhydene.2025.06.103.*

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