

Spatial assessment of the impact of hydrogen production on European freshwater resources

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2026



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Joint Research Centre

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JRC148090

EUR 40879

PDF ISBN 978-92-68-44006-3 ISSN 1831-9424 doi:10.2760/8505125 KJ-01-26-424-EN-N

Luxembourg: Publications Office of the European Union, 2026

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How to cite this report: Bolard, J., Serafini, M., Lara, K., Pistocchi, A. and Weidner, E., *Spatial assessment of the impact of hydrogen production on European freshwater resources*, Publications Office of the European Union, Luxembourg, 2026, <https://data.europa.eu/doi/10.2760/8505125>, JRC148090.

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Abstract

The large-scale deployment of hydrogen production in Europe presents both opportunities for decarbonisation and challenges for freshwater resource management, as the production of hydrogen requires significant amounts of water, which can be sourced from various locations, including freshwater, such as rivers, lakes, and groundwater. The European domestic hydrogen production capacity is expected to grow significantly in the following years, as evinced by the ambitions expressed in the Renewable Energy Directive. This increase in hydrogen production will lead to a rise in water demand, with impacts on freshwater sources. The study aims to investigate the impact of hydrogen economy on European water resources, considering the water demand for hydrogen production and the potential for water scarcity, particularly in regions where freshwater is already limited. The results show that most hydrogen production assets are currently located in basins with low to moderate water stress, but under pessimistic climate scenarios, nearly one in ten plants could be operating in basins where hydrogen abstraction constitutes a noticeable share of renewable water resources.

The European Water Resilience Strategy and other EU water policy instruments provide a framework for sustainable water management, but their implementation varies across Member States. Effective integration of water efficiency measures and reuse strategies can mitigate operational risks and enhance water sustainability in the hydrogen production. Furthermore, the deployment of new desalination plants in coastal areas could reduce the impact on freshwater sources, and the use of alternative water sources, such as wastewater and brackish water, could also help to alleviate water scarcity. Overall, the study highlights the need for careful planning and management of water resources to ensure the sustainable development of the hydrogen sector in Europe.

Acknowledgements

The authors are grateful for the collaboration with JRC colleagues from Unit B.5:

- Sonia FERERES, European Commission, Joint Research Centre (JRC), Seville, Spain.
- Nicoletta Valeria TROTTA, European Commission, Joint Research Centre (JRC), Seville, Spain.
- Ioannis STAMOU, European Commission, Joint Research Centre (JRC), Seville, Spain.

The fruitful collaboration was related to the stakeholder survey conducted in 2024 on the environmental effect of large-scale deployment of electrolytic hydrogen production systems. The valuable information collected from this survey related to the prioritisation of parameters for the location of hydrogen projects is summarised in **Figure 1**.

The authors are grateful for the support and help received from the Energy and Industry Geography Lab team for the mapping of hydrogen assets, most especially:

- Ignacio HIDALGO GONZALEZ, European Commission, Joint Research Centre (JRC), Petten, Netherlands.

The authors are also grateful for the highly valuable review and comments provided by Marc Steen, active senior at the European Commission, Joint Research Centre (JRC), Petten, Netherlands.

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1. Introduction

The production of hydrogen through electrolysis requires a significant amount of water, which can be sourced from various locations. Currently, the most common source of water for hydrogen production is freshwater, such as rivers, lakes, and groundwater (Serafini et al., 2025). Freshwater is widely used for hydrogen production due to its low salinity and fewer impurities compared to other sources, making it a preferred choice for many electrolysis technologies as also identified by JRC in a previous stakeholder consultation (European Commission. Joint Research Centre., 2024).

The rapid and large-scale deployment of low-carbon and renewable hydrogen production (**Box 1**) in Europe presents both opportunities for decarbonisation and challenges for the European freshwater resource management. Independently of the technology pathway, the production of hydrogen requires water at the production site, usually both as a feedstock and as cooling agent for the equipment.

Freshwater sources are often used directly for hydrogen production, with minimal treatment required. However, the use of freshwater for hydrogen production may compete with other essential uses, such as human consumption, agriculture, industry and nature. This competition can lead to water scarcity and sustainability concerns, particularly in regions where freshwater is already limited. However, across the EU, these resources are threatened by multiple pressures. To address this, the WFD requires Member States to promote sustainable use and long-term protection of available water resources.

According to the aspirational goals presented in the REPowerEU (European Commission, 2022b), the European domestic hydrogen production capacity might reach 10 Mt of hydrogen per year by 2030. Current projections indicate that achieving the European Union's 2030 target would require approximately 140 GWe of electrolysis capacity, a 280-fold increase from early 2025 levels estimated around 500 MWe (European Commission. Joint Research Centre., 2024).

A rough estimation shows that the equivalent of 0.08 - 0.12 % of the European freshwater annual demand will be needed to reach its 2030 REPowerEU goals¹. Similarly, the most ambitious scenario of the Clean Hydrogen Undertaking envisions that reaching 67.5 Mt of renewable hydrogen production by 2050 (Fuel Cells and Hydrogen 2 Joint Undertaking, 2019) would require the equivalent of 0.57 - 0.82 % of the European annual freshwater demand. Although these numbers do not seem to indicate a major issue, the water demand for electrolysis could potentially exacerbate water scarcity during droughts in particular water stressed areas.

The Europe's state of water 2024 report from the European Environment Agency (EEA) concludes that the quality of European freshwater resources is not improving and that climate change exacerbates water stress, affecting 20 % of European territory (EU 27 + AL, BA, IS, MK, NO, RS, CH, TR) and 30 % of the population, with impacts on social cohesion and stability (European Environment Agency, 2024).

¹ Considering a medium-range water need (feedstock + cooling) for an electrolyser systems of 17 kg(H₂O)/kg(H₂) (Newborough et al., 2021) and a range of European freshwater demand of 140-200 billion m³/year (Pistocchi et al., 2026). The REPowerEU targets translates into 170 million tonnes of annual freshwater demand.

This document provides a starting point to investigate how much the large-scale deployment of renewable hydrogen will impact the European freshwater resources.

Box 1. Definitions of renewable and low-carbon hydrogen

In this report, renewable hydrogen refers to hydrogen produced by water electrolysis.

Low-carbon hydrogen is the hydrogen produced by conventional fossil-fuel reforming technologies (e.g. coal gasification, natural gas-SMR, natural gas-ATR) combined with carbon capture, utilisation and storage (CCUS).

Box 2. Definition for water related terminology adopted in the report

Catchment: A term for a basin or sub basin; it denotes the land area from which precipitation collects and flows into a particular watercourse, reservoir or aquifer.

Basin: A geographical area that drains all surface water (rivers, streams, lakes) and groundwater into a single main watercourse or outlet, typically ending at a sea, lake or major river.

Raw water consumption: The amount of untreated (i.e., “raw”) water that is permanently removed from the source, usually expressed before any treatment or reuse steps are applied.

Renewable water supply: The portion of the water cycle that is naturally replenished on an annual basis (e.g., precipitation, surface runoff, groundwater recharge) and can therefore be sustainably abstracted without depleting the resource over the long term.

Sub basin: A smaller drainage unit contained within a larger basin, characterised by its own network of tributaries that feed into the main river system of the parent basin.

Water abstraction: The removal of water from any natural source, irrespective of whether the water is returned to the source after use.

Water availability: The quantity of water that is physically present in a river basin or aquifer and is potentially accessible for human use after accounting for ecological flow requirements and existing commitments.

Water consumption: The portion of abstracted water that is not returned to the original source because it is incorporated into a product, evaporated or otherwise lost from the water cycle.

Water use: The total volume of water taken from the environment for a specific activity (e.g., domestic, industrial, agricultural). It comprises both the abstracted volume and the portion that is ultimately consumed.

Water withdrawal: Synonymous with water abstraction.

1.1. Scope and objectives

This study aims to provide policymakers with a more geographically and temporally accurate vision of water consumption for hydrogen production in 2030 and 2050 in Europe. As water stress and shortage is expected to increase across EU in the mid- and long-term (European Commission. Joint Research Centre., 2020), a better understanding of the regional and seasonal water availability for hydrogen production is needed to contribute to the achievement of the EU emission reduction objectives. This will also help securing a higher public acceptance level of hydrogen technologies and reduce investment risks such as the generation of stranded assets because of water scarcity.

Given the challenges of forecasting hydrogen production sites, this study will first focus on locations where there is a high level of confidence that hydrogen-intensive projects will be developed by 2030. Such locations include current refining and ammonia production plants where hydrogen demand is already well established, as well as planned renewable hydrogen production hubs. This part will only consider the production of hydrogen produced locally and will not consider the impact of hydrogen imports on the European production. Secondly, this study will investigate scenarios with forecasts beyond 2030. In these scenarios, it will consider infrastructure developments for hydrogen transportation such as retrofitted pipeline projects ('The European Hydrogen Backbone (EHB) initiative | EHB European Hydrogen Backbone', 2026).

This study does not intend to focus on each water-related parameter that might impact the freshwater sources, such as type of water source used by each production hubs, the water footprint of electricity systems or the avoided impact of replaced industrial processes. Instead, this study considers a realistic scenario that maximises the pressure on water sources as we aim to identify the most critical areas regarding water availability.

Therefore, this study seeks to address the following questions:

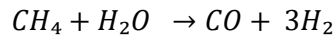
- Will the availability of freshwater be a limiting factor for the aspirational increase in hydrogen production by 2030, assuming production is limited to domestic sites and no transport infrastructure built? If so, which regions will become most critical?
- Will the availability of freshwater be an issue in meeting the most ambitious hydrogen production forecasts for 2050?

2. Hydrogen production technologies

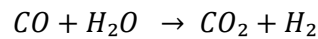
This section examines the main hydrogen production methodologies currently employed or under development, with specific focus on water use across these processes. Water is used either as a direct reactant, or process medium in hydrogen production, or as cooling agent. The rate of water abstraction and consumption can vary significantly across plants even between plants using the same technology. The following sections also emphasise where water is needed for the cooling requirements of thermal and non-thermal systems.

2.1. Steam Methane Reforming

Steam Methane Reforming (SMR) represents the predominant industrial hydrogen production method globally. This process involves the reaction of methane with steam at elevated temperatures (700-1000 °C) in the presence of nickel-based catalysts (Lewis et al., 2022). The primary reaction proceeds as:



This primary reaction is then followed by the water-gas shift reaction:



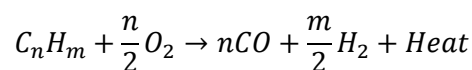
Lewis and colleagues provide a very detailed description of the water balance of a selection of cases of hydrogen production (Lewis et al., 2022). A typical SMR plant with hydrogen production capacity of 20 125 kg(H₂)/h requires approximately 6.7 m³(H₂O)/min or 402 m³(H₂O)/h, leading to a total water demand of 20 kg(H₂O)/kg(H₂). From this water demand, 16.7 kg(H₂O)/kg(H₂) is used for steam generation and 3.3 kg(H₂O)/kg(H₂) for cooling purposes. A share of the water is retrieved from the syngas condensate (3.5 kg(H₂O)/kg(H₂)), and a small share of the cooling water is discharged to the environment. This leads to an actual raw consumption of the plant of approximately 15.7 kg(H₂O)/kg(H₂). In the same report, Lewis and al. also describe a plant with carbon capture and storage (CCS) auxiliaries. This second case has a hydrogen production capacity of 20 125 kg(H₂)/h with a total raw water abstraction of 29.8 kg(H₂O)/kg(H₂) and a raw water consumption of 24 kg(H₂O)/kg(H₂) (Lewis et al., 2022).

For both SMR processes the water quality requirements are moderately stringent, as impurities can affect catalyst performance and process efficiency.

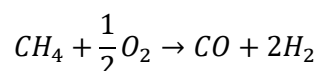
2.2. Partial oxidation

Partial oxidation (POX) is a mature and exothermic (heat-releasing) process used for hydrogen production from hydrocarbon feedstocks such as natural gas, heavy oils, coal, and even biomass. Unlike SMR which uses steam, POX utilises a controlled amount of oxygen (or air) that is less than the stoichiometric amount required for complete combustion. This controlled oxidation at high temperatures (typically 1150-1315 °C for the non-catalytic reaction, and around 950 °C for catalytic POX) partially converts the hydrocarbon fuel into a hydrogen-rich synthesis gas (syngas), primarily composed of hydrogen (H₂) and carbon monoxide (CO) (Nikolaidis et al., 2017).

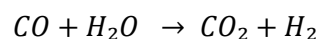
The general ideal reaction for partial oxidation of a hydrocarbon (C_nH_m) can be represented as:



For instance, the partial oxidation of methane (CH_4), the main component of natural gas, proceeds as follows:



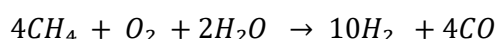
The resulting syngas is cooled down by water injection or quenching, generating steam (Ghasemzadeh et al., 2018). Water is then injected into the water gas shift reactor directly (Hajjaji et al., 2013).



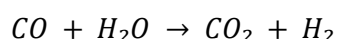
2.3. Auto-thermal reforming

Auto-thermal reforming (ATR) combines the two processes POX and SMR in a single reactor. The process involves the reaction of hydrocarbon feedstock (typically natural gas) with both oxygen and steam. The exothermic partial oxidation reaction provides the thermal energy required for the endothermic steam reforming reaction, creating a thermally self-sustaining (auto-thermal) process (Lee et al., 2005; Rice, Steven, D. et al., 2007).

A typical auto-thermal reforming reaction follows this simplified equation:



Followed by the water-gas shift reaction as described in the SMR process:

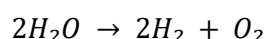


In addition to its use as a reactant in the steam reforming and water-gas shift reactions, water is also used as a temperature moderator to prevent excessive temperatures from the exothermic oxidation reaction.

Similarly to SMR, Lewis and colleagues provide a very detailed description of an ATR system of 27 500 kg(H_2)/h hydrogen production capacity and its water balance (Lewis et al., 2022). According to the study, an ATR plant requires 34.9 kg(H_2O)/kg(H_2), including 28.3 kg(H_2O)/kg(H_2) for the cooling process. As some water becomes available from the syngas condensate, the water withdrawal rate reaches 30.5 kg(H_2O)/kg(H_2). The raw water consumption is 24 kg(H_2O)/kg(H_2) including 21.8 kg(H_2O)/kg(H_2) for cooling process (Lewis et al., 2022). This shows the high impact of the cooling requirements for the production of hydrogen via ATR.

2.4. Water electrolysis

Water electrolysis employs electrical current to decompose water molecules directly:



This process has a theoretical minimum water consumption of 9 L/kg(H_2); however, practical systems typically require additional water when accounting for cooling requirements, membrane hydration, and other auxiliary processes. Information from manufacturers gives a range from 10 to 22 L/kg(H_2) of water processed within the electrolyser, with a sufficient level of purity to maintain water conductivity within the limits specific for the considered electrolysis technology (Simoes et al., 2021).

Water is also used as a cooling agent in most industrial settings to safely manage the heat produced by the electrolysis stack and balance-of-plant components and to prevent overheating. The water consumption depends on the cooling technology used on site, ranging from lower water-intensive technologies (air-cooled heat exchangers) to highly water-intensive technologies (cooling towers). For electrolysis supplied by non-freshwater (seawater or wastewater), the amount of water required depends on the technology used to desalinate and/or purify it to reach electrolyser requirements. Using seawater and desalination systems will abstract around 3.3 times the amount of pure water required from freshwater but will release a large part of it as brine (EuroWater, 2022).

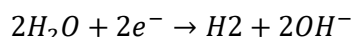
According to some estimates on the life-cycle water consumption of hydrogen production via electrolysis, the nature of electricity source has the highest impact on the overall water footprint. Fossil-based electricity could increase the total water footprint of hydrogen by more than 180 L/kg(H₂), while renewable electricity does not seem to have a significant additional impact on the total life-cycle water consumption (Elgowainy, 2016).

2.4.1. Alkaline water electrolysis

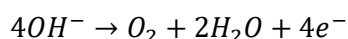
Alkaline water electrolysis (AWE) represents the most mature and commercially established water electrolysis technology. The system operates at temperatures between 60-90 °C and pressures typically ranging from atmospheric to 30 bar in advanced systems. The electrolyte consists of an aqueous potassium hydroxide (KOH) solution with concentrations of 25-30 wt%, which provides high ionic conductivity.

The cell configuration comprises two electrodes separated by a diaphragm that prevents the mixing of produced oxygen and hydrogen while allowing the transport of hydroxide ions. The diaphragm must maintain chemical and thermal stability in the highly caustic environment.

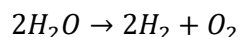
At the cathode, water molecules receive electrons, generating hydrogen gas and hydroxide ions:



The hydroxide ions migrate through the diaphragm to the anode, where they discharge electrons and form oxygen:



The overall cell reaction is:

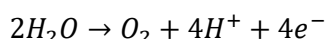


The water in alkaline electrolysis is not only used as a primary reactant, since 9 kg of water is consumed to produce 1 kg of hydrogen, but constitutes the major part (70-75 %) of the electrolyte solution as it serves as a solvent for KOH. It also serves as heat management medium since the system's electrochemical inefficiencies generate heat that must be removed, often using water circulation systems. Finally, water is added in gas washing stages to remove trace of KOH from the product hydrogen. The total water consumption typically ranges from 21 to 24 litres per kg of hydrogen produced (IRENA and Bluerisk, 2023).

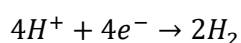
2.4.2. Proton exchange membrane electrolysis

Proton Exchange Membrane (PEM) electrolysis is a water electrolysis technology that operates at relatively low temperatures (typically between 60-80 °C) and high pressures (up to 100 bar). The system uses a solid polymer electrolyte, typically a perfluorinated sulfonic acid polymer (such as Nafion), which provides high proton conductivity and separates the anode and cathode compartments.

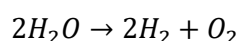
The cell configuration consists of a membrane-electrode assembly (MEA), where the anode and cathode are deposited on either side of the polymer electrolyte. At the anode, water molecules are oxidised to form oxygen gas and protons:



The protons migrate through the polymer electrolyte to the cathode, where they are reduced to form hydrogen gas:



The overall cell reaction is:

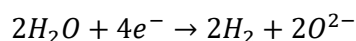


PEM electrolysis has several advantages, including high efficiency, compact design, and ability to operate at high pressures. The technology is widely used for hydrogen fuelling stations, power-to-gas applications, and other industrial processes. However, PEM electrolysis uses noble-metal catalysts (usually iridium-oxide on the anode for the oxygen-evolution reaction and platinum-group metals on the cathode for the hydrogen-evolution reaction). These catalysts and the membrane used in PEM are sensitive to impurities, requiring ultra-pure water purity to avoid impacts on durability and performance (Yoshimura et al., 2022). The total water consumption for PEM electrolysis typically ranges from 17 to 18 litres per kg of hydrogen produced (IRENA and Bluerisk, 2023).

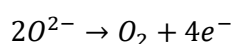
2.4.3. Solid oxide electrolysis

Solid Oxide Electrolysis (SOEL) is a high-temperature water electrolysis technology that operates at temperatures between 500-1000 °C. The system uses a solid oxide electrolyte, typically a ceramic material such as yttria-stabilised zirconia, which provides high oxide ion conductivity and separates the anode and cathode compartments.

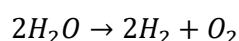
The cell configuration consists of a three-layer structure, with the anode and cathode deposited on either side of the solid oxide electrolyte. At the cathode, gaseous water molecules (steam) are reduced to form hydrogen gas and oxide ions:



The oxide ions migrate through the solid oxide electrolyte to the anode, where they are oxidised to form oxygen gas:



The overall cell reaction is:



SOEL has several advantages, including high efficiency and low susceptibility to contamination. However, SOEL is still in the early stages of development, and the technology faces challenges related to material durability, scalability, and cost.

The total water consumption for SOEL typically ranges from 11 to 17 litres per kg of hydrogen produced (IRENA and Bluerisk, 2023; Sánchez et al., 2026). However, the actual water consumption may vary depending on the specific system design and operating conditions.

3. Hydrogen-water nexus literature review and state-of-art

The literature on the water needs for hydrogen production processes is very abundant. In this work we decided to focus on studies that specifically address the impact of hydrogen production deployment on water resources.

3.1. Overview of the latest works on the assessment of water resources for hydrogen production systems

The International Renewable Energy Agency (IRENA) together with BlueRisk published a comprehensive report on water needs for hydrogen production systems (IRENA and BlueRisk, 2023). The authors provide an overview of the water withdrawal and consumption levels of hydrogen production technologies. They conclude that hydrogen production via coal gasification is the most water intensive (with a consumption of 31 L/kg(H₂)), 22.3 L/kg(H₂) for AWE, while SMR and PEM are the most efficient, only requiring 17.5 L/kg(H₂) of water consumption. The report concludes that freshwater withdrawals for global hydrogen production will increase from 2.2 billion cubic meters in 2020 to 7.3 billion cubic meters by 2040 and to 12.1 billion cubic meters by 2050. However large these numbers are, they represent only 0.6 % of the total water needs for the energy sector today and 2.4 % in 2040 at global level. The authors overlapped the mapping of renewable and low-carbon hydrogen projects locations with water stress conditions to provide a spatially explicit insight about potential conflicts. From a local impact perspective, the report concludes that over 35 % of global renewable and low-carbon hydrogen production capacity is located in highly water-stressed regions, with India, China, and the EU-27 facing significant water stress challenges. In EU, the most exposed countries are Portugal, Italy, Spain where 72 %, 69 % and 46 % of the operational and announced projects are respectively located, with high or extremely high water stress conditions in 2040. However, the report does not consider the size of projects at asset level as well as the relative share of water withdrawal for hydrogen production against the local total water withdrawal.

Tonelli and colleagues conducted an analysis on the land and water requirements for hydrogen production at global level (Tonelli et al., 2023). Their analysis starts from estimating country-specific hydrogen demand for 2020 and 2050 for hydrogen produced by water electrolysis (including for 2020 production levels). The report provides factual and counterfactual scenarios, investigating if the production of hydrogen is triggering a phenomenon of water scarcity in a given country.

Shi and colleagues proposed an evaluation of the water footprint of hydrogen production through electrolysis in Australia (Shi et al., 2020). They focus in particular on the entire supply chain of the system including the water needs for the generation of electricity. The case study analyses the water footprint of hydrogen produced with electricity from the Australian grid, as well as dedicated wind or solar power plants. Factors like solar radiation, as well as photovoltaic module lifetime and efficiency are also considered. The study used the AWARE characterisation model to calculate the water equivalent consumption (Boulay et al., 2018) for the water footprint of the production of 3.2 million metric ton of hydrogen in 2040. It concludes to a significant difference depending on whether the system is supplied by the electrical grid or photovoltaic, with grid-supplied systems consuming approximately 9 829 GL(H₂O)_{eq} against 3 126 GL(H₂O)_{eq} for photovoltaic powered systems or 1 216 GL(H₂O)_{eq} for wind-powered systems. Besides freshwater, other potential sources of water for electrolyser hydrogen production are being investigated. Due to the close relationship between coastal areas and availability of renewable electricity, seawater is a possible candidate.

However, seawater is not a suitable direct feedstock for common electrolysis technologies due to the presence of electrochemically active ions that interfere and compete with water-splitting reactions (Dresp et al., 2019). While research is ongoing on developing reliable technologies for direct seawater electrolysis, currently seawater used for direct hydrogen production needs to be treated and purified, which can add significant energy and cost requirements to the process (Serafini et al., 2025).

With over 20 000 desalination plants operating worldwide, producing around 90 million m³/day of freshwater, desalination of seawater is a mature technology and could be an easy option for producing freshwater for hydrogen production (Ginsberg et al., 2022). The most common desalination technologies are reverse osmosis (RO), multi-stage flash distillation (MSF), and multi-effect distillation (MED), with RO being the most energy efficient. Desalination can provide a reliable source of freshwater for hydrogen production, and the required energy input is 0.14 % of the energy required for the electrolysis process ('Chbika Hydrogen Project', 2024; Serafini et al., 2025). However, there are only few studies on desalination environmental impacts, such as brine disposal and marine ecosystem disruption.

Wastewater and brackish water are also potential sources of water for hydrogen production, although they are less commonly used due to their variable quality and treatment requirements ('Annual Report Anemel 2025', 2025). Wastewater treatment plants can provide a consistent supply of water, and the use of wastewater for hydrogen production can help to reduce the energy otherwise required for wastewater treatment and disposal. Brackish water, which is water with a salinity higher than freshwater but lower than seawater, can also be used for hydrogen production, particularly in coastal areas where it is abundant.

Regarding water quality, per- and polyfluoroalkyl substances (PFAS) constitute a class of thousands of synthetic chemicals with varying properties, safety profiles, and applications across multiple industries (OECD, 2021), including water electrolysis. These substances have gained regulatory attention due to their environmental persistence, with authorities from Denmark, Germany, the Netherlands, Norway, and Sweden submitting a proposal to the European Chemicals Agency (ECHA) in January 2023 calling for a near-complete phase-out of PFAS manufacture, import, sale, and use under the EU Regulation on the registration, evaluation, authorisation and restriction of chemicals ('REACH', 2006).

The fluorinated membranes in PEM systems provide essential functions including elevated proton conductivity and high durability under the harsh operating conditions of electrolysis. PFAS are integrated into multiple electrolyser components (Konchakova et al., 2022), serving as:

- Membrane materials, where their chemical stability, thermal resistance, and proton conductivity properties are essential for efficient hydrogen production,
- Catalyst binders in electrode coatings, enhancing the electrochemical performance and durability of reaction sites,
- Sealing materials and gaskets across various electrolyser technologies, including both PEM and alkaline systems, providing necessary chemical resistance against corrosive electrolytes,
- Hydrophobic treatment for gas diffusion layers (GDLs), facilitating effective water management within the electrochemical cell.

However, so far, the analysis of their degradation and impacts are limited. There is no reliable and defined technique to identify and distinguish the different organic fluorine compounds (Bodner et al., 2017). Therefore, in 2025 a call from the Clean Hydrogen Partnership was launched ('HORIZON-

JU-CLEANH2-2025', 2025) to understand the potential of PFAS emissions and their root cause. The participating projects are also encouraged to propose alternative solution to reduce or replace PFAS.

3.2. Overview of the EU water policy framework

Over the past two decades, the EU has built a comprehensive legislative framework to protect and manage water resources. These efforts have intensified in response to climate change, water scarcity, pollution, and industrial sustainable use concerns. For energy systems reliant on water, such as hydrogen production infrastructure, this evolving policy environment introduces both constraints and opportunities. This chapter reviews the key EU water policy instruments, the newly adopted European Water Resilience Strategy, and the interaction of water governance with energy and industrial decarbonisation frameworks, with a particular focus on hydrogen production in industrial clusters.

The foundation of EU water governance is the **Water Framework Directive** (WFD) ('Water Framework Directive', 2000), which aims to ensure all surface waters and groundwater achieve at least "good ecological and chemical status." Its river basin management approach requires Member States to manage water resources across natural hydrological boundaries rather than administrative ones, promoting integrated planning. Despite progress, many Member States face persistent challenges in meeting its objectives due to pollution as well as hydro morphological pressures, such as river channelisation, damming, and excessive water abstraction, which alter the natural flow and physical structure of water bodies (European Environment Agency, 2024).

Implementing the WFD, a set of derivate directives have been introduced to address specific pressures:

- The **Groundwater Directive** ('Directive - 2006/118 - EN - EUR-Lex', 2006)– sets quality standards and measures to prevent and control groundwater pollution.
- The **Environmental Quality Standards Directive (EQSD)** ('Directive - EU - 2026/805 - EN - EUR-Lex', 2026) – sets limits for priority substances in surface waters, including heavy metals and synthetic organic micropollutants, aiming at reducing or eliminating their release from industrial, agricultural, and urban sources. The 2026 amendment updated the previous directive by introducing new Environmental Quality Standards for a sum of 25 PFAS substances. While the European Parliament has advocated for a broader regulation based on total PFAS, the Scientific Committee on Health, Environmental and Emerging Risks (SCHEER) has raised concerns about the feasibility and legal basis of such an approach, pointing to methodological uncertainties in reliably measuring total PFAS concentrations in surface water ('SCHEER - Scientific Opinion on "Draft Environmental Quality Standards for PFAS total under the Water Framework Directive" - Public Health', 2025).

- The **Urban Waste Water Treatment Directive** ('Directive - 91/271 - EN - EUR-Lex', 1991) – establishes standards for the collection, treatment, and discharge of urban wastewater, which has significantly improved sanitation infrastructure and reduced pollution from municipal and certain industrial sources across Europe since its adoption. The recast of this directive (2024/3019/EU) entered into force in January 2025 and introduces stricter requirements for nutrient removal, mandatory treatment for micropollutants (including pharmaceuticals and personal care product), the control of stormwater overflows and, if necessary, sewers separation, and more stringent checks on industrial discharges to urban sewers. These changes are expected to affect primarily industries that discharge indirectly into municipal wastewater systems, as they may face higher treatment charges, tighter pre-treatment requirements, or enhanced monitoring obligations to ensure compliance with upgraded municipal treatment capabilities ('Directive - 2024/3019 - EN - EUR-Lex', 2024).
- The **Drinking Water Directive** ('Drinking Water Directive', 2020)– sets quality standards for water intended for human consumption and includes provisions on emerging pollutants such as PFAS, endocrine disruptors, and microplastics. It also promotes leakage reduction and greater efficiency of supply systems. While primarily aimed at public health protection, these measures can indirectly affect water resource availability in regions where industrial use competes with drinking water demand.

Adopted by the European Parliament in summer 2025, the **European Water Resilience Strategy** ('European Water Resilience Strategy', 2025) represents an integrated policy framework linking water management with climate adaptation, biodiversity protection, and economic resilience. While building on existing directives, it brings a renewed and more coordinated focus on emerging challenges and intensifying pressures – such as prolonged droughts, PFAS contamination, and unsustainable abstraction – that increasingly affect industrial regions, particularly in southern and central Europe. Its novelty lies in unifying previously separate policy threads into a strategic approach with measurable EU-wide targets.

The strategy is organised around three core objectives:

1. Restoring and protecting the water cycle, including improving retention in landscapes and addressing pollutants such as PFAS in drinking water sources.
2. Building a water-smart economy by promoting sustainable use across sectors, setting an EU-wide target of at least 10 % improvement in water-use efficiency by 2030, and encouraging the setting of national-level water efficiency targets.
3. Ensuring clean and affordable water and sanitation for every citizen, through infrastructure modernisation limiting losses, and narrowing regional gaps in service provision.

Although the WRS does not reference hydrogen specifically, its emphasis on improving water-use efficiency across economic sectors indicates that hydrogen production needs to consider these efficiency targets and resilience measures in water-stressed regions (Anzaldúa et al., 2025; 'European Water Resilience Strategy', 2025).

3.3. From EU water regulations to national implementation

While the WFD and related EU instruments set the overarching objectives for sustainable water management, they leave key implementation details – such as permit thresholds, competent

authorities, and charging schemes – to Member States. As a result, water-use permitting for electrolyzers is decided at national or sub-national level (European Environment Agency, 2024).

Two points are relevant for project developers at EU level:

- **Non-harmonised permit and fee thresholds:** regulatory practices related to water abstraction and pricing vary significantly across Member States. This leads to a diverse landscape of water management practices in Europe (European Environment Agency, 2024) (EEA 2024).
- **Scope of the Industrial Emissions Directive (IED):** Under current law, many electrolyzers remain outside the IED as plants below 50 t H₂/day are not subject to IED requirements (Clean Hydrogen Observatory, 2025; 'Industrial Emissions Directive 2.0', 2024). Consequently, many projects are authorised under general water and environmental rules rather than industrial-emission permits.

3.3.1. National examples of implementation in EU

Germany exemplifies federal differentiation. The Federal Water Act (EWE, 2025) sets common principles, while the 16 *Länder* define permit triggers, responsible authorities, and water-abstraction charges (*Wasserentnahmeentgelt*). There is substantial variation by state in how much abstraction costs per cubic metre depending on the intended use (Federal Environment Ministry, 2024). A more detailed dive is available in Annex 1.

Spain treats surface and groundwater as part of the public hydraulic domain. Administrative concessions are generally required for private abstraction, and the *Confederaciones Hidrográficas* (river-basin confederations) issue authorisations. This uniform “concession first” approach supports basin planning but offers limited exemptions for small abstractions (Ministerio para la Transición Ecológica y el Reto Demográfico, 2024).

France water abstractions are managed by six basin agencies (*Agences de l'eau*). Each agency establishes basin-specific rules that distinguish between a declaration (a simple notification required for low-volume, low-impact withdrawals) and an authorisation (a formal licence needed when the planned abstraction exceeds a volume threshold or could affect water-level, water-quality or ecological status). The choice between the two depends on the abstraction volume and the local hydrological conditions. Industrial abstraction charges (*redevances*) are set per basin with strong variation among them, reflecting source, scarcity zone, and use ('Les redevances | Agence de l'Eau Rhin-Meuse', 2025).

The Netherlands regulates groundwater and surface-water abstractions mainly through provincial and water-board authorities under the Environment and Planning Act (*Omgevingswet*). Developers typically require a provincial permit for industrial abstraction, and water-board or local authority involvement for works near water bodies. Thresholds and conditions are established in regional regulations ('What the Environment and Planning Act means for businesses - Environment and Planning Act - Government.nl', 2024).

Other Member States also have different approaches and thresholds, authorities, and permitting timelines, highlighting the fragmented nature of water regulation implementation at EU-level (European Environment Agency, 2024).

3.4. Interaction with climate and industry

Water governance is increasingly intertwined with EU energy and climate policy, shaping the conditions under which large-scale industrial hubs can develop by regulating how water is sourced, reused, and discharged, which may also impact hydrogen production facilities. As deployment accelerates in line with EU decarbonisation goals, the sector's reliance on high-quality water intersects with resource management regulations, creating both compliance obligations and innovation incentives.

These constraints are reinforced by the IED ('Industrial Emission Directive', 2010) and its recent revision adopted in 2024 ('Industrial Emissions Directive 2.0', 2024), which expands environmental performance standards for industrial installations, including water-intensive processes such as electrolysis. In particular, the directive's emphasis on Best Available Techniques (BAT) influences hydrogen production by imposing stricter requirements on water use efficiency and pollutant discharge thresholds.

In the early-2020s the EU began to embed sustainability requirements into its emerging hydrogen agenda. The **EU Hydrogen Strategy** ('EU Hydrogen Strategy', 2020) and the **REPowerEU Plan** (European Commission, 2022b) both emphasised the importance of sustainability criteria for hydrogen deployment. These priorities were embedded in the **EU Taxonomy for Sustainable Activities** ('EU Taxonomy for Sustainable Activities', 2020), which defines environmentally sustainable economic activities and guides investment toward projects aligned with the EU's climate and environmental objectives, including the **European Green Deal** and net-zero targets. For hydrogen production, the technical screening criteria address not only greenhouse gas emissions but also environmental safeguards such as efficient water use, minimisation of pollutant discharge, and sustainable sourcing. Projects seeking a sustainable investment label under this framework must demonstrate that they meet these safeguards across their operational life cycle (Generic criteria for dnsH to sustainable use and protection of water and marine resources).

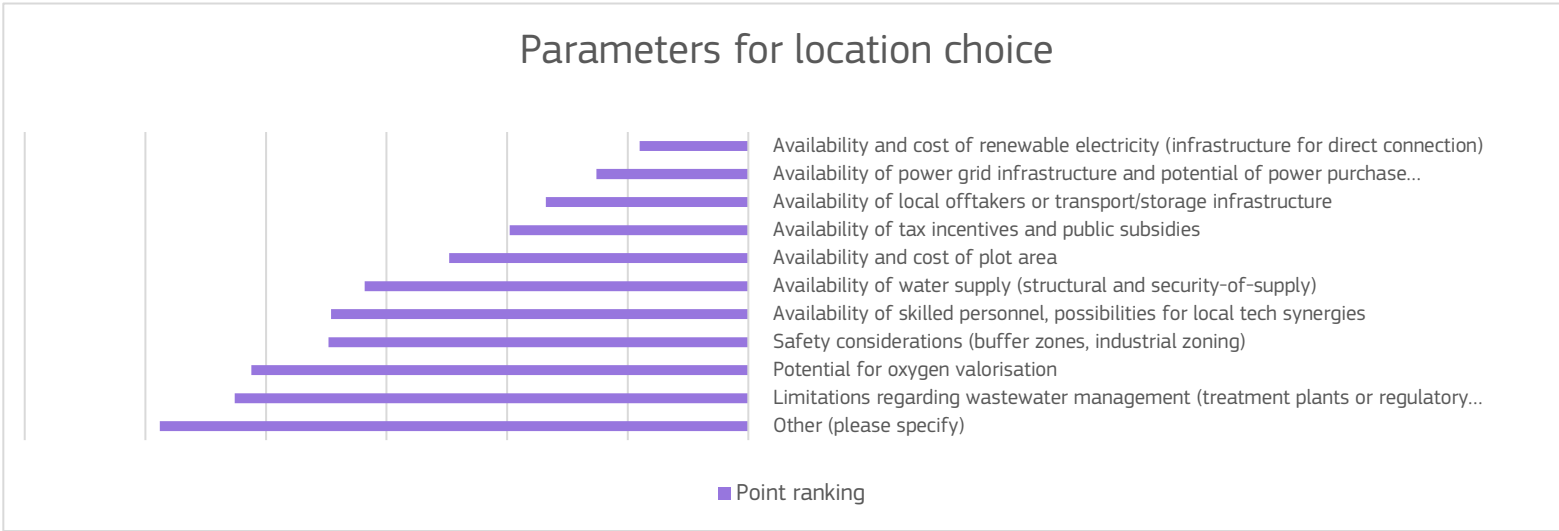
While there is no uniform legal requirement on water use across all EU funding mechanisms, water considerations are becoming more prominent. Calls under **Horizon Europe** have increasingly encouraged applicants to reduce freshwater consumption, integrate water reuse, or adopt non-conventional sources, particularly in water-stressed regions. In specific coastal contexts, desalination is emerging as an additional option to diversify water supply, particularly during periods of drought. Although not governed by a standalone directive, desalination is acknowledged in the WFD ('Water Framework Directive', 2000) as a potential supplementary measure in water-scarce regions. It is also recognised under the EU Taxonomy for Sustainable Activities ('EU Taxonomy for Sustainable Activities', 2020) as an eligible economic activity, provided strict environmental safeguards on energy use, emissions, and biodiversity are respected. In addition, the **Water Reuse Regulation** ('Water Reuse Regulation', 2020) sets detailed quality requirements for treated wastewater reuse. Beyond regulatory and funding measures, the EU is promoting innovative approaches to industrial sustainability. For instance, the **Circular Economy Action Plan** ('Circular Economy Action Plan', 2020) advocates for creating circular systems where waste is minimised and resources are used as efficiently as possible. Implementing these approaches in hydrogen production can help reduce freshwater demand while supporting regional resilience and sustainability objectives.

Water availability may be a potential constraint to hydrogen deployment in parts of Europe, particularly in southern and southeastern regions where competition with agriculture, industry, and municipal supply is high. In already water-stressed areas, hydrogen production will need to be

planned with careful consideration of local water availability and competing demands. Tonelli et al. (Tonelli et al., 2023) highlight that ensuring sufficient water resources for hydrogen deployment will require strategic site selection and the early integration of water efficiency and reuse measures. By adopting such practices, hydrogen projects can support sustainable growth while contributing to regional water resilience and broader EU sustainability objectives.

From an industrial perspective, the Joint Research Centre performed a survey collecting data from 26 respondent involved in hydrogen production facilities projects in EU (European Commission. Joint Research Centre., 2024). The data show that water availability and wastewater management are currently not a primary concern in the definition of a new electrolyser location, while giving priority to the availability and cost of renewable electricity (**Figure 1**).

Figure 1. Ranking parameters for electrolyser location plan from survey of 26 respondent. Water availability is the 6th parameter for importance.



Source: Joint Research Centre (2024)

Water is both a constraint and an enabler in Europe’s industrial decarbonisation plan. The EU’s tightening water policy framework may affect how hydrogen production facilities will be planned, financed, and permitted. Effective integration of water efficiency measures and reuse strategies can not only mitigate operational risks but also enhance sustainability and resilience in the hydrogen sector. However, water-use regulation for hydrogen electrolysis in Europe is multi-layered and fragmented: EU directives set broad objectives for sustainable water management, but concrete obligations arise at national and even regional levels. Permit triggers, fee schedules, and competent authorities differ not only between Member States but often within states and between river basins. For developers, this means that two plants of identical size can face very different permitting routes and water abstraction charges depending on location. Projects must therefore engage early with local authorities, assess site-specific availability of freshwater or reclaimed sources, and integrate water efficiency into design. In short, the regulatory and investing landscape is complex: understanding local rules and tailoring water-supply strategies is as important as the electrolyser technology itself for bringing green-hydrogen capacity online.

4. Hydrogen production impacts on EU water resources

4.1. Methodology

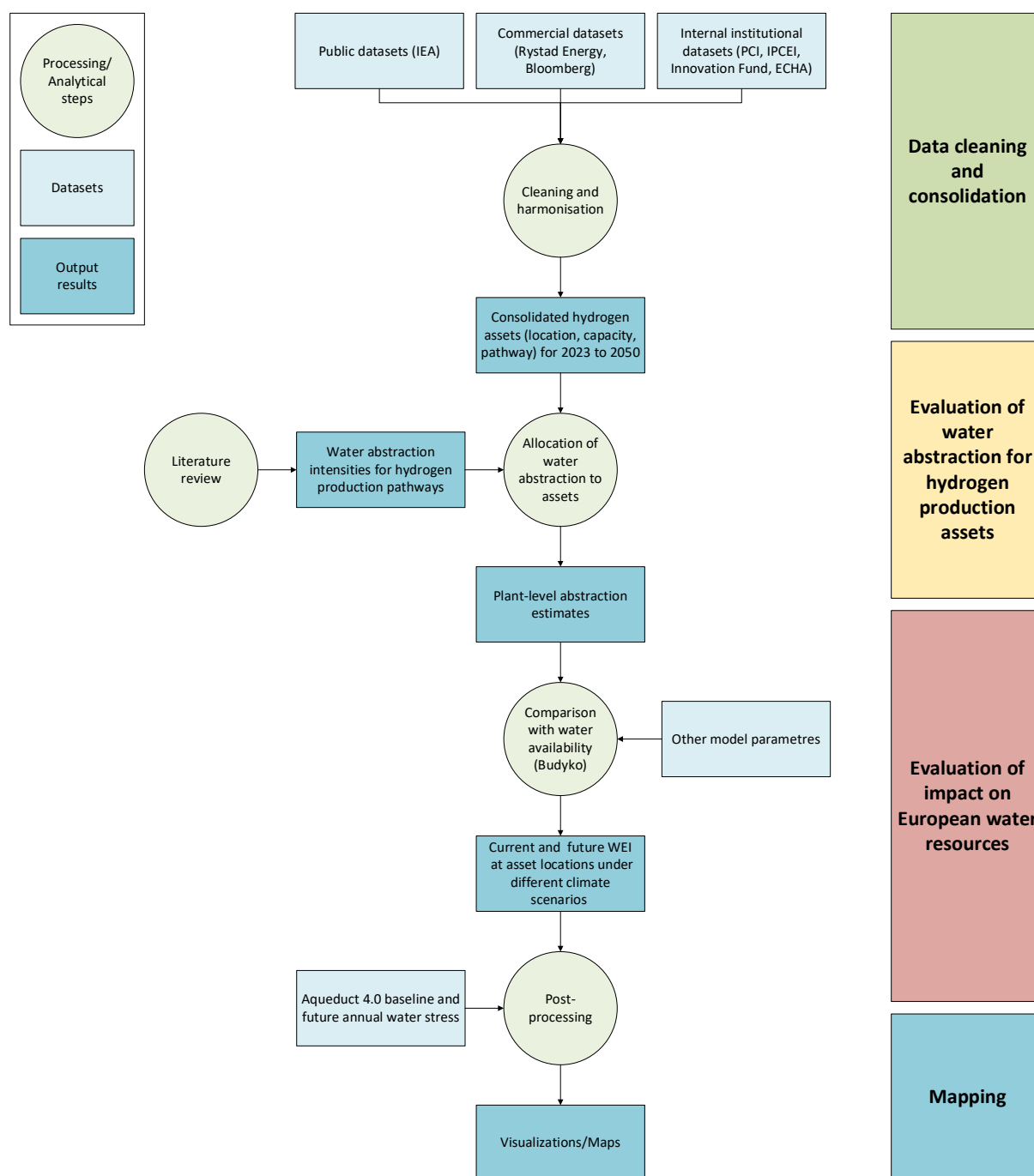
This chapter presents the methodological framework developed to estimate the impact of hydrogen production plants on European water resources. The analysis integrates data on hydrogen assets with technology-specific water abstraction intensities, a continental-scale hydrological model, and complementary datasets on water stress. Together, these components provide a spatially explicit picture of how hydrogen deployment may interact with water scarcity under different climate scenarios and time horizons. The relation with water abstraction for hydrogen and water scarcity is expressed through the calculation of the **Water Exploitation Index (WEI)** (**Box 3**). A graphical overview of the methodological framework is given in **Figure 2**.

Box 3. Note on the choice of using the Water Exploitation Index (WEI)

The Water Exploitation Index (WEI) measures water appropriation by calculating the ratio of total freshwater abstraction to total renewable freshwater resources. The WEI values range from 0 to 1, and it is possible to use it as an indicator of water scarcity. A modified WEI indicator, called WEI+, replaces abstraction with water consumption, is generated by the EEA using data from the WISE SoE-Water quantity database, as well as other open sources like Eurostat and OECD, and incorporates gap-filling methods to estimate missing values ('Water exploitation index, plus (WEI+)' (sdg_06_60)', n.d.). National-level WEI+ calculations may not accurately capture water stress, as they do not account for regional and seasonal variations in water resources. The WEI+ indicator has been associated to low (<0.1), medium (0.1-0.2), high (0.2-0.4), and high water scarcity (>0.4) (European Commission. Joint Research Centre., 2020).

We chose to use the WEI indicator as for its simplicity and directness (Pistocchi et al., 2026). However, there are numerous discussions about the relevance of a given parameter used to evaluate the stress on water resources over another (Hoekstra 2016). The AWARE indicator was also considered instead of the WEI. The AWARE methodology (Available WATER REmaining) has been developed following a 2-year consensus building among LCA experts belonging to the Water Use in Life Cycle Assessment (WULCA) group, a working group of the UNEP-SETAC Life Cycle Initiative (Boulay et al. 2018). AWARE is also used in Life Cycle Assessments (LCAs) to quantify environmental impacts of water use in products and supply chains. It focuses on water deprivation potential for humans and ecosystems in specific watersheds and evaluates how water consumption impacts the remaining availability relative to local hydrological conditions. This differs from the WEI which measures water scarcity by comparing total freshwater consumption (abstraction minus returns) to renewable freshwater resources at regional/national scales.

Figure 2. Data processing flow of the evaluation of hydrogen impacts on European water resources.



Source: Joint Research Centre (2025)

4.1.1. Data sources

The foundation of the assessment is a consolidated dataset of hydrogen production plants in Europe for the period 2023 to 2050. Information was collected from distinct sources: the publicly available IEA Hydrogen Projects Database (IEA, 2024), the Hydrogen Solution by Rystad Energy (Rystad Energy, 2024), the Innovation Fund dashboard (CINEA, 2025), as well as information on hydrogen-related Projects of Common Interest (PCI) (European Commission, 2022a) and Important Projects of Common European Interest (IPCEI) (European Commission, 2025). These diverse sources were systematically unified and checked through a comprehensive cleaning and consolidation

process, resulting in a harmonised dataset that provides standardised information on hydrogen plant locations, technological pathways, and production capacities across this period. Plant locations were verified and corrected, as a number of projects were misclassified by data providers. In total, approximately 1 300 assets were retained after processing.

4.1.2. Water abstraction estimation

The second step involved linking each plant to expected water abstraction levels. A review of estimates provided in the literature was conducted to compile abstraction intensities for different hydrogen production pathways, which vary depending on the technology and cooling system. On this basis, pathway-specific water intensity factors were established. For the analysis, a conservative “maximalist” scenario was applied, assuming that plants operate continuously at full capacity and rely on wet cooling, the most water-intensive option. While these assumptions likely overestimate actual abstraction, they provide an upper-bound estimate of water abstraction. Annual abstraction for each plant was then derived by multiplying the annual hydrogen production capacity at asset level by the relevant factor. When ranges were reported an average value was taken into account for this work.

4.1.3. Impact on European water sources for different scenarios

Assessing the significance of hydrogen production-related water use requires situating it within the broader hydrological context. A litre of water withdrawn in a water-abundant basin has a very different environmental impact from the same litre abstracted in a region already under stress. To capture these spatial dynamics, the study employed the long-term annual average streamflow according to the Budyko equation model (Pistocchi et al., 2026) which was proven to be a proxy for more sophisticated estimations according to the LISFLOOD hydrological model (‘LISFLOOD hydrological model’, 2025) developed by the Joint Research Centre (Van der Knijff, Younis and De Roo, 2010)) and used for floods, droughts and water resources assessment at the European and global scale. The Budyko equation model was applied to both current and climate scenario conditions under representative concentration pathways (RCPs) 4.5 and 8.5 as detailed in the work of Pistocchi et al.

In this study, the Budyko equation model was used to calculate a plant-specific **Water Exploitation Index (WEI)**, which expresses the ratio of total water abstraction for the plant and renewable water availability for the plant’s hydrographic catchment. Hydrogen production water demand was integrated into this framework, enabling the derivation of plant-specific WEI values. The calculation was repeated for the abstractions estimated in years 2023, 2030, 2040 and 2050 under three climate scenarios: current climate (based on representative long-term average conditions), RCP4.5 (representing an intermediate emissions pathway), and RCP8.5 (high emissions scenario). This enabled the assessment of both temporal and spatial trends in this water stress indicator associated with hydrogen under each climate scenario. Out of 1 319 hydrogen assets across EU27 + EFTA + UK + TK, 64 production sites were excluded from the analysis because they correspond to coastal grid cells where the model does not return an estimate of freshwater availability, and not necessarily considering water coming from alternative sources (e.g. desalination). The remaining 1 255 assets were retained for further analysis and mapping.

4.1.4. Complementary datasets: Aqueduct 4.0

The LISFLOOD model and its Budyko equation proxy have been used to calculate water scarcity indicators with a spatial resolution down to 1 arc-minute for EU27 + EFTA + UK + TK taking into account water demand/abstractions from sectors including public water supply, irrigation, livestock, industrial use and energy generation (Pistocchi et al., 2026).

However, for reasons of comparability with other studies on the subject, such as the IRENA and Bluerisk report (IRENA and Bluerisk, 2023) in this study it has been decided to complement the asset-level WEI values generated with Budyko equation model with the water scarcity indicators from **Aqueduct 4.0**, a publicly available global water risk dataset developed by the World Resources Institute (Kuzma, 2023). Aqueduct 4.0 is a dataset compiling several indicators related to water resources from multiple models. The study incorporates the Water Stress Indicator which is calculated using the PCR-GLOBWB 2 global hydrological model ('PCR-GLOBWB 2.0', 2026; Sutanudjaja et al., 2018), which simulates water supply and demand dynamics and was updated in 2023 to reflect newer climate observations, enhanced soil mapping, and a high-resolution digital elevation dataset. The model delivers sub-basin-scale (30 arc-seconds) indicators of baseline (a snapshot of the present-day situation) and future water risks, spanning physical (quantity and quality) and reputational dimensions, using 13 indicators aggregated into composite scores.

The dataset incorporates irrigation, industrial, household, and livestock water needs, as well as reservoir storage from global databases. The indicators are further aggregated at country and provincial levels, with sub-basins weighted by demand.

The Aqueduct 4.0 baseline is calculated using collected data over the period 1979–2019. This baseline period provides data for annual assessment at sub-basin scale, which aligns temporally and geographically with the annualised hydrogen production capacity dataset prepared for this study. Aqueduct integrates climate projections from the CMIP6 ensemble (Eyring et al., 2016) and simulates future water conditions under three combined shared socioeconomic pathway (SSP) and representative concentration pathway (RCP) scenarios: SSP1–RCP2.6 (optimistic, sustainability-oriented future with strong mitigation), SSP3–RCP7.0 (business-as-usual trajectory with fragmented international cooperation and continued high emissions), and SSP5–RCP8.5 (pessimistic, fossil fuel-intensive development pathway with very high emissions). Projections are provided for the years 2030, 2050, and 2080, based on 30-year moving averages to smooth short-term climate variability.

4.1.5. Water stress analysis

The datasets generated from Aqueduct 4.0, Budyko model and the annualised hydrogen production capacity were integrated, and the results translated into an asset-specific risk assessment. The WEI values for each asset were obtained from the Budyko model, indicating the additional water stress solely due to the water abstraction of hydrogen assets under different scenarios and time horizons. These hydrogen-specific WEI were combined with the basin-level Aqueduct's Water Stress Indicator, allowing both contextual and specific assessment of the water stress. Each assets-specific risk was classified according to **Table 1**:

Table 1. Classification of each hydrogen asset according to their contextual and specific hydrogen abstraction.

	Low-project impact (WEI < 20 %)	Medium project impact (20 % ≤ WEI < 40 %)	High project impact (WEI ≥ 40 %)
Low contextual stress	Low risk	Low-medium risk	Medium risk
Medium contextual stress	Low-medium risk	Medium risk	High risk
High contextual stress	Medium risk	High risk	Critical risk

Source: Joint Research Centre analysis (2025)

Outputs were processed and visualised using QGIS ('QGIS', 2025) and Python-based data pipelines. Maps and charts were produced to illustrate absolute water demand, additional water stress attributable to hydrogen, and the location of assets in basins crossing critical thresholds (medium stress at WEI between 20-40 %, high stress at WEI ≥ 40 %). The Aqueduct's Water Stress Indicator was arbitrarily divided in threshold for clear visualisation (0-2 for low and low-medium stress, 0.2-0.4 for medium-high, 0.4-0.8 for high and ≥ 0.8 for extremely high).

4.2. Results and discussion

This chapter presents the main findings of the spatial analysis linking hydrogen production assets with projected water stress in Europe. The LISFLOOD results are shown for the baseline year (2023) and for future horizons (2030 and 2050) under different RCP scenarios. While a full set of scenario maps is provided in the Annex 2, this chapter focuses on a selection that illustrates the critical scenario dynamics of the water-hydrogen nexus on the EU27 + EFTA + UK + TK territory:

1. 2023 under current climate conditions.
2. 2030 under pessimistic, high-emissions trajectories (RCP8.5).
3. 2050 under moderate and pessimistic, high-emissions trajectories (RCP4.5 and RCP8.5).

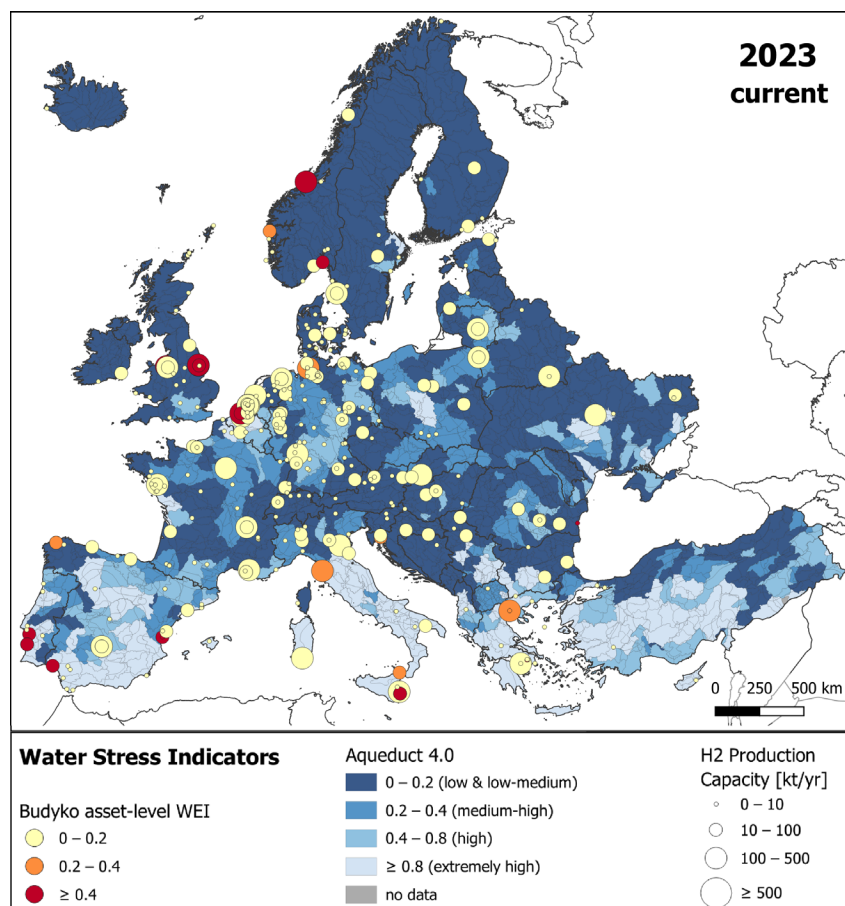
4.2.1. Current situation 2023 baseline

The Aqueduct's model indicates that most hydrogen production assets in 2023 are currently located in basins with low to medium water stress (Aqueduct's water stress < 0.2) (**Figure 3**). This applies in particular to large clusters in Northern and Central Europe, where renewable water availability remains relatively high. Out of 404 operating hydrogen production plants in 2023, almost 93 % (375 assets) are located in basins with low additional abstraction (WEI < 0.2), while only 29 assets are located in water scarce conditions (WEI ≥ 0.2). This suggests that current hydrogen production does not yet represent a major water pressure in most regions. Nonetheless, regional differences emerge when hydrogen demand is compared with Aqueduct's baseline water stress indicator:

- **Southern Europe** (Spain, southern Italy, Portugal) is already characterised by structural water scarcity in Aqueduct, coinciding with irrigation-intensive agriculture and warmer climate. However, Budyko shows that hydrogen plants in these areas generally add only modest additional abstraction compared to availability (as shown by asset-level WEI), but the coincidence with pre-existing scarcity highlights the importance of monitoring the development of the hydrogen production sites.
- **North Sea industrial hubs** (Belgium, Netherlands, North-West Germany): Aqueduct shows low-to-moderate baseline stress and Budyko values mostly remain below 0.2, but the large scale of individual projects with very large production capacities (> 500 ktH₂/yr) implies that localised water demand could become significant in the future if not mitigated.
- **Scandinavia**: Aqueduct indicates generally low regional water stress, and Budyko confirms that most projects operate with negligible additional impact. Some large plants show higher WEI values locally, which presumably rather reflects the relative size of the facility compared to the catchment dimensions than an absolute water scarcity.

Overall, about ~5 % of existing hydrogen production plants is associated with Budyko asset-level WEI values ≥ 0.4 , which means they are located in catchments indicating a degree of additional local stress. When viewed against Aqueduct's regional baselines, this stress is mostly concentrated in areas already facing challenges, and the incremental contribution from hydrogen remains relatively limited at present.

Figure 3. Map of the fossil and renewable hydrogen production assets located in the EU27 + EFTA + UK + TK and their WEI compared to the local water stress for 2023 in current scenario.



Source: Joint Research Centre analysis (2025)

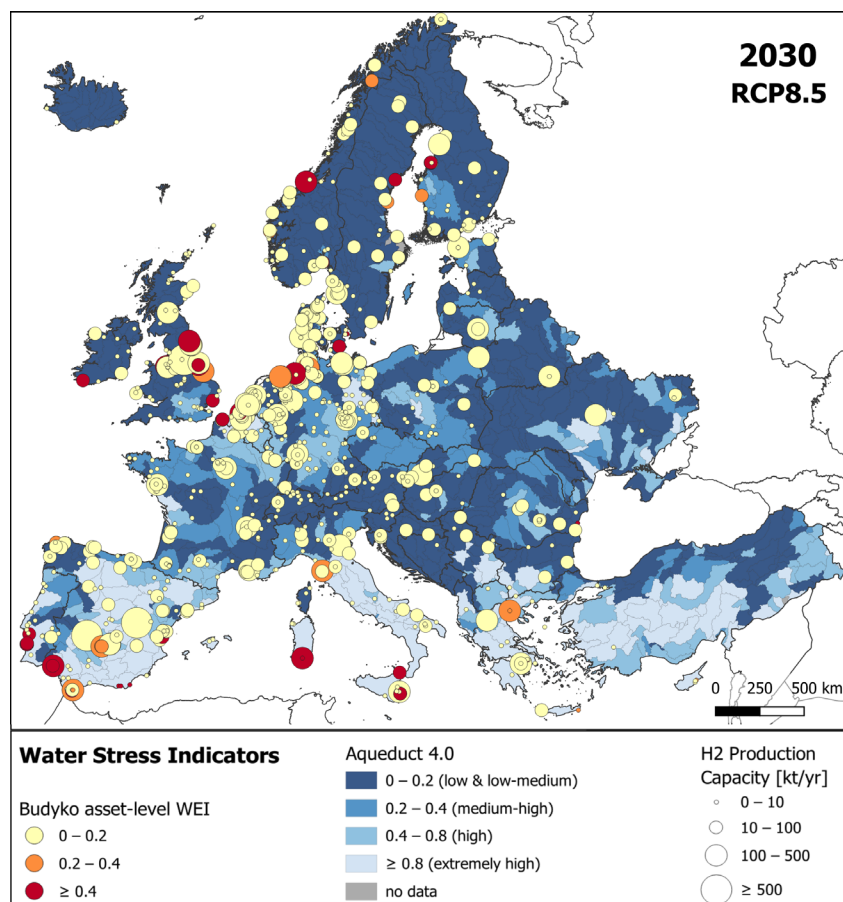
4.2.2. Near-term future: 2030

By 2030, hydrogen deployment is estimated to expand to 1 162 assets. Under the pessimistic climate projection RCP8.5, Budyko asset-level WEI indicates that several high-capacity electrolysis projects are located in basins where abstraction represents a more notable share of available resources (**Figure 4**).

While around 7 % of assets (78) are projected to operate in basins where they cause stress at asset-level (WEI ≥ 0.4), a vast majority of 91 % (1 056 assets) is located in catchments where abstraction for hydrogen production indicates minimal additional pressure on local resources (WEI < 0.2). Compared to 2023, this represents a modest increase in the share of projects in more stressed areas, but the results confirm that most hydrogen facilities continue to be situated in contexts where they represent limited additional water pressure.

In regions with abundant water (e.g. Scandinavia, parts of Central and Eastern Europe), both Budyko and Aqueduct show that hydrogen expansion would add minimal stress. Moreover, Aqueduct data indicates that the regions where high WEI have been found by Budyko (e.g. southern Europe, parts of France, northern Italy, Greece) are already characterised by structural baseline stress from agriculture, population or other sector's water demand. This indicates that hydrogen demand is not the primary driver of scarcity, but its development may amplify pre-existing challenges and reinforce the need for integrated water management.

Figure 4. Map of the fossil and renewable hydrogen production assets located in the EU27 + EFTA + UK + TK and their WEI compared to the local water stress under 2030 pessimistic (RCP8.5) scenario.



Source: Joint Research Centre analysis (2025)

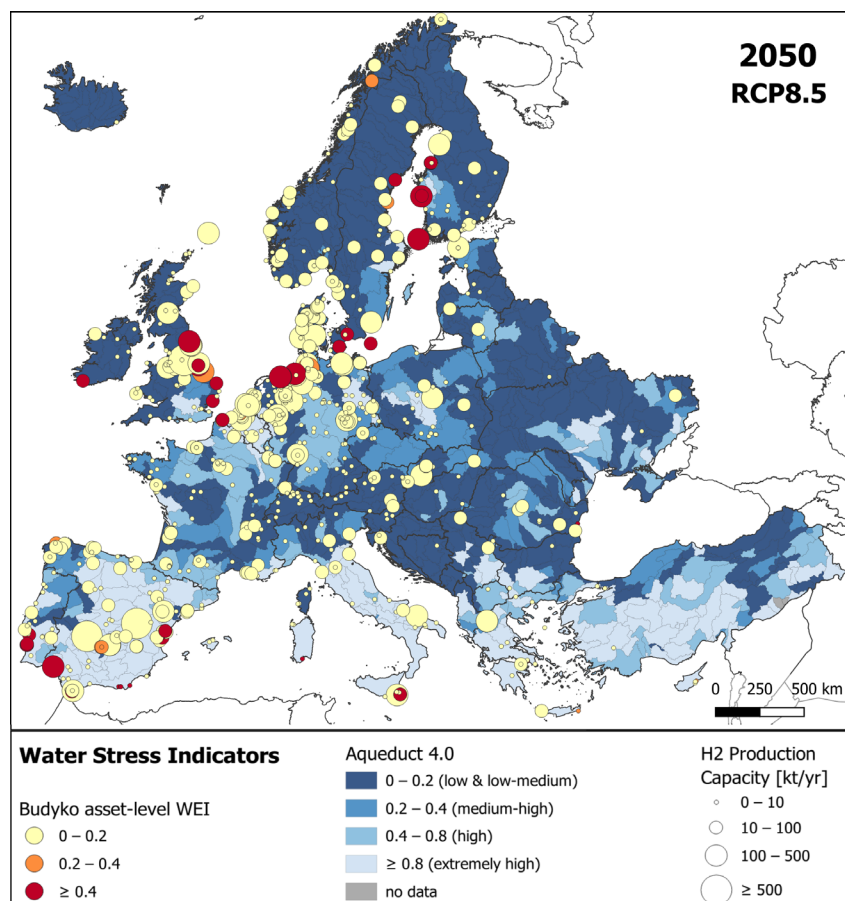
4.2.3. Long-term outlook: 2050

By 2050, the number of hydrogen production assets across Europe is estimated at around 1 095 assets. The divergence between climate scenarios becomes more pronounced at this horizon.

- **RCP4.5 (intermediate mitigation):** Budyko results indicate that the majority of assets – around 90 % (987 sites) – are situated in basins where hydrogen-related abstraction remains very limited relative to available resources. Only a small share appears in more sensitive contexts: 2 % (20 sites) are estimated with WEI between 0.2 and 0.4, and 8 % (88 sites) with $WEI \geq 0.4$. Aqueduct projections confirm that such cases mainly occur in structurally water-scarce regions in southern Europe, where scarcity would be a challenge irrespective of hydrogen deployment (Annex 2).
- **RCP8.5 (pessimistic):** In a high-emissions world, hydrogen plants account for a more significant share of local abstraction. Budyko results show 25 assets (2.3 %) with an estimated WEI between 0.2 and 0.4, and 92 assets (8.4 %) with $WEI \geq 0.4$. This implies that nearly one in ten plants would be operating in basins where hydrogen abstraction constitutes a noticeable share of renewable water resources. These cases are concentrated in Greece, Spain, Italy, Portugal, and parts of central Europe. Aqueduct data confirms that these are also the regions where water risks are projected to escalate most strongly under high emissions, pointing to a wider regional vulnerability rather than a hydrogen-specific driver (**Figure 5**).

Overall, the comparison highlights that while mitigation pathways (RCP4.5) keep the additional water footprint of hydrogen relatively modest, under RCP8.5 the role of hydrogen becomes more relevant in specific basins that are already water-stressed. Still, it is important to stress that even in the pessimistic scenario, the majority of hydrogen assets (almost 90 %) is estimated to remain in basins with low relative abstraction levels, underscoring that hydrogen deployment is not expected to become a dominant driver of European water scarcity.

Figure 5. Map of the fossil and renewable hydrogen production assets located in the EU27 + EFTA + UK + TK and their WEI compared to the local water stress under 2050 pessimistic (RCP8.5) scenario.



Source: Joint Research Centre analysis (2025)

4.3. Limitations

Some limitations should be borne in mind when interpreting the results. First, hydrogen plant data remain incomplete and, in some cases, uncertain, with project locations requiring manual verification for each data point. The study considers the worst-case scenarios for which all projects are considered, independently of their development stage (e.g. all project status ranging from planned, conceptual, financial investment decision taken, under construction or already operational are included in the analysis). Moreover, some coastal plants were excluded from the analysis, as they fell outside the model domain and therefore lacked WEI coverage. Additionally, the abstraction estimates rely on conservative assumptions as the average abstraction values were considered, therefore accounting for suboptimal highly water-intensive cooling processes. In addition, plants were assumed to run continuously at full capacity. This likely overstates actual water abstraction but provides a worst-case estimate that helps identify potential risks. Also, baseline water demand

from other sectors was assumed constant after 2023, meaning that potential increases in agricultural or industrial abstraction are not accounted for. Furthermore, some assets were excluded from the analysis because the Budyko model does not return an estimate of freshwater availability for the coastal grid cells.

5. Further research and recommendations

While this work investigates the impacts on water sources of hydrogen production, the holistic impacts of an extended hydrogen economy are not included. Impacts caused by the additional dedicated energy production, hydrogen transportation, storage and use cases may vary (Arrigoni et al., 2024).

Data improvement:

Further research is necessary to enhance the accuracy and reliability of the data used in the assessment of hydrogen production's impact on water resources. This includes developing more consistent data and assumptions across different hydrogen production pathways, such as real running times and capacity, water abstraction and cooling processes. Moreover, there is a need for more detailed and comprehensive datasets on water abstraction, consumption, and reuse in various hydrogen production processes. The development of such datasets would enable more precise calculations of the water footprint of hydrogen production and help identify areas where water savings can be achieved. Furthermore, other sources of water such as wastewater, seawater and brackish water should be considered for a holistic assessment for assets, especially when considering the coastal grid cells. Temporal resolution would also be an important parameter to evaluate in order to understand how does the seasonal water scarcity impact hydrogen production in general.

Environmental impacts and recommendations:

In terms of environmental impacts, further research is required to investigate the effects of seasonality, brine management, and other sources of water. This could involve examining the potential benefits and drawbacks of using alternative water sources, such as desalination or direct seawater electrolysis, assessing the potential environmental implications of large-scale hydrogen production on aquatic ecosystems, and distinguish the effects of water abstraction compared to the water consumed. Integrate the pathways with lower impacts on freshwater sources should be adopted in future strategies in order to increase the sustainability of the whole hydrogen sector and mitigate the risks.

Additionally, the impact of hydrogen production on water resources should be investigated in a broader energy scenario modelling context, considering how the increased use of hydrogen could reduce the water use from other energy sources and evaluating burden shifting of environmental impacts. This would help policymakers and industry stakeholders make informed decisions about the development of hydrogen production infrastructure and the management of water resources.

6. Conclusions

The water demand for the production of fossil-based, renewable and low-carbon hydrogen is not expected to represent an important share of the future water balance when looking at the aggregated EU level. However, it may represent an important share of total water demand in specific river basins, especially from industrial hubs in the Netherlands, Belgium and North-West Germany where very large-scale projects are planned for deployment.

The additional water stress caused by the increasing hydrogen production is expected to be generally limited at the local level. Today, most assets (95 %) are located in basins with low to moderate water stress, while the remaining 5 % of assets are located in area which are already under structural water stress. Most of the hydrogen produced is not expected to drive significant additional impacts relative to the existing water abstraction caused by other human activities, with partial exceptions particularly in the Iberian Peninsula and southern Italy.

By 2030, our analysis shows that it is highly likely that 91% of the production assets will add negligible to minimal additional pressure. The remaining share of assets (9 %) will not be the primary driver of scarcity, but might amplify pre-existing challenges in certain regions (e.g. southern Europe, parts of France, northern Italy, Greece) already characterised by structural baseline stress from agriculture, population or other sector's water demand. This reinforces the need for integrated water management in those areas.

By 2050, under intermediate and pessimistic climate scenarios, our analysis shows that between 10% and 10.7% of the analysed assets will be located in more sensitive water context, where hydrogen abstraction constitutes a noticeable share of renewable water resources. These cases are concentrated in Greece, Spain, Italy, Portugal and parts of central Europe. This additional stress in those regions is rooted within wider regional vulnerability rather than specifically caused by the hydrogen offtakes.

Furthermore, while the water demand for electrolysis may not be a major issue during “average” water availability conditions, it could exacerbate water scarcity during droughts in particular areas, especially under high-emissions scenarios.

The European Water Resilience Strategy and other EU water policy instruments provide a framework for sustainable water management, but their implementation varies across Member States. Effective integration of water efficiency measures and reuse strategies can mitigate operational risks and enhance sustainability in the hydrogen sector. Furthermore, the deployment of new desalination plants in coastal areas could reduce the impact on water sources.

Further research is needed to better understand the impact of hydrogen storage options on water resources, seasonality, brine management, and other water sources for a holistic assessment. Improved data and modelling frameworks are also required to capture local water availability and the water impacts of emerging hydrogen production technologies, but this work represents a first attempt to connect the impact on water sources by the rising need generated by the expanding hydrogen economy, with focus on the hydrogen production.

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List of abbreviations and definitions

Abbreviations	Definitions
ATR	Auto-thermal Reforming
AWE	Alkaline water electrolysis
IED	Industrial Emissions Directive
IPCEI	Important Projects of Common European Interest
MEA	Membrane-electrode assembly
PCI	Projects of Common Interest
PEM	Proton Exchange Membrane
POX	Partial oxidation
RCP	Representative concentration pathway
SMR	Steam Methane Reforming
SOEL	Solid Oxide Electrolysis
SSP	Shared socioeconomic pathway
WEI	Water exploitation index
WFD	Water Framework Directive

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Annexes

Annex 1. Germany Federal Framework and State-Level Application case

Under the Federal Water Act (*Wasserhaushaltsgesetz*, WHG), both abstraction and discharge require authorisation, while each state sets the specific thresholds, fees, and competent authorities ('*Wasserentnahmeentgelte der länder*', 2025). For hydrogen electrolyzers, the key variables are the permitting authority and the water-abstraction charges once exemption limits are passed.

Baden-Württemberg – Example of State Implementation

Baden-Württemberg demonstrates how EU water policy is implemented at the state level. The region introduced a water abstraction charge (*Wasserentnahmeentgelt*) in 1988, which was revised in 2010 to enhance incentives for water conservation and internalise environmental costs. Abstractions below 4,000 m³/year are exempt, although permits may still be required, while larger withdrawals require approval by higher authorities (Regierungspräsidium). Water governance is tiered: local authorities handle routine permits, regional councils supervise larger or complex withdrawals, and the Ministry of Environment acts as the supreme authority (Möller-Gulland et al., 2015).

This framework is directly relevant for hydrogen production via electrolysis, which consumes roughly 9 L of water per kg H₂ for the reaction and 15–30 L/kg when including purification and cooling (Hydrogen Europe, 2020; Slanger, 2023). With typical electricity demand of 50–55 kWh/kgH₂, the 4,000 m³/year exemption corresponds to approximately 1–3 MW continuous electrolyser capacity, or 2–6 MW if operating around 4 000 hours per year. This means pilot and small commercial electrolyzers usually remain below the fee threshold, while larger projects (≥5–10 MW) are subject to state water charges.

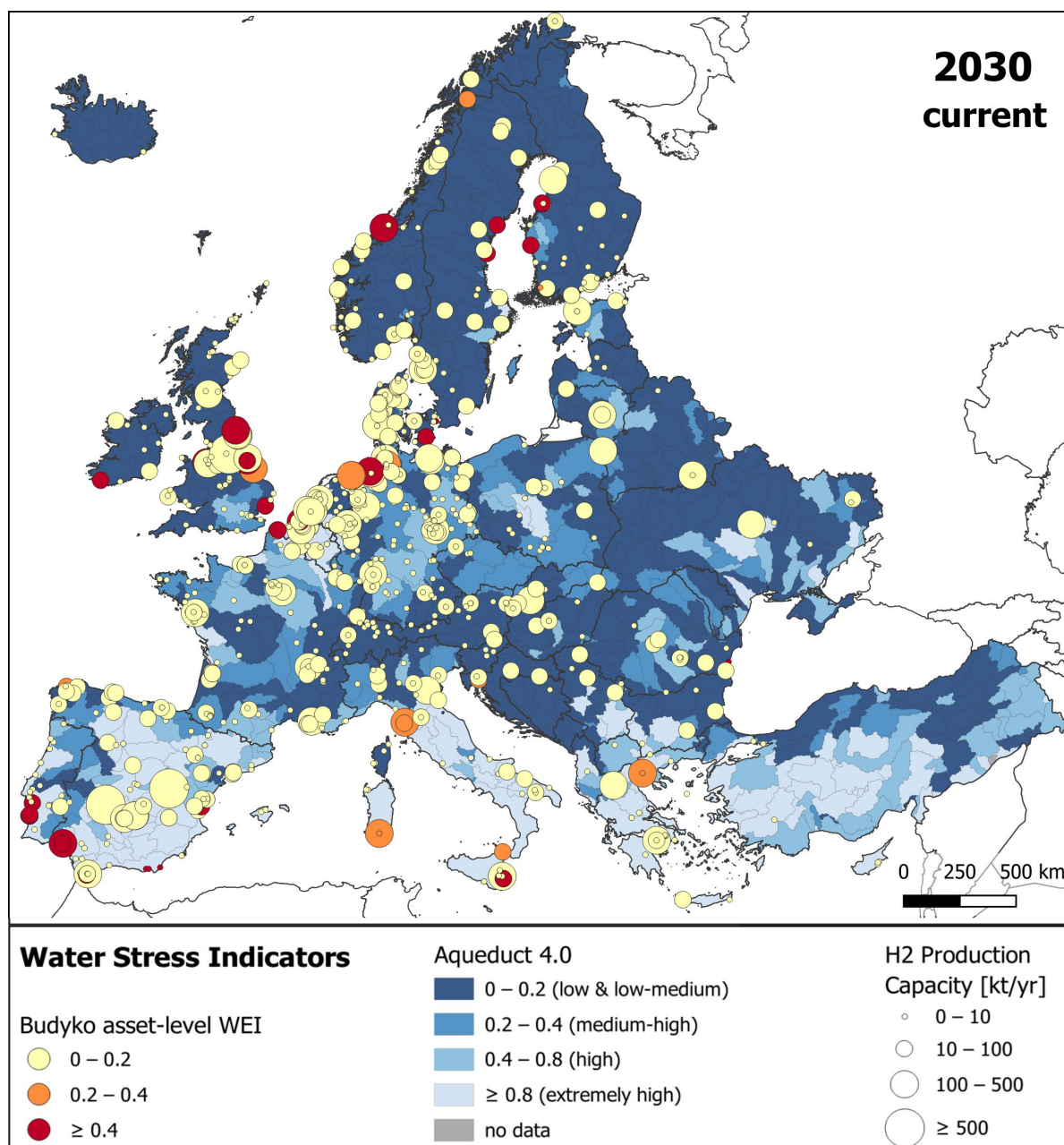
Regional Practice and Project Examples

Recent hydrogen projects across Germany illustrate how state-level water rules translate into practice and how regional strategies influence site selection. The BASF 54 MW PEM electrolyser in **Ludwigshafen**, described by the company as the world's largest of its type when commissioned in 2025, has undergone the full suite of environmental and water approvals, including authorisations under the WHG and the relevant Rhineland-Palatinate implementing regulations (BASF, 2025). Coastal Länder leverage access to abundant water resources and renewable electricity. **Lower Saxony**, for example, hosts the 10 MW "Brake" electrolyser developed by Lhyfe, part of a wider strategy to build port-based hydrogen hubs around Wilhelmshaven and other North Sea sites ('Lhyfe is building a green hydrogen plant in the seaport city of Brake in Lower Saxony (Germany)', 2024). Further inland, the state of **Brandenburg** has assessed water availability for large-scale hydrogen deployment. A 2024 state study estimated that even gigawatt-scale electrolysis would account for only a small fraction of the state's current water withdrawals, while highlighting treated municipal wastewater as a promising non-potable source for industrial projects (Zerta et al., 2024).

These cases show how national principles set by the WHG are adapted to local conditions: industrial clusters with integrated infrastructure can navigate comprehensive permitting, coastal regions benefit from seawater and port facilities, and inland areas prioritise reclaimed or non-potable sources. Beyond electrolyser size, site selection and water-source choice – fresh, brackish or reclaimed – are decisive factors in the feasibility of hydrogen projects in Germany.

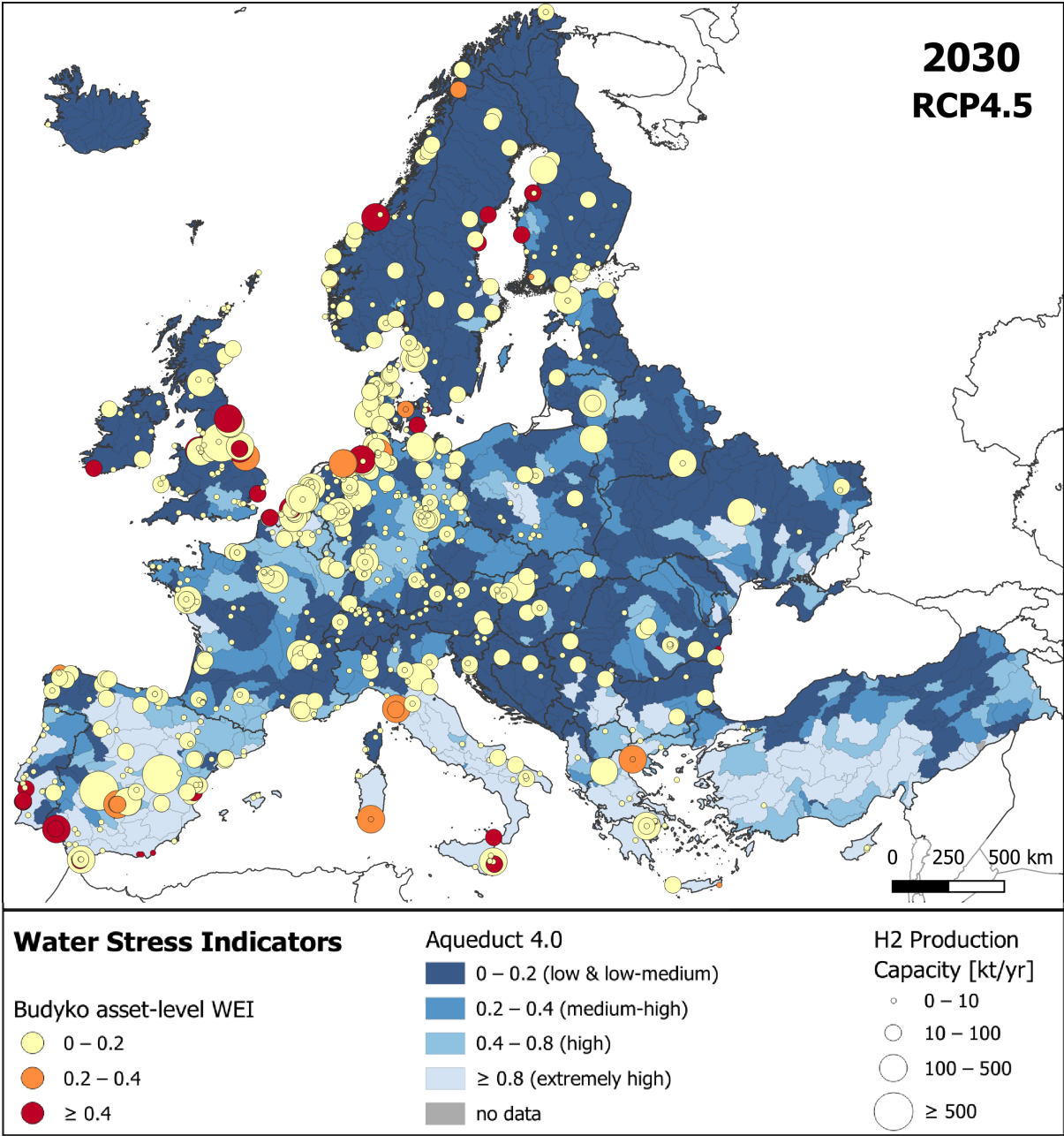
Annex 2. Maps

Figure 6 Map of the fossil and renewable hydrogen production assets located in the EU27 + EFTA + UK + TK and their WEI compared to the local water stress under 2030 emission in current scenario.



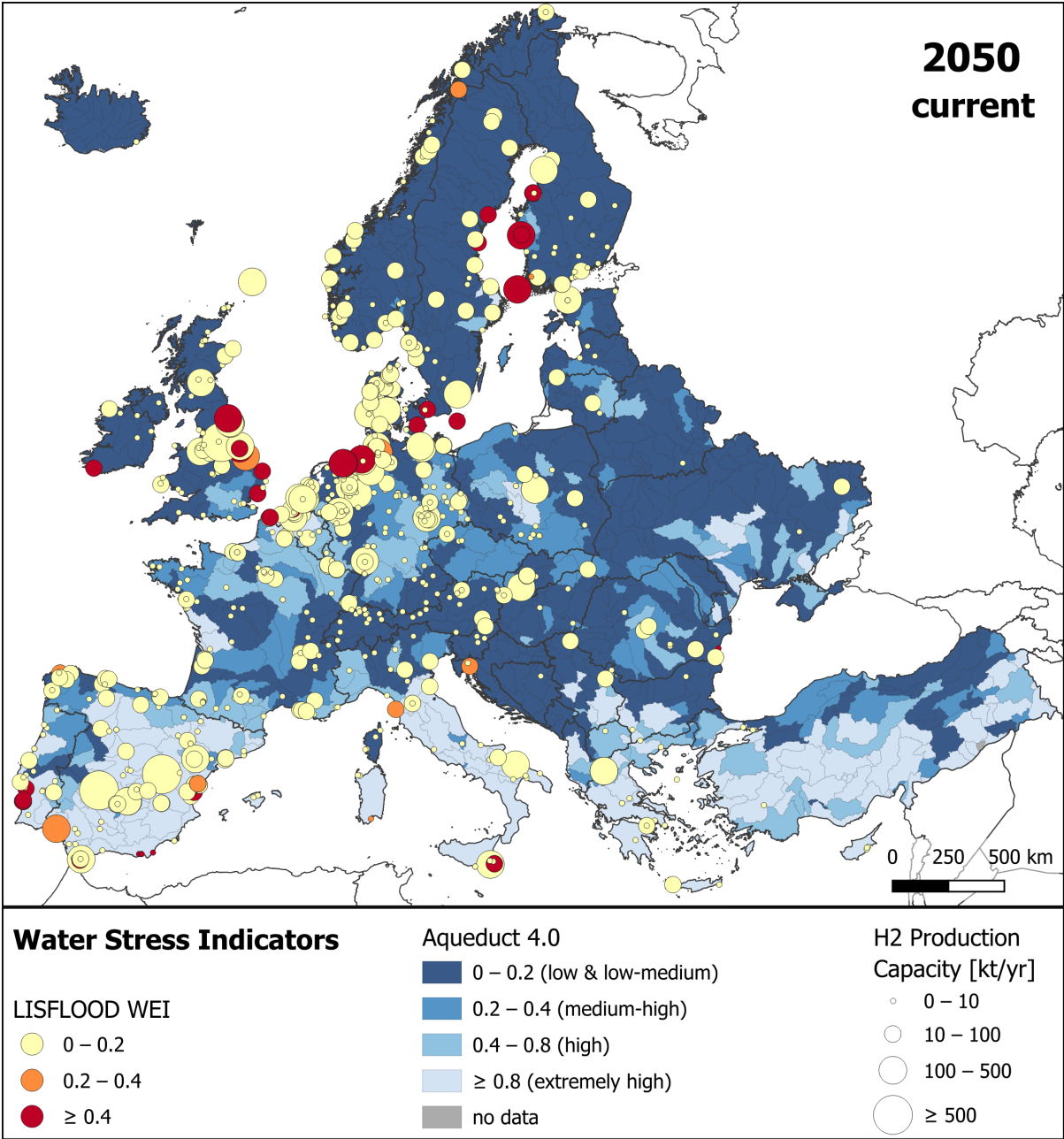
Source: Joint Research Centre analysis (2025)

Figure 7. Map of the fossil and renewable hydrogen production assets located in the EU27 + EFTA + UK + TK and their WEI compared to the local water stress under 2030 intermediate emission (RCP4.5) scenario.



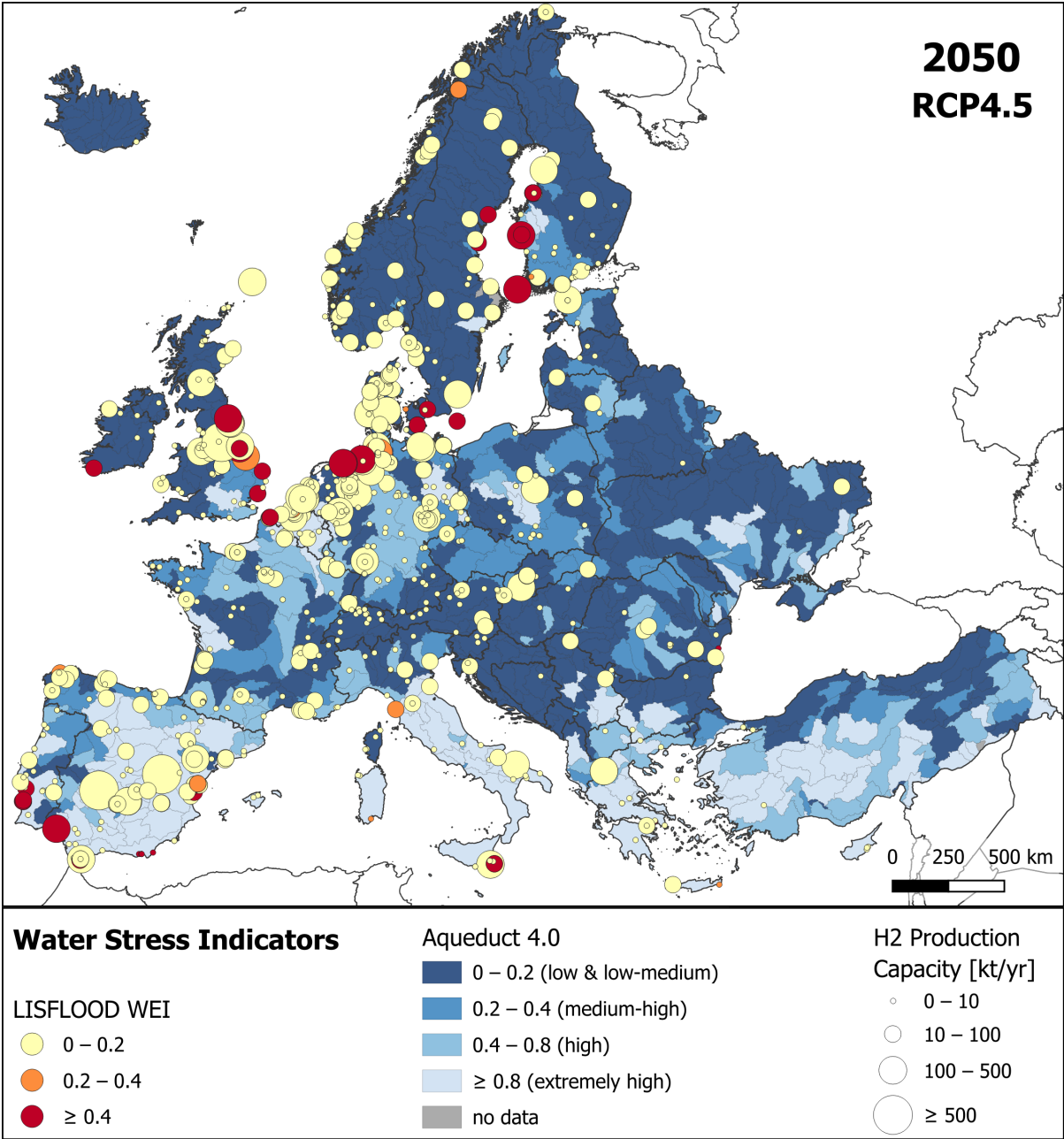
Source: Joint Research Centre analysis (2025)

Figure 8. Map of the fossil and renewable hydrogen production assets located in the EU27 + EFTA + UK + TK and their WEI compared to the local water stress under 2050 emission in current scenario.



Source: Joint Research Centre analysis (2025)

Figure 9. Map of the fossil and renewable hydrogen production assets located in the EU27 + EFTA + UK + TK and their WEI compared to the local water stress under 2050 intermediate emission (RCP4.5) scenario.



Source: Joint Research Centre analysis (2025)

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