NUCLEAR-COUPLED HYDROGEN PRODUCTION: VISION, POLICY LANDSCAPE AND VIABILITY PATHWAYS

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OUTLOOK ON HYDROGEN PRODUCTION

Hydrogen is increasingly recognized as a cornerstone for achieving a carbon-neutral economy. In the short term, hydrogen is seen as an energy vector useful for decarbonizing high-energy-consuming industrial sectors that cannot be decarbonized through direct electrification. In the long term, hydrogen is expected to provide flexibility services to electricity grids with high shares of renewables [1].

Despite its potential, most hydrogen today is produced from fossil fuels – around 95% globally according to the International Energy Agency (IEA) [2]- which undermines climate goals. This gap has sparked interest in low-carbon hydrogen production methods, and nuclear energy stands out as a promising solution. By leveraging the continuous, high-capacity output of nuclear reactors, hydrogen can be produced reliably and with minimal emissions, supporting both energy security and decarbonization objectives.

Moving from vision to reality requires addressing key questions: What technologies are ready? How do regulations shape deployment? And is nuclear hydrogen technical and economically viable at scale? These challenges and opportunities define the next frontier in the energy transition.

THE VISION ON NUCLEAR-COUPLED HYDROGEN PRODUCTION

The transition to climate neutrality is bringing about profound changes in an energy system with a growing share of non-manageable sources and greater electrification. In this new context, nuclear power plants are expected to be affected by a higher demand for flexible operation and by an increase in the number of hours with market prices close to 0, and therefore, below their production costs [3]. In order to face these challenges, new modes of operation for nuclear reactors are being investigated and producing hydrogen is seen as a promising lever to enhance nuclear competitiveness [1].

Recent market analyses carried out within the EURATOM funded project NPHyCo- Nuclear-Powered Hydrogen Cogeneration-, whose economic work package was led by Westinghouse, reveal a growing polarization of day-ahead electricity prices in several European countries where nuclear power plants are currently operating. Although the degree of polarization varies by country, the trend is consistent: an increasing share of hours falls below a reference Levelized Cost of Energy (LCOE) for nuclear plants, selected as a benchmark to assess this trend. According to report "2023 Levelized Cost of Energy" issued by Lazard [5], the LCOE for operating plants is estimated between 29 USD/MWh (27 €/MWh) and 34 USD/MWh (31 €/MWh). Using this range as a reference, the NPHyCo analysis shows that Spain is particularly affected due to its high photovoltaic penetration, with values for 2024 approaching 2500 hours below the reference LCOE (Figure 1) [4], and projections for 2025 approaching 3000 hours, creating a significant economic pressure on its nuclear fleet.

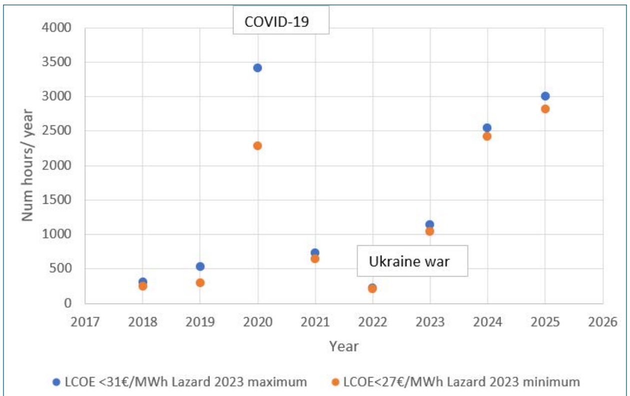

Figure 1. Number of hours with day-ahead market prices lower than reference LCOEs for already operating NPPs. Spain day-ahead market [Own elaboration based on NPHyCo data].

Another important aspect is that the LCOE of nuclear plants is highly sensitive to capacity factor: lower utilization significantly increases generation costs [6]. In the Net Zero Emissions scenario, the average capacity factor of the global nuclear fleet is projected to fall from 84% in 2030 to around 76-77% by 2040-2050, despite an increase in installed capacity [7]. As renewable integration grows, these dynamics highlight the need for nuclear plants to adapt beyond conventional baseload roles.

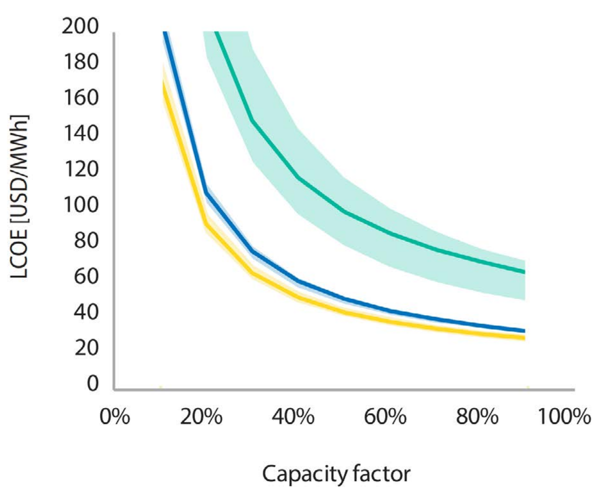

Figure 2. Sensitivity of LCOE of new build and LTO of NPPs to capacity factor [6].

Hydrogen production offers a practical solution to counter this effect while creating new value streams. By integrating technologies such as high-temperature electrolysis or thermochemical cycles, nuclear plants can operate at full capacity and convert surplus electricity or heat into storable energy carrier. This not only diversifies revenues but also supports grid stability and sector coupling. In the face of increasing market volatility and declining capacity factors, hydrogen production emerges not only as a technical solution but as a strategic evolution for nuclear energy. By leveraging the unique capabilities of nuclear reactors—continuous operation, high-temperature output, and low-carbon footprint—hydrogen cogeneration can transform economic challenges into opportunities.

REGULATORY AND POLICY LANDSCAPE OF NUCLEAR HYDROGEN

The regulatory and policy for nuclear hydrogen is evolving rapidly, shaped by regional priorities, energy security concerns, and climate commitments. While hydrogen strategies are proliferating globally, the inclusion of nuclear-based hydrogen within these frameworks remain uneven and often politically sensitive.

European Union

In the European Union, hydrogen is central to the Green Deal's goal of climate neutrality by 2050. The EU Hydrogen Strategy targets 40GW of electrolyser capacity by 2030, but as of 2022, over 90% of hydrogen production still came from fossil fuels [8]. Clean hydrogen – whether renewable or nuclear-based- remains marginal.

The energy crisis arising from Russia's invasion of Ukraine triggered a renewed interest in nuclear energy. The REPowerEU plan and the EU Taxonomy now recognize nuclear as low-carbon energy source, essential for energy security. However, nuclear-derived hydrogen is not yet fully integrated in the EU's hydrogen regulation, limiting its access to incentives and certification schemes.

Recent developments, such as the Clean Industrial Deal and the Delegated Act on Low-Carbon Hydrogen, have opened the door to broader definitions of clean hydrogen, including nuclear-powered electrolysis. Still, formal recognition of nuclear hydrogen as "low-carbon" is postponed until 2028, creating uncertainty for investors [9].

A notable shift occurred in August 2025 with the Franco-German Energy Roadmap, where Germany and France agreed to cooperate on nuclear and hydrogen infrastructure [10]. This alliance could accelerate regulatory alignment and unlock EU-wide support for nuclear hydrogen.

United States

In contrast to the EU's regulatory approach, the United States embraced a strong incentive-driven framework to accelerate clean hydrogen deployment, including nuclear-derived hydrogen.

The 45V Clean Hydrogen Production Tax Credit-introduced under the Inflation Reduction Act (IRA) signed into law in August 2022 – remains active and offers up to $3/kg for hydrogen produced with low lifecycle emissions. The final regulations, issued in January 2025, eased key requirements such as hourly matching and incrementality, making it easier for nuclear-powered hydrogen projects to qualify [11].

However, despite these incentives, many nuclear operators remain hesitant to invest, citing concerns over regulatory complexity, uncertain market demand, and especially the political volatility surrounding long-term support for clean hydrogen programs. The credit applies for 10 years to facilities commissioned before January 1, 2028, but the lack of guaranteed policy continuity and stable offtake agreements continues to limit large-scale investment [12].

Asia

Japan is taking a pioneering role in nuclear hydrogen development, centered around its High Temperature Engineering Test Reactor (HTTR), aiming to start hydrogen production by 2028. This project is backed by national strategies promoting advanced reactors and hydrogen as tools for industrial decarbonization [13].

South Korea has integrated nuclear hydrogen into its clean energy roadmap, supported by legislation and a certification system launched in 2024. The country is developing hydrogen hubs powered by Small Modular Reactors (SMRs), including the Uljin Nuclear Hydrogen Complex and a planned 1,000 km pipeline network [14].

Both countries combine clear regulation, infrastructure investment, and advanced reactor deployment, positioning themselves as leaders in nuclear hydrogen innovation in Asia.

STATE OF THE ART OF NUCLEAR-COUPLED HYDROGEN PRODUCTION

Hydrogen production using nuclear energy is gaining traction as a strategic solution for large-scale decarbonization. Three main technological pathways are being explored [15]:

1. **Low temperature electrolysis (LTE)** includes alkaline and Proton Exchange Membrane (PEM) technologies. These are the most mature (TRL 7-9), with alkaline offering high durability and PEM systems providing advantages such as compact design, flexible operation, and the ability to produce compressed hydrogen.
2. **Steam electrolysis (HTSE)**, based on solid oxide electrolyzer cells (SOEC), operates at high temperatures (650–1000 °C) and achieves the highest electrical efficiency (up to 81%) by utilizing both electricity and thermal energy from the reactor. This dual-input approach makes HTSE particularly well-suited for integration with nuclear power plants. Despite its current limitations—mainly material degradation and short stack lifetimes (TRL 5–7)—HTSE is widely regarded as the most promising long-term solution for large-scale, low-carbon hydrogen production.
3. **Thermochemical cycles**, such as sulfur-iodine and copper-chlorine, use high temperature heat to split water through chemical reactions. While they offer high theoretical efficiency and are suitable for large-scale hydrogen production, they remain at low maturity (TRL 4-6) and face material and integration challenges. Globally, they are not expected to be commercially viable in the next decade, though Japan is advancing pilot-scale development.

Nuclear energy is emerging as a key option for low-carbon hydrogen production, with current developments following two complementary deployment tracks. In the short term, the focus is on integrating low-temperature electrolysis (LTE) systems with existing nuclear reactors. These systems are already operational in several plants and offer a commercially viable pathway to begin decarbonizing hydrogen production. In the long term, the strategy expands to include high-temperature systems, notably high-temperature steam electrolysis (HTSE) and thermochemical cycles. HTSE is being evaluated both for advanced reactors—such as HTGRs and SMRs—and for existing nuclear plants, where thermal coupling strategies can enable partial use of reactor heat to improve efficiency. Thermochemical cycles, on the other hand, require very high temperatures and are primarily considered in conjunction with high-temperature reactors. These pathways reflect a progressive shift toward more efficient and scalable hydrogen production technologies, tailored to reactor capabilities and national deployment strategies.

PROJECTS OVERVIEW: R&D INITIATIVES

This section provides and overview of current and completed R&D projects led by Westinghouse, which have investigated the integration of hydrogen production systems into nuclear power plants. These studies address three key dimensions of viability- technical, operational, and economic- with a particular focus on existing nuclear plants and the application of both low- and high-temperature electrolysis technologies.

Leveraging its presence in both Europe and the United States, Westinghouse has played a central role in consolidating technical knowledge and practical experience across different regulatory, technological, and market environments.

Each of the three dimensions of viability has been explored through a dedicated R&D initiative, either completed or currently underway. These initiatives provide the foundation for the conclusions presented in the following section.

- **Technical and economic viability in the European context** is explored through the EURATOM funded project **NPHyCo**, that was completed in February 2025. The project aimed to demonstrate that nuclear hydrogen cogeneration is feasible and competitive compared with other low-carbon hydrogen production methods and to design a pilot plant deployable within 5-10 years. It focused on integrating existing GEN II/III nuclear reactors with new hydrogen facilities, optimizing the degree of coupling to maximize mutual benefits. The consortium included 12 partners from 8 EU countries and Ukraine, combining expertise in nuclear systems and hydrogen electrolysis (Framatome, Tecnatom, Ansaldo), alongside organizations working closely with VVER operators (ESG). Research institutes and universities (CEA, GRS, NRG, TUD, CVR) contributed scientific excellence, while Nucleareurope led communication, stakeholder engagement and socio-economic analysis.
- **Operational viability** is assessed through the **HydroGen Sim** project, developed in collaboration with the Idaho National Laboratory (INL). It evaluates the integration of high-temperature electrolysis into a conventional Westinghouse nuclear plant via a steam extraction. Using a full scope glass-top simulator, the project tested normal and emergency scenarios to ensure safe operation and identify necessary updated in control systems, instrumentation, and procedures.
- **Technical and economic viability in US context** is being studied under a DOE funded Front-End Engineering Design (FEED) study, which focuses on the integration of HTSE using SOECs in multiple site-specific light-water reactor facilities across the United States. The study includes design development for both pressurized water reactors (PWRs) and boiling water reactors (BWRs), considering extraction power levels ranging from 20MWe to 500MWe. These evaluations are critical to understanding the impacts of large-scale integration, identifying challenges in scaling up energy extraction, and assessing the necessary adaptations for each reactor type. By doing so, the study aims to promote equitable opportunities for nuclear energy use beyond electricity generation, while providing a comprehensive cost and market assessment for hydrogen production.

TECHNICAL, OPERATIONAL AND ECONOMIC VIABILITY OF NUCLEAR HYDROGEN

At the time this article is being presented, the **technical feasibility** of nuclear-coupled hydrogen production is supported by findings from several complementary R&D initiatives. Notably, the NPHyCo project assessed the integration of hydrogen production with VVER-type reactors, evaluating both LTE and HTSE technologies and delivering a conceptual pilot plant design. In parallel, U.S.-based FEED studies validated large-scale HTSE integration (up to 500 MWe) with light-water reactors, confirming feasibility through detailed multidisciplinary engineering. Together, these efforts provide a solid foundation for future deployment and reinforce the technical viability of coupling nuclear energy with hydrogen production.

As part of the NPHyCo project, a dedicated work package was developed to analyze the **licensing and regulatory framework** for hydrogen production coupled with NPPs in Europe. This effort aimed to identify applicable regulations and assess how licensing requirements vary depending on the degree of integration between the hydrogen production plant (HPP) and the NPP.

The analysis concluded that such coupling is generally not prohibited under European regulations. While NPPs are governed by strict nuclear rules, HPPs fall under general industrial legislation derived from EU directives such as Seveso, ATEX, PED, and IED.

There is no hydrogen-specific regulatory regime, and licensing depends on the degree of integration:

- Minimal coupling (e.g., electricity supply only): No impact on the NPP license if safety distances are respected.
- Onsite HPP without shared systems: Requires updating the NPP license and safety case.
- Highly integrated systems (e.g., steam or cooling water): Demands a full safety reassessment and license update.

In summary, the more integrated the systems are, the greater the licensing effort required—necessitating a clear justification based on technical and economic benefits.

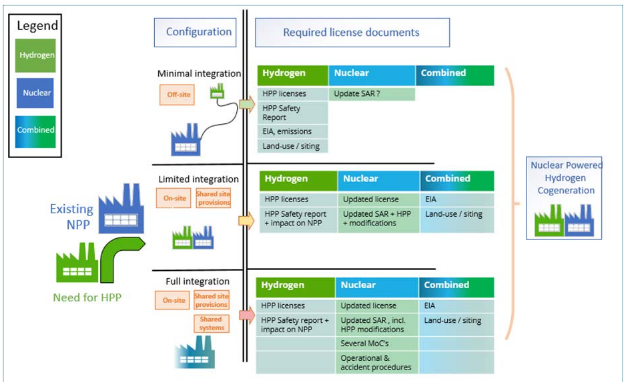

Figure 3. Required license documents depending on the NPP-HPP degree of integration [16].

In parallel, the U.S.-based FEED has also initiated a regulatory impact analysis under 10 CFR 50.59. This process will determine the licensing steps required for the hydrogen plant, providing a structured pathway for regulatory compliance in the U.S. context.

The HydroGen Sim project has confirmed that nuclear hydrogen production via HTSE is **operationally viable**. By leveraging digital twins and full scope simulators, the project enables iterative analysis and testing that support the optimization of system design and contribute to accelerate market readiness for these emerging technologies.

The simulation platform allowed for:

- Component-level testing of the Thermal Power Dispatch system, revealing opportunities to improve equipment sizing and control strategies.
- Integrated system testing under normal operating conditions, confirming safe and efficient hydrogen production while identifying the need for new alarms and indications in the main control room.
- Emergency scenario analysis, particularly the case of a steam generator tube rupture, which could contaminate the hydrogen plant and release radiation beyond containment. The simulator highlighted the critical need to ensure rapid and automatic isolation at the earliest indication of tube failure.

Overall, the project demonstrated that operational integration between NPPs and HPPs is feasible, although several technical challenges remain such us clarifying control room responsibilities. These results provide a strong foundation for advancing nuclear hydrogen production within the global energy landscape.

Figure 4. HydroGen Sim.

If there is one decisive factor for the deployment of nuclear-coupled hydrogen production, it is **economics**. While technical and operational feasibility have been demonstrated, the ability to achieve competitive costs will ultimately determine whether this integration becomes a viable solution for decarbonization.

An analysis was carried out within the NPHyCo project, as part of a broader European business plan for nuclear hydrogen production. Although the financial modelling focused on a specific European nuclear power plant, the methodology and conclusions are intended to guide strategic decisions across multiple countries and sites.

The assessment was performed using OptimHyzer, a techno-economic modelling tool developed by Westinghouse, which enables detailed evaluation of hydrogen production strategies, cost structures, and financial performance under different scenarios. The objective was to determine the conditions under which nuclear-coupled hydrogen production becomes economically viable, considering both PEM and SOEC technologies.

The study targeted a hydrogen competitive price of 2,5-3 €/kgH_2, aligned with market break-even values and an IRR> 20% as the profitability threshold. Current conditions, however, show that achieving this target requires substantial financial support. For the European plant reference case (Rivne NPP), PEM technology would need a subsidy of approximately 6€ / kgH_2 and SOEC technology a subsidy of 8.5€/kgH_2 to reach the competitive range.

However, by 2030, under LTO conditions (LCOE around 36,5 €/MWh), higher hydrogen production rates (up to 6.000kg/h), CO_2 monetization, and expected technology progress, nuclear hydrogen could be offered at approximately 2.5€/kgH_2 to meet profitability targets, with subsidies of 2- 2,5€/kgH_2, comparable to US IRA incentives for both technologies.

In addition, a techno-economic assessment (TEA) will be also carried out in the coming months by INL, building on the outputs of the FEED Study and tailored to the US regulatory and market framework. This will enable a cross- continental validation of economic models and assumptions, strengthening the global case for nuclear-coupled hydrogen production.

NUCLEAR HYDROGEN AS A STRATEGIC SOLUTION FOR LARGE-SCALE DECARBONIZATION

Hydrogen production using nuclear energy is emerging as a strategic solution for large-scale decarbonization, offering a unique combination of dispatchability, high energy density, and zero-carbon emissions. This article has reviewed the evolving policy and regulatory landscape, the state of the art in hydrogen production technologies, and the viability of nuclear-coupled systems based on recent R&D initiatives in Europe and the United States.

The integration of hydrogen production into existing nuclear power plants has been technically validated through U.S. FEED studies and the European NPHyCo project, confirming the feasibility of coupling HTSE and LTE technologies with various reactor types. From a regulatory standpoint, NPHyCo concluded that no European regulation explicitly prohibits the coupling of hydrogen production with nuclear plants, although licensing requirements vary depending on the level of integration. In the U.S., the FEED studies initiated a licensing impact assessment under 10 CFR 50.59.

Operational viability was demonstrated via the HydroGen Sim project with INL, which tested control interfaces and emergency scenarios using a full-scope simulator. Economically, NPHyCo showed that while current conditions require significant subsidies (6–8,5 €/kgH_2), future scenarios with LTO, CO_2 monetization, and technology progress could reduce support needs to 2–2,5 €/kgH_2, aligning with U.S. IRA incentives. A forthcoming TEA by INL will further refine the U.S. case and enable cross-continental validation of strategies.

Despite this progress, several barriers remain: the need for increased R&D investment, a coherent and technology-neutral regulatory framework, robust market mechanisms, and demand-side adaptation. While the U.S. offers strong incentives, political uncertainty hampers investor confidence. In contrast, Europe and countries like Japan and South Korea are advancing clearer frameworks and infrastructure plans, positioning themselves as leaders in nuclear hydrogen innovation.

To unlock its full potential, nuclear hydrogen must be recognized as a low-carbon solution based solely on carbon intensity. With aligned policies, accelerated demonstration efforts, and access to support mechanisms such as IPCEI, the Hydrogen Bank, and Contracts for Difference, nuclear-coupled hydrogen can become a cornerstone of a resilient, decarbonized energy system..

REFERENCES

[1] Nuclear Energy Agency (NEA). "The role of Nuclear Power in the Hydrogen Economy. Cost and Competitiveness". 2018.

[2] International Energy Agency (IEA). "Global Hydrogen Review 2025". Paris: IEA, 2025. https://www.iea.org/reports/global-hydrogen-review-2025

[3] Idaho National Laboratory (INL). "Evaluation of Non-electric Market Options for a Light-Water Reactor in the Midwest". August 2019.

[4] NPHyCo Consortium (2024). "Techno-economic incomes models for NPHyCo Business Plan. Operational strategies for nuclear powered hydrogen – Deliverable D2.3". Funded by the European Union under Grant Agreement No. 101061007. Available at: https://www.nphyco.org

[5] "Lazard's Levelized Cost of Energy Analysis". April 2023. 2023 Levelized Cost Of Energy+ | Lazard

[6] International Energy Agency (IEA), Nuclear Energy Agency (NEA), "Projected Costs of Generating Electricity", 2020.

[7] International Energy Agency (IEA), "Net Zero by 20259: A Roadmap for the Global Energy Sector", 2021.

[8] European Hydrogen Observatory. "The European hydrogen market landscape". November 2023, updated February 2024 https://observatory.clean-hydrogen.europa.eu/sites/default/files/2024-02/Report%2001%20-20The%20European%20hydrogen%20market%20landscape%20-%20February%20update.pdf

[9] European Commission. "Delegated Act on Low Carbon Hydrogen". July 8, 2025. Delegated act on low-carbon hydrogen

[10] France and Germany vow to deepen ties on green rules, power links in energy 'reset' – POLITICO

[11] U.S. Department of Energy. "The Hydrogen Production Tax Credit Explained for Nuclear Power Plants", January 16, 2025. The Hydrogen Production Tax Credit Explained for Nuclear Power Plants | Department of Energy

[12] Hydrogen Industry Leaders. "How will the Trump administration affect hydrogen growth in the US?., How will the Trump administration affect hydrogen growth in the US? - Hydrogen Industry Leaders

[13] Application for changes to reactor installation of the High Temperature Engineering Test Reactor to demonstrate hydrogen production technology by high temperature gas-cooled reactor (Notice) | Press Releases | Japan Atomic Energy Agency

[14] South Korea's largest province unveils plans for 100MW of nuclear hydrogen and a 1,000km pipeline network | Hydrogen Insight

[15] NPHyCo Consortium (2024). "Project Frame of Reference – Deliverable D1.1". Funded by the European Union under Grant Agreement No. 101061007. Available at: https://www.nphyco.org

[16] NPHyCo Consortium (2024). "Roadmap for HPP and NPP coupling. Overview for stakeholders – Deliverable D4.4". Funded by the European Union under Grant Agreement No. 101061007. Available at: https://www.nphyco.org ■