

Sustainable Paths for the Use and Management of Water in the Hydrogen Value Chain

Public summary report



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List of Acronyms

AI	Aridity Index
AEL	Alkaline Electrolyser
ASEC	Adiabatic Sonic Evaporation and Crystallization
ATR	Autothermal Reforming
AEM	Anion Exchange Membrane
CAPEX	Capital Expenditure
CHP	Combined Heat and Power
CCUS	Carbon Capture Utilization and Storage
CO₂	Carbon Dioxide
EDI	Electrodeionisation
EHB	European Hydrogen Backbone
EU	European Union
FTE	Full Time Equivalent
FID	Final Investment Decision
DSE	Direct Seawater Electrolysis
GDP	Gross Domestic Product
LCA	Life Cycle Assessment
LCOH	Levelized Cost of Hydrogen
LCIA	Life Cycle Impact Assessment
LISFLOOD	Hydrological model LISFLOOD
NUTS	Nomenclature of Territorial Units for Statistics
PEM	Proton Exchange Membrane
PPA	Power Purchase Agreement
PV	Photovoltaic
RO	Reverse Osmosis
SSP3-7.0	Shared Socioeconomic Pathway 3 – 7.0 – reference scenario
SSP5-8.5	Shared Socioeconomic Pathway 5 – 8.5 – pessimistic scenario
SOEC	Solid Oxide Electrolysis Cell
SMR	Steam Methane Reforming
SPI	Standardized Precipitation Index
TRL	Technology Readiness Level
WEI	Water Exploitation Index
WWTP	Wastewater Treatment Plant
ZLD	Zero Liquid Discharge

Executive Summary

This study was performed to **assess whether the expected expansion of renewable hydrogen production can remain compatible with sustainable water use** across Europe and neighbouring strategic regions, with particular attention to water-stressed areas. Building on the technical, regional and case-study analyses developed, this report provides a consolidated interpretation of the evidence and translates it into **practical conclusions and recommendations** for policymakers, project developers and regional stakeholders.

Renewable hydrogen is often discussed as an energy challenge, but it is also a water-management challenge. The analyses carried out in this study and in previous ones indicate that renewable hydrogen production is not intrinsically water intensive. Yet process water demand alone provides only a partial picture. The **actual water footprint** of a hydrogen project is determined by the **quality of the available water**, the **treatment** required to meet process specifications, the **cooling** system adopted and, crucially, the **local hydrological conditions** in which the plant operates. The study highlights some of the main findings regarding green hydrogen production:

- Renewable electrolysis technologies typically require approximately **9–13 litres of process water per kilogram of hydrogen produced**.
- Cooling systems can increase total water requirements far beyond direct electrolysis demand and often become the dominant determinant of a plant's water footprint.
- Alkaline electrolysis (AEL) and proton exchange membrane (PEM) systems require similar amounts of water for hydrogen generation, their total water footprint depends on the purity level required, the efficiency of treatment systems, cooling configuration and reject-stream management.
- Improvements in electrolyzers' efficiency reduce cooling requirements, making renewable electrolysis increasingly competitive not only on carbon emissions but also on water use.
- The choice of water source (freshwater, brackish water, seawater or other alternative water sources) strongly influences treatment requirements, recovery rates and overall water withdrawal
- Seawater and treated wastewater emerge as one of the most promising options from a circular-economy perspective because they can reduce pressure on conventional resources while supporting industrial symbiosis and resource recovery.

At the scale of Europe as a whole, **the projected expansion of renewable hydrogen does not appear likely to become a major driver of water demand**. Even under ambitious deployment scenarios towards 2050, the additional water withdrawals associated with hydrogen production remain modest compared with those of established sectors, generally amounting to around **1.5% or less of existing withdrawals**. However, this aggregate picture should not obscure important local realities. In water-stressed basins, where environmental flows are already constrained and competition among users is high, a single large hydrogen facility may exert a disproportionate influence on available resources: **while hydrogen remains a relatively minor water user in aggregate terms, its effects may become decisive at local scale, particularly in regions already exposed to water scarcity**.

Hydrogen's impact on water resources is small in aggregate, but it can be decisive locally.

To understand these dynamics, the study combined technological assessment, continental-scale mapping and project-level analysis. The assessment examined **five representative Hydrogen Valleys** located in **Spain, Greece, France, Slovakia and Croatia**. Across these different geographical contexts, a consistent pattern emerged: **the sustainability of hydrogen production depends less on the quantity of water required by electrolysis itself than on the interaction between water sourcing, treatment requirements, cooling needs and basin-level water availability**. Consequently, **projects with similar hydrogen output may have markedly different implications for local water systems**.

The technical analysis further highlights the importance of considering **hydrogen production as an integrated water-management system**. Water source selection strongly influences treatment needs,

recovery rates and overall withdrawals, while cooling often becomes a more significant determinant of plant-level water use than electrolysis itself. The study also identifies an important performance threshold: as electrolyser **efficiency** improves from around **70% to 80%**, cooling requirements decline sufficiently to reverse the relative water-performance advantage often attributed to fossil-based hydrogen pathways. In this sense, advances in electrolysis efficiency improve not only carbon performance but also water performance.

Environmental assessment confirms that water is only one part of the sustainability equation. The life-cycle assessment shows that **the carbon intensity of renewable hydrogen is driven primarily by the electricity source used for electrolysis**. At the same time, choices intended to reduce water consumption can introduce additional trade-offs. For example, desalination and dry cooling can significantly reduce dependence on freshwater resources but may increase energy consumption and, depending on the electricity mix, associated greenhouse-gas emissions. Sustainable hydrogen deployment therefore requires managing a broader **water–energy–carbon trade-off** rather than optimizing a single indicator in isolation.

To better understand this water–energy–hydrogen nexus, a visual analytics web-tool has been developed to support evidence-based planning, the **Clean Hydrogen Explorer**¹. This publicly accessible interactive platform combines hydrological, energy and hydrogen-development datasets in an interactive environment, allowing users to explore regional water availability, renewable energy potential and planned hydrogen capacity under both current and future climate conditions.

Overall, the study concludes that renewable hydrogen can be deployed in a manner compatible with sustainable water management, but only if water considerations are integrated into planning from the outset. Water source selection, treatment systems, cooling technology and local hydrological conditions should be treated as strategic design parameters rather than secondary engineering choices.

The evidence does not suggest that water availability will become a universal barrier to renewable hydrogen deployment. However, it does demonstrate that water cannot be regarded as an afterthought. Future hydrogen projects should be planned using a water-aware approach that combines basin-level assessment, climate-resilience considerations, alternative water sourcing and efficient cooling and treatment solutions. The most successful projects will be those that align hydrogen production with local hydrological realities, ensuring that decarbonisation objectives can be achieved without compromising water security, ecosystem protection or the needs of other users.

¹ Link to the url: <https://cleanh2.soft-water.it/>

1 BACKGROUND AND FRAMING

1.1 Why water matters for hydrogen

The accelerated deployment of renewable hydrogen has become a central pillar of European decarbonisation strategies. Initiatives such as REPowerEU and the European Hydrogen Strategy envisage a rapid scale-up of electrolysis capacity to support industrial decarbonisation, energy security and the integration of renewable energy sources. As hydrogen projects move from demonstration scale to large industrial facilities, access to suitable water resources is increasingly becoming a strategic siting consideration rather than a secondary operational issue.

The relationship between hydrogen and water extends way beyond the water directly consumed during electrolysis. Water quality requirements, treatment processes, cooling systems and local hydrological conditions all influence the overall water footprint of a plant and its interaction with surrounding water resources.

At the same time, many regions that are expected to play an important role in future hydrogen production are already experiencing increasing pressure on water resources due to climate change, growing demand and more frequent droughts. Understanding how hydrogen deployment interacts with water availability is therefore essential to ensure that decarbonisation objectives can be achieved while safeguarding water security and ecosystem resilience.

1.2 Study Scope and Objectives

To address the demands linked to the trade-off between hydrogen and water, the **Clean Hydrogen Partnership** launched the study Sustainability of Water Use and Management in Renewable Hydrogen Production under tender CLEANH₂/2024/OP/0003. The study has been developed by a consortium composed of RINA Consulting S.p.A., covering the role of consortium leader, and ARAGON HYDROGEN FOUNDATION (FHa) and Softwater S.r.l., acting as consortium members.

The study aims to deliver a comprehensive technical assessment to address the challenges of optimizing water use in renewable hydrogen production. Geographically, the study concentrated on European Member States, Horizon Europe Associated Countries (excluding Canada and New Zealand), and North African nations along the Mediterranean. To explore the local implications of hydrogen deployment on water resources, **five representative Hydrogen Valleys across Spain, Greece, France, Slovakia and Croatia** were examined. The study included seasonal insights for key timeframes (2025, 2030, 2040, and 2050, aiming for the NUTS2 level or lower).

To achieve this, the following four main tasks have been defined and implemented over a one-year project duration.

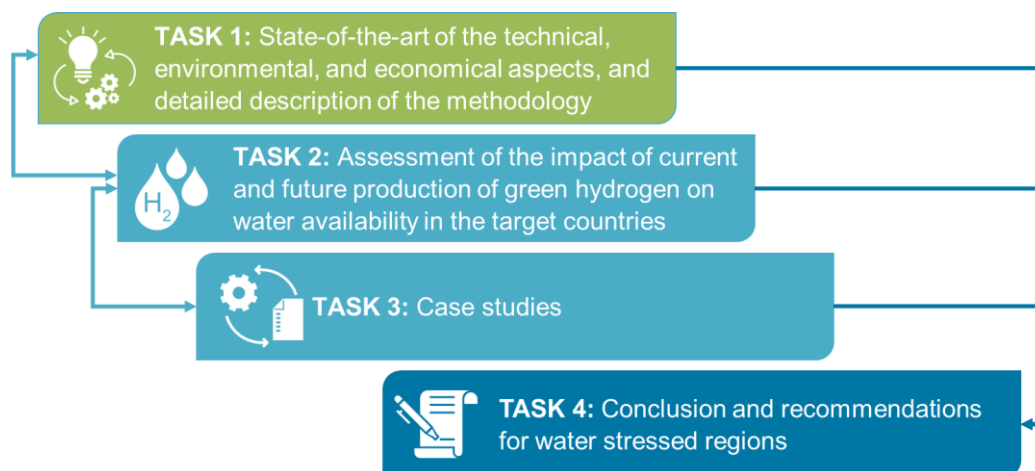


Figure 1-1: Overview of key project tasks

The study was developed through a **progressive analytical approach structured around four complementary tasks**.

- **Task 1 established the state of the art and the methodological foundation of the study.** It reviewed the main technical, environmental and economic aspects of renewable hydrogen production, including hydrogen production technologies, water sources, treatment requirements, cooling configurations, water-related constraints and the methodological framework used throughout the assessment.
- **Task 2 assessed the impact of current and future green hydrogen production on water availability across the target countries.** It combined hydro-meteorological, renewable energy and hydrogen-development datasets to examine present and future water conditions, renewable energy potential and hydrogen deployment under different climate scenarios, supporting a consistent comparison across Europe and neighbouring regions.
- **Task 3 translated the regional assessment into project-level evidence through five representative case studies in Spain, France, Greece, Slovakia and Croatia.** The analysis examined local and seasonal water constraints, basin-level availability, operational resilience, environmental performance and possible water-management strategies under different territorial and climatic conditions.
- **Task 4 consolidated the evidence generated in the previous tasks and developed conclusions and recommendations for water-stressed regions.** It assessed the broader implications of future hydrogen deployment, identified the main risks and trade-offs, and formulated practical guidance on water-aware siting, mitigation strategies, water management in large-scale plants, the use of seawater and lower-quality water sources, and circular approaches to water reuse.

This **Summary of the Study** brings together the results of all four tasks within a **single, coherent and accessible narrative**. Its purpose is to present the study's main technical findings, regional and case-study evidence, and final recommendations in an integrated form, clarifying what the results mean for future renewable hydrogen deployment.

By connecting the **technical, regional, project-level and strategic dimensions** of the study, the Summary aims to support **policymakers, project developers and regional stakeholders** in integrating water considerations into hydrogen planning from the earliest stages. It highlights where the main risks and trade-offs arise and how hydrogen deployment can contribute to decarbonisation objectives while protecting **water security, ecosystem needs and existing water users**.

1.3 Technology scope

The assessment of water uses in hydrogen production developed in this study is based on a differentiated technological framing, reflecting both the current maturity of hydrogen production routes and their relevance for near- and medium-term deployment. The primary focus is placed on **renewable hydrogen production technologies as Alkaline Electrolysis (AEL) and Proton Exchange Membrane Electrolysis (PEM)**, which currently represent the most mature and industrially relevant technologies for renewable hydrogen production. As highlighted in the study, these are the only water electrolysis technologies that have already reached a level of maturity compatible with deployment in large-scale hydrogen production plants, while other electrolysis routes such as **solid oxide electrolysis cells (SOEC)** and **anion exchange membrane electrolysis (AEM)** remain at a pre-commercial stage and are therefore better interpreted as emerging alternatives rather than immediate reference solutions for broad market uptake.

Among mature electrolysis technologies, AEL and PEM have similar direct water requirements but differ significantly in system configuration. AEL is a robust and cost-effective technology with lower feedwater quality requirements, whereas PEM offers greater flexibility, higher current densities and a more compact design, making it well suited to variable renewable electricity. However, PEM requires ultrapure water and relies on noble-metal catalysts, resulting in more demanding treatment systems

and higher costs. Consequently, while process-water demand remains broadly comparable, technology choice strongly influences water treatment needs, ancillary systems and overall plant performance.

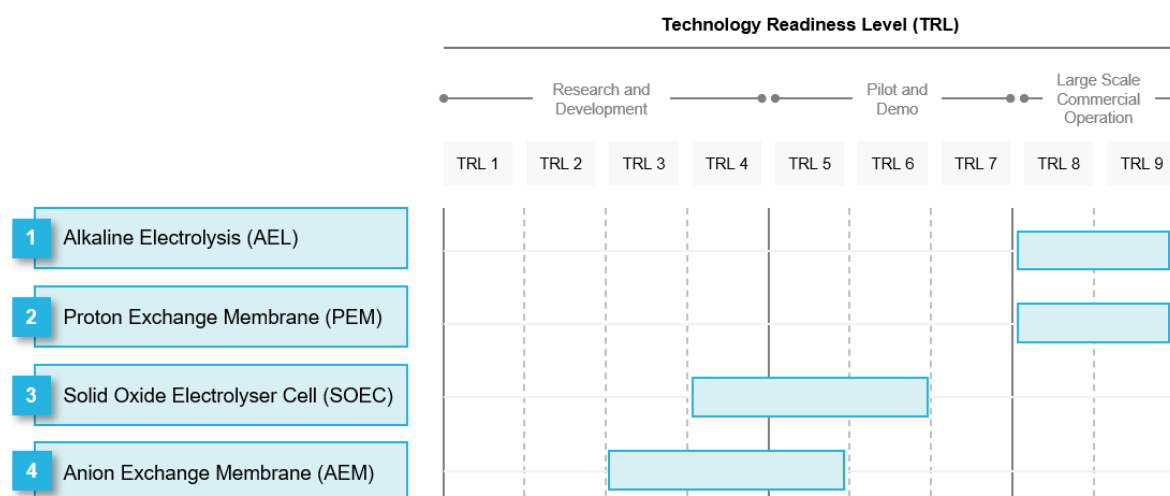


Figure 1-1: Renewable hydrogen production technologies TRLs

The analysis also considers **steam methane reforming (SMR)** and **autothermal reforming (ATR)** with carbon capture and storage as comparative benchmarks. These pathways generally require less high-purity process water than electrolysis, but their overall performance remains strongly influenced by cooling requirements and carbon-capture systems. **SMR + CCS** represents the most mature fossil-based benchmark, while **ATR + CCS** may offer lower water intensity due to more efficient carbon capture. Their role is not to identify a preferred pathway, but to provide a reference for comparing the water implications of fundamentally different hydrogen production routes.

Beyond mature electrolysis and fossil-based pathways, the study also considers **emerging technologies** designed to reduce dependence on freshwater through the use of **alternative water sources**, including seawater and treated wastewater. **Direct seawater electrolysis (DSE)** is particularly attractive for arid and coastal regions, as it could potentially eliminate the need for freshwater abstraction. However, the technology remains at an early stage (**TRL 2–3**) and faces significant challenges related to chlorine evolution, corrosion, scaling and catalyst stability, making industrial deployment unlikely in the near term.

A more promising option is represented by **wastewater-based hydrogen pathways**, which support circular water management and resource recovery. Advanced treatment systems can achieve recovery rates of up to **90–95%**, while several biochemical, electrochemical, photonic and thermal routes are being explored to produce hydrogen from wastewater streams. Nevertheless, these technologies remain largely experimental (**TRL 3–5**), with limited operational experience and uncertain scalability. Although they offer significant long-term potential for improving water resilience, their maturity remains well below that of conventional fossil routes and mature electrolysis technologies.

The same applies to other low-carbon process innovations, such as **methane cracking**, **chemical looping** and **concentrating solar fuels (CSFs)**. These technologies are being developed to reduce carbon emissions and improve process efficiency, but their current Technology Readiness Levels remain generally low, typically between **TRL 3 and 7**, and their industrial uptake will depend on further advances in materials, process stability, integration with renewable energy systems and cost reduction. In this context, the technological landscape emerging from the study is relatively clear. On the one hand, **AEL and PEM** define the realistic basis for evaluating water use in renewable hydrogen deployment over the coming years. On the other hand, **SMR and ATR with CCS** provide useful comparative references for understanding broader water and decarbonisation trade-offs. Finally, the various **emerging pathways** point toward potentially more circular and water-resilient futures but remain insufficiently mature to serve as the main analytical basis for present deployment strategies.

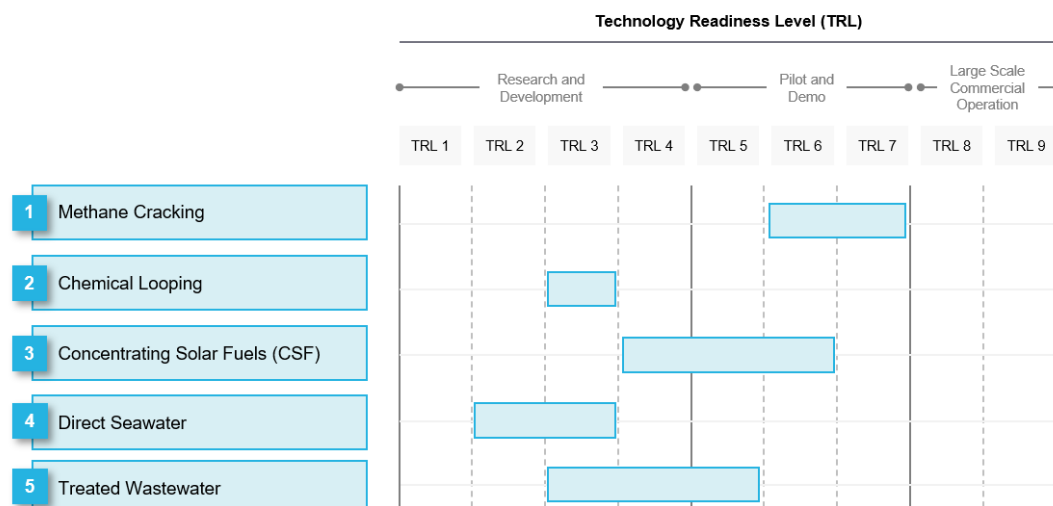


Figure 1-2: Low-Carbon innovative hydrogen production technologies TRLs

Overall, this technological framing is important because it shows that the water dimension of hydrogen production cannot be assessed in isolation from technology maturity and system readiness. Mature electrolysis systems already allow large-scale deployment but remain dependent on high-quality water and supporting treatment infrastructure; fossil-based routes may exhibit lower direct process water requirements but remain constrained by carbon capture integration and broader sustainability limits; and emerging water-based pathways offer strong theoretical potential, especially in terms of reduced freshwater dependency, but still require substantial development before they can contribute at scale. For this reason, the present study adopts **AEL and PEM as the core analytical reference**, while using fossil-based and emerging technologies to contextualise the water implications of hydrogen production across a broader technological spectrum.

Table 1-1: Main hydrogen production technologies

Technology	Main production route	TRL	Main water-related implication
PEM	Renewable electrolysis	8–9	Low direct process water demand , but very high feedwater purity requirement and more complex treatment.
AEL	Renewable electrolysis	8–9	Slightly higher direct process water demand than PEM , but lower feedwater purity requirement.
SOEC	Emerging renewable electrolysis	4–6	Higher direct water demand , but no dedicated water cooling and partial water reuse potential.
AEM	Emerging renewable electrolysis	3–5	Process water demand comparable to PEM , with lower maturity and still uncertain large-scale performance.
DSE	Emerging water-based renewable route	2–3	Strong freshwater-saving potential , but major issues with chlorine evolution, corrosion and system stability.
Wastewater-based	Emerging circular water-based route	3–5	High water reuse potential and circularity benefits, but limited validation and uncertain scalability.
ATR + CCS	Fossil-based reforming with carbon capture	5–6	Low direct process water demand , but significantly higher total water use once cooling and CCS are included.
SMR + CCS	Fossil-based reforming with carbon capture	5–9	Low direct process water demand , but high cooling and CCS-related water demand at system level.

2 WATER NEEDS FOR RENEWABLE HYDROGEN PRODUCTION

This section **presents the main findings of the study** concerning the relationship between renewable hydrogen production and water use and management. It brings together the technical, environmental and regional evidence developed throughout the study to provide a consolidated view of the main factors influencing the water dimension of hydrogen deployment.

The analysis covers three complementary dimensions:

- it examines **water use in hydrogen production systems**, considering the main technologies addressed in the study and the distinction between direct process water demand and the broader system-level water requirements associated with treatment and cooling.
- it considers **the role of water sources, treatment requirements and management options**, including the implications of using conventional and non-conventional sources under different operating conditions.
- it reviews the broader **sustainability implications of hydrogen deployment across regions**, taking into account environmental, socio-economic and comparative aspects relevant to future planning.

Taken together, these findings show that the relevance of water in renewable hydrogen production cannot be assessed solely on the basis of the theoretical water demand of electrolysis. It depends on a wider set of interrelated factors, including the production technology, the origin and quality of the available water source, the treatment train required to meet process specifications, the cooling configuration adopted, and the territorial context in which hydrogen production is developed.

2.1 Water quantity by production technology

The comparison of hydrogen production technologies cannot be limited to direct process water demand alone. As highlighted in chapter 1.3, mature electrolysis routes such as **PEM** and **AEL** show relatively similar process-water requirements and remain within the same overall order of magnitude. However, these values describe only the water directly involved in hydrogen generation and do not capture the full water requirement of the production system. Once the perspective is extended from the electrolyser itself to the entire plant configuration, the comparison between technologies changes, because the overall water impact also depends on the volumes that must be abstracted, conditioned, circulated and managed in order to support plant operation.

In this broader perspective, the distinction between **water consumption** and **water withdrawal** becomes essential: the former refers to the share of water effectively lost from the original source, while the latter refers to the total volume that must be abstracted to supply the system. This distinction is particularly relevant when comparing technologies such as PEM and AEL, since a slightly lower process-water demand does not necessarily translate into a lower overall system-level requirement. In practice, the final balance is strongly influenced by the quality of the water required by the process, the intensity of the treatment chain needed to reach that quality and thus the related water source, and the auxiliary services necessary to operate the plant. For this reason, system-level water impacts must be assessed by considering not only the process itself, but also the wider plant configuration through which water is sourced, prepared and used.

From the perspective of **direct process water demand**, the study shows that the main hydrogen production technologies considered do not perform in the same way, although the differences are more nuanced than a purely theoretical reading might suggest. Among the mature renewable routes, **alkaline electrolysis (AEL)** and **proton exchange membrane electrolysis (PEM)** remain within a relatively similar range. Indicative values reviewed in the study show a direct process water requirement of around **11.1 L/kg H₂** for AEL and **9.2 L/kg H₂** for PEM. These values confirm that, among the mature electrolysis technologies, neither route offers a decisive advantage in purely process-related water consumption, even if PEM tends to display a slightly lower water footprint in hydrogen generation. For emerging electrolysis technologies, the evidence remains less consolidated. **AEM** appears broadly comparable to PEM in terms of process water demand, although with lower technological maturity and less robust large-scale evidence. **SOEC** shows a higher direct water requirement, around **12.8 L/kg H₂**, although part of this amount, approximately **3.8 L/kg H₂**, can be internally recovered and reused.

Overall, the findings suggest that renewable electrolysis technologies tend to remain within the same order of magnitude, roughly **9-13 L/kg H₂**, when only direct process demand is considered.

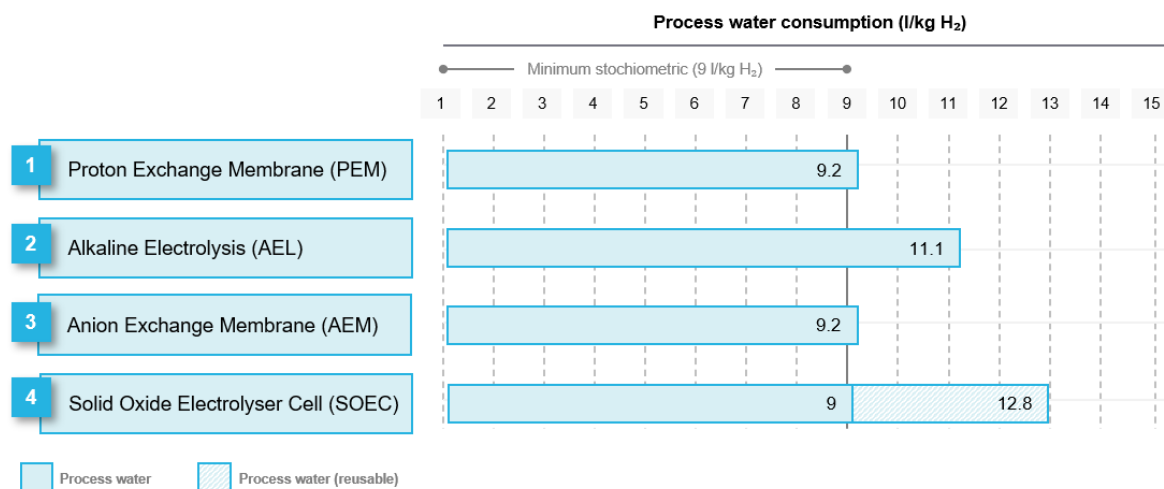


Figure 2-1: Process water consumption for electrolysis

A broader comparison with non-renewable benchmark routes confirms that direct process demand alone does not provide a sufficient basis for judging the overall water performance of hydrogen production pathways. In direct process terms, fossil-based reforming routes generally require less high-purity water than electrolysis systems, since hydrogen is derived from hydrocarbon feedstocks rather than from water splitting. Indicative values reported in the study show approximately **5.2 L/kg H₂** for **steam methane reforming (SMR)** and **2.6 L/kg H₂** for **autothermal reforming (ATR)**, the latter benefiting from internal water recovery via syngas condensation. By contrast, **coal gasification** remains considerably more water-intensive, often exceeding **30 L/kg H₂**, mainly due to coal properties and the need for extensive gas clean-up. These comparisons show that renewable electrolysis is not necessarily the lowest-demand option when considering process water alone. At the same time, they also confirm that the direct process requirement captures only one part of the overall water dimension of hydrogen production. For this reason, the interpretation of these values must be complemented by the broader analysis of feedwater requirements, treatment needs and system configuration presented in the following subsection.

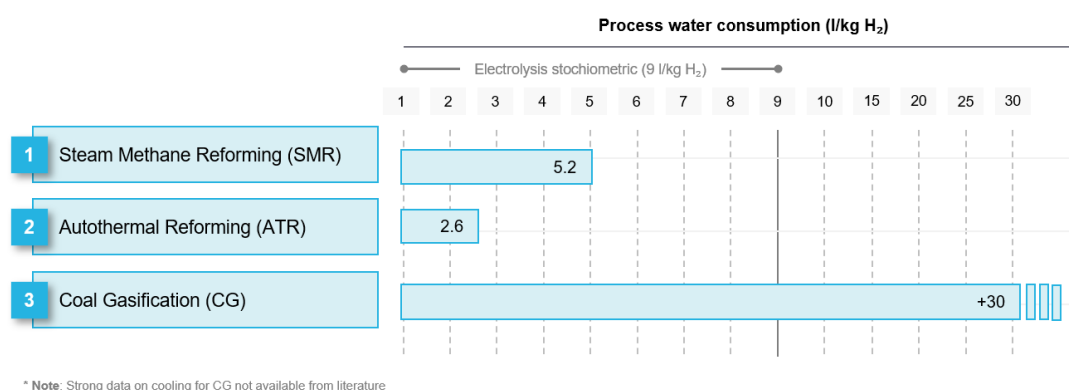


Figure 2-2: Process water consumption for low-carbon hydrogen production technologies

However, direct process **water demand alone does not explain the actual water footprint of hydrogen production systems**, which also depends on feedwater quality requirements, treatment intensity and cooling configuration. These aspects are discussed in the following subsections.

2.1.1 Water sources and their trade-offs

The selection of the water source is one of the main factors shaping the overall water performance of hydrogen production systems. Water sources differ not only in terms of physical availability, but also

with respect to salinity, impurity content, accessibility, infrastructure requirements, treatment intensity and environmental implications. As a result, the same hydrogen production technology may face very different water-related conditions depending on whether it is supplied by freshwater, brackish water, seawater or treated wastewater. This is particularly relevant in regions affected by water scarcity, where the use of conventional freshwater sources may increase competition with agriculture, industry and municipal demand, while the use of non-conventional sources may reduce pressure on freshwater resources but require more complex treatment and management solutions. In this perspective, water sourcing cannot be treated as a secondary design choice, but rather as a structural component of hydrogen project feasibility and sustainability.

Water sources can be considered both according to their **origin** (tap water, groundwater, surface freshwater, or seawater) and to their **salinity** (freshwater, brackish water, and seawater), the latter being one of the main parameters determining treatment needs and overall feasibility. From this perspective, the main source categories include **freshwater**, **brackish water** and **seawater**, with additional attention given to **reclaimed wastewater** and, where relevant, **rainwater** as a complementary option. This classification is important because salinity directly affects osmotic pressure, treatment complexity, energy demand and the generation of reject streams such as brine. In practical terms, moving from freshwater to brackish water and then to seawater generally implies a progressive increase in treatment intensity, lower recovery ratios and greater operational complexity, even when the final process-grade water demand remains unchanged. For this reason, the classification of water sources by salinity provides a useful technical basis for interpreting both treatment requirements and broader water management implications in hydrogen production systems.

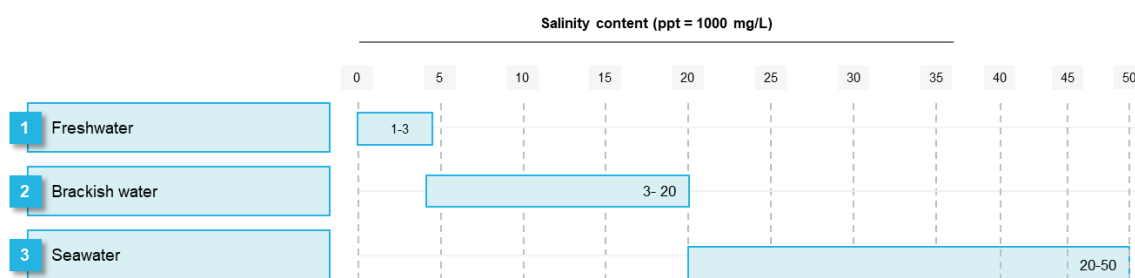


Figure 2-3: Classification of water sources according to the salinity content

- **Freshwater** remains the most straightforward option from a treatment perspective, since its lower salinity reduces purification complexity and generally allows higher recovery efficiencies. In many cases, freshwater can be supplied through existing infrastructure, such as drinking water or surface and groundwater abstraction systems, and may therefore appear as the most practical solution from a purely technical point of view. However, its use is often the most sensitive in environmental and territorial terms. In water-stressed regions, dependence on freshwater may generate direct competition with other users, especially agriculture and municipal supply, and may therefore become **difficult to justify from a sustainability perspective, even when treatment requirements are relatively limited**. For this reason, freshwater may be technically convenient, but it is not always the most appropriate option for hydrogen production in areas where water scarcity is already a structural constraint.
- **Brackish water** represents an intermediate category that is often particularly relevant for hydrogen deployment in water-constrained contexts. **Compared with seawater, it generally requires less energy-intensive treatment** and can achieve more favourable recovery ratios, making it potentially more attractive from both an operational and economic perspective. At the same time, its use is not neutral from an environmental point of view. Brackish resources are frequently associated with vulnerable aquifers or transitional ecosystems, and excessive abstraction may contribute to groundwater depletion, contamination, salinity increase, land subsidence or saltwater intrusion in coastal areas. Their use therefore requires careful hydrogeological assessment, monitoring and site-specific management. When properly managed, brackish water can reduce dependence on freshwater and complement other non-conventional sources, but **its long-term viability depends on maintaining the ecological and quantitative balance of the aquifers** from which it is drawn.

- **Seawater** is the most abundant source and is particularly relevant for coastal and island contexts, where its availability may offer a clear strategic advantage over increasingly constrained freshwater resources. From a resource availability standpoint, seawater may therefore appear highly attractive for future hydrogen deployment, especially in arid regions or in coastal hydrogen valleys. However, its use also implies the highest treatment burden among conventional water sources. Because of its high salinity, **seawater requires desalination and subsequent polishing** before it can reach the purity needed by electrolysis systems. This results in greater energy demand, lower recovery rates and larger generation of concentrated saline reject streams. In other words, seawater may reduce direct dependence on freshwater, but it does so by shifting the challenge toward treatment efficiency, brine management and broader environmental trade-offs. For this reason, seawater should be interpreted less as a universally preferable solution and more as a technically viable but treatment-intensive option whose **sustainability depends strongly on local conditions and system integration**.
- **Reclaimed wastewater** is one of the **most interesting options from the perspective of circular water management**. Unlike freshwater or seawater, its relevance lies not only in resource availability, but also in its capacity to link hydrogen production with water reuse, pollution reduction and local industrial symbiosis. In territories where urban or industrial wastewater streams are available in sufficient quantity and continuity, treated wastewater may reduce pressure on conventional water resources and support a more circular water supply chain. At the same time, its use is **highly dependent on local quality characteristics**, regulatory conditions and treatment reliability. Wastewater is therefore not a universal substitute for conventional water sources, but it can become a particularly valuable option where hydrogen projects are embedded in wider territorial strategies aimed at reuse and resource recovery. This is also consistent with the broader technological perspective emerging from the study, which identifies wastewater-based pathways as one of the most promising future directions for reducing freshwater dependency, even though many of the more advanced hydrogen-from-wastewater routes **remain at relatively low maturity**.
- Finally, **rainwater** may play a complementary role, particularly in urban or industrial settings where harvesting systems can be integrated into broader blue-green or climate-resilient infrastructure. However, its contribution remains inherently limited by seasonal variability, storage constraints and local surface conditions. For this reason, rainwater is **best understood not as a primary water source for hydrogen production, but as a supplementary resource** that may contribute to reducing pressure on conventional supplies in specific local contexts.

Taken together, these distinctions show that water source selection is not a neutral upstream choice, but one of the central variables shaping the technical and environmental configuration of hydrogen production systems. Freshwater offers operational simplicity but may intensify local competition; brackish water may provide an effective compromise but requires careful aquifer management; seawater offers large availability but shifts the burden toward desalination and brine handling; treated wastewater supports circularity but depends on local treatment chains and quality reliability; and rainwater remains a minor complementary source. On this basis, the assessment of water sources must be coupled with a clear understanding of the quality requirements imposed by the selected hydrogen production technology, which determine the necessary treatment train and, ultimately, the overall system-level water demand.

2.1.2 Feedwater quality and treatment

Feedwater quality requirements for electrolysis technologies

While the direct water demand of electrolysis technologies remains relatively similar, **feedwater quality requirements** vary considerably and strongly influence treatment needs and overall system configuration. Water purity affects electrolyser performance, durability and efficiency, making source

suitability dependent not only on availability but also on the treatment required to meet process specifications.

Among mature technologies, **PEM electrolyzers** have the most stringent requirements, typically requiring **ultrapure deionised water (ASTM Type II, <0.1 $\mu\text{S}/\text{cm}$)** to prevent membrane degradation and performance losses. **AEL systems** are more tolerant and can generally operate with water quality around **5 $\mu\text{S}/\text{cm}$** , reducing treatment complexity compared with PEM. For emerging technologies, **AEM electrolyzers** appear to have intermediate requirements, being less restrictive than PEM but more demanding than AEL. **SOEC systems**, which operate with steam at high temperature, are subject to different constraints: they are generally less sensitive to ionic purity but remain vulnerable to particulate contamination and gaseous impurities in the steam feed.

These differences mean that technologies with similar process-water demand may require substantially different treatment trains and therefore exhibit different system-level water implications.

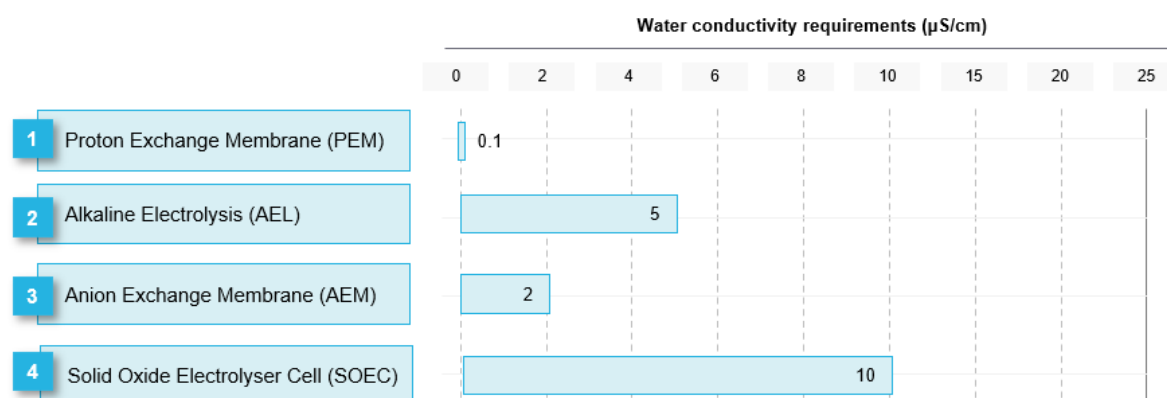


Figure 2-4: Feedwater quality requirements for electrolysis technologies

Taken together, these findings confirm that the water dimension of hydrogen production cannot be described only in volumetric terms. A technology requiring slightly less process water may still generate a more demanding overall water balance if it depends on more intensive purification and polishing stages. Conversely, a more tolerant technology may reduce treatment complexity while still requiring careful conditioning of the incoming water. For this reason, **the assessment of hydrogen production systems must consider not only how much water is needed, but also what quality of water is needed**, since feedwater purity is one of the main factors connecting water source selection to treatment intensity, recovery performance and overall plant sustainability.

Treatment intensity and recovery ratios

Once the quality requirements of the main electrolysis technologies are taken into account, the assessment of water use must also consider the **intensity of the treatment chain** required to convert a given source into process-grade water. This chain is typically structured in three sequential stages: **pre-treatment** (filtration, coagulation, ultrafiltration, activated carbon and softening), which removes suspended solids, organics and hardness but **not the dissolved salts**; **desalination** (most commonly reverse osmosis - RO), which is the stage that actually reduces salinity; and **final polishing** (electrodeionisation - EDI, or ion exchange), which achieves the ultrapure quality required by the electrolyser.

Treatment requirements increase with the salinity and impurity content of the source. Freshwater generally requires only limited conditioning. **Brackish water** typically relies on filtration, RO and EDI, while **seawater** and **reclaimed wastewater demand more complex pre-treatment** (and, for seawater, often a two-pass RO) before final polishing. A key point is that **the recovery ratio of the overall chain is governed primarily by the desalination stage**: pre-treatment and polishing (EDI) operate at high and relatively stable recovery rates (around 90–95%), whereas RO recovery falls markedly as feed salinity increases — from roughly 70–85% for freshwater to about 30–50% for seawater, where a preliminary RO step (hereby called SWRO) is needed to reduce the salinity of the incoming seawater to a level suitable for a subsequent RO stage. Because the dissolved-salt load can only be removed by desalination itself, and cannot be eliminated upstream by pre-treatment, **more**

saline sources inevitably yield less usable water per litre abstracted. As treatment intensity increases, so do water losses, energy consumption and abstraction requirements, meaning that the volume withdrawn from the source can be significantly higher than the volume ultimately supplied to the electrolyser.

Figure 2-5, Figure 2-6 and Figure 2-7 illustrate conventional treatment trains for freshwater, brackish water and seawater, respectively.

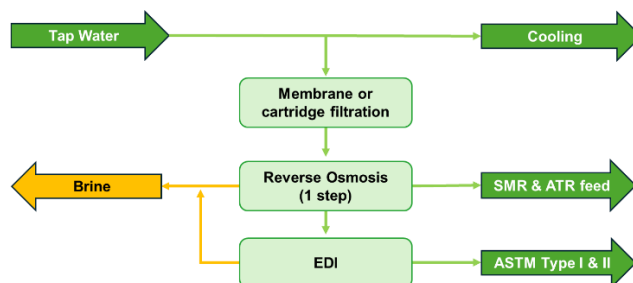


Figure 2-5: Conventional treatment train from tap water

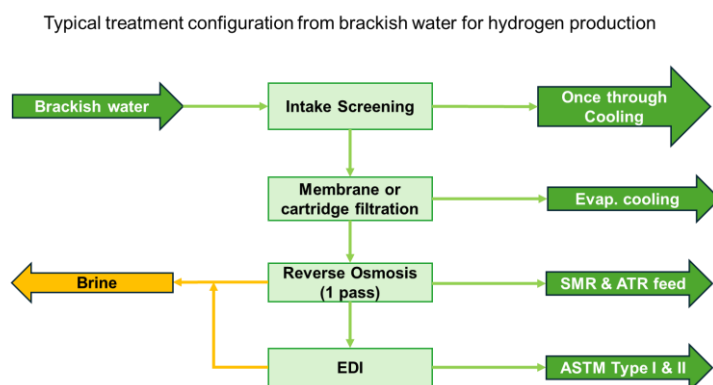


Figure 2-6: Conventional treatment train from brackish water

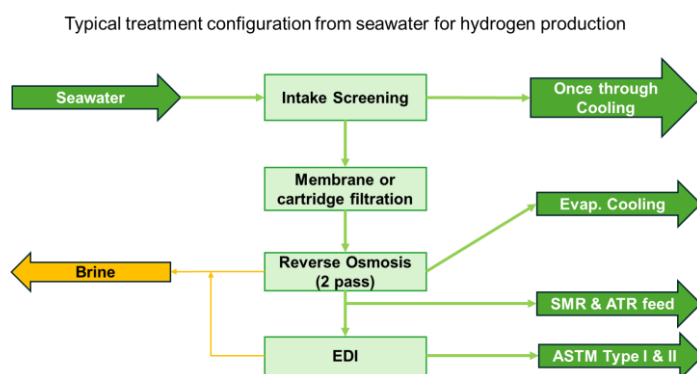


Figure 2-7: Conventional treatment train from seawater

In this context, the concept of recovery ratio becomes central. **Recovery ratio expresses the share of incoming raw water that is successfully converted into usable treated water**, while the remaining fraction is discharged as reject stream, concentrate or brine. Because hydrogen production relies on multi-stage treatment trains rather than single technologies, recovery performance depends on both the water source and the final purity required by the electrolyser. As a result, the same process-water demand can correspond to very different abstraction requirements.

As highlighted above, the desalination stage is the main factor governing the overall recovery ratio of the treatment chain. The most widely adopted desalination technologies are **Reverse Osmosis (RO)** and **Electrodialysis (ED)**, both membrane-based and best suited to low-to-medium salinity waters, and the thermal processes **Multi-Stage Flash (MSF)** and **Multi-Effect Distillation (MED)**, which are more appropriate for high-salinity feeds like seawater. Among these, RO is by far the most versatile and the reference option for hydrogen production. The **Table 2-1** reports the recovery ratios of these technologies for different water sources, showing how they decrease as feed salinity increases — most evidently for RO. In general, due to its limited salinity, **freshwater** offers the highest recovery ratios and the lowest treatment intensity, **brackish water** occupies an intermediate position and may provide a useful compromise in water-stressed regions, while **seawater** is associated with the lowest recoveries and the highest treatment burden. In the latter case, larger abstraction volumes and the generation of concentrated brine streams become important operational and environmental considerations.

Table 2-1: Recovery Ratio for different water treatment trains

Water Source	Treatment train	Filtration	SWRO	RO	EDI	Overall
Freshwater	RO + EDI	–	–	0,73	0,93	0,68
Brackish	FILTR + RO + EDI	0,96	–	0,73	0,93	0,65
Seawater	FILTR + SWRO* + RO + EDI	0,96	0,43	0,73	0,93	0,28

* **SWRO**: Due to the higher salinity of seawater compared with freshwater and brackish water, seawater treatment requires an additional desalination step before final polishing. In this treatment train, the first reverse osmosis stage is identified as Seawater Reverse Osmosis (SWRO). Its function is to reduce the salinity of the incoming seawater to a level suitable for a subsequent RO stage, which further refines the water quality before EDI polishing.

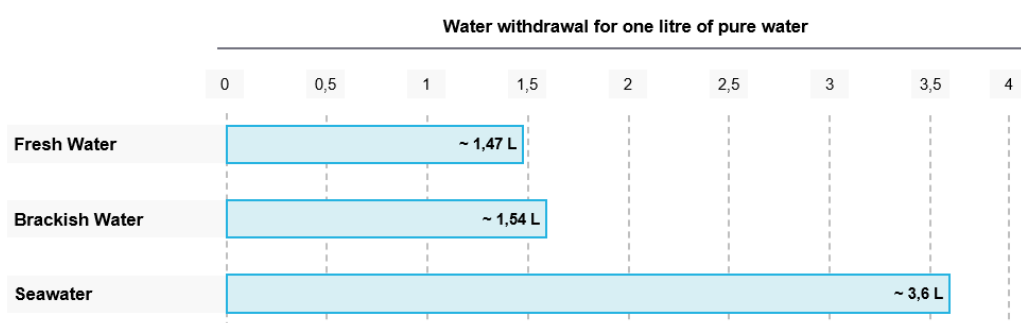


Figure 2-8: Water withdrawal to produce 1L of pure water, starting from different water sources

This has important implications for the interpretation of water demand in hydrogen production systems. A source with abundant physical availability does not necessarily translate into a favourable water balance if the treatment chain required to make it usable is highly inefficient. Conversely, a source with more limited availability may still be attractive if it allows high recovery and moderate treatment intensity. The study therefore shows that **water source selection and treatment design cannot be assessed separately**. They form a single system-level decision, in which feedwater characteristics, electrolyser requirements and treatment efficiency jointly determine the actual water footprint of the plant. This is particularly relevant when comparing PEM and AEL systems: even where their direct process-water demand remains relatively close, the more stringent purity requirements of PEM may imply a more demanding treatment train and therefore a different balance between process water, withdrawal and reject streams. In other words, **the same process demand may correspond to a very different abstraction requirement once treatment performance is considered**.

Taken together, these findings confirm that treatment is not simply a preparatory step upstream of electrolysis, but a core component of the system-level water balance. **Recovery ratio, reject**

generation and purification intensity directly affect the relation between source abstraction and useful process water, and therefore determine whether a given water source is technically, economically and environmentally appropriate for hydrogen production. This also provides the natural link to the next part of the analysis, namely the management of brine and other treatment by-products, which becomes increasingly relevant as hydrogen systems rely more heavily on saline or non-conventional water sources.

Brine management and broader management implications

The increasing reliance on saline and non-conventional water sources makes brine management one of the most relevant environmental and operational issues associated with hydrogen production systems. Whenever desalination or advanced treatment is required, part of the incoming water is converted into a concentrated reject stream that must be managed appropriately in order to avoid adverse impacts on aquatic or terrestrial environments. In the case of seawater and, to a lesser extent, brackish water, these **saline residual streams represent the main system-level loss associated with treatment** and are therefore a key component of the overall water balance. Their management cannot be treated as a secondary downstream issue, since it directly affects the environmental acceptability and, in some cases, the economic feasibility of the selected water sourcing strategy.

Conventional brine disposal options, such as marine discharge, evaporation ponds or deep-well injection, remain widely used because of their relative simplicity and lower immediate cost. However, their applicability is increasingly constrained by site-specific environmental conditions, regulatory requirements and local acceptance. **As treatment intensity increases, particularly in seawater desalination systems, the management of concentrated saline effluents becomes more critical**, both because of the larger volumes involved and because of the need to control dilution, plume behaviour and potential ecological effects. This is why the study highlights the importance of considering brine not simply as a waste stream, but as a relevant part of the overall water management strategy associated with hydrogen production.

At the same time, the analysis also points toward a gradual shift from conventional disposal approaches to more **circular and resource-oriented strategies**. Advanced and hybrid solutions, including concentration systems, selective salt recovery and **Zero Liquid Discharge (ZLD)** concepts, offer the possibility of reducing liquid waste volumes and, in some cases, recovering materials of potential value. **Although these approaches remain more energy-intensive and costly, they illustrate the direction in which sustainable hydrogen-water systems are likely to evolve**, especially where dependence on seawater or brackish water becomes structural. In this perspective, the management of treatment by-products is not separate from water sourcing and treatment design, but part of the same integrated decision-making framework.

Taken together, these findings confirm that the selection of a water source for hydrogen production cannot be assessed solely in terms of physical availability or direct treatment efficiency. It must also account for the broader management implications associated with reject streams, long-term environmental compatibility and the potential integration of reuse and recovery strategies. This is particularly important in water-stressed or coastal regions, where the attractiveness of non-conventional sources may depend not only on access to water itself, but also on the capacity to manage their downstream impacts in a technically reliable and environmentally responsible way.

2.1.3 Cooling – the system-level driver

Cooling represents one of the main factors determining the transition from **direct process water demand to system-level water impacts** in hydrogen production. While the core hydrogen generation step may require relatively similar amounts of water across several production technologies, the additional water needed to remove excess heat can substantially modify the overall balance of the plant. For this reason, cooling cannot be treated as a secondary auxiliary service but must be considered a central component of the water footprint of hydrogen production systems. This is particularly relevant because **the influence of cooling is not uniform across technologies**: its contribution depends on the thermal characteristics of the process, the efficiency of the conversion system, the selected cooling configuration, and the local operating context. As a result, two hydrogen production routes with comparable direct process-water demand may exhibit markedly different overall water requirements once cooling is taken into account. From this perspective, the study shows that the assessment of

hydrogen-related water use must move beyond the process itself and include the broader thermal management needs of the plant, since these may significantly alter both the magnitude and the nature of the resulting pressure on water resources.

Cooling configurations and their water implications

Before discussing the water implications of cooling, it is useful to distinguish between the three main cooling configurations considered in the study.

- **Once-through cooling** relies on the abstraction of large volumes of water from an external source, such as a river, lake or marine body, which are used once to remove heat and then returned to the source. This configuration is typically associated with sites where abundant water is available and where large-scale heat dissipation is feasible.
- **Wet recirculating or evaporative cooling** uses water in a closed or semi-closed loop, but dissipates heat through evaporation, thereby reducing withdrawal compared with once-through systems while increasing net water consumption. This configuration is often adopted where water availability is more constrained but water-based cooling remains necessary for thermal performance.
- **Dry cooling**, by contrast, removes heat through air rather than water and is therefore attractive in water-scarce contexts, although it may involve efficiency penalties and is not always suitable under all operating conditions. Taken together, these configurations show that cooling design is not neutral from a water perspective, since each option shifts the balance differently between operational performance, water abstraction and consumptive losses.

Nevertheless, cooling systems differ not only in their technical configuration, but also in the type of water pressure they exert on the surrounding resource. From a system-level perspective, the key distinction is between **water withdrawal** and **water consumption**: **the first refers to the total volume of water abstracted from the source to supply the system, whereas the latter refers to the fraction of that water that is effectively lost and not returned to the original source**. Cooling arrangements such as **once-through systems** are characterised by very high withdrawal rates, since they rely on large volumes of water abstracted from rivers, lakes or marine bodies to dissipate heat, but they generally involve limited net consumption because most of the water is returned to the original source. By contrast, **evaporative cooling** leads to lower withdrawal volumes but higher actual consumption, because part of the water is irreversibly lost through evaporation during operation. **Dry cooling** largely avoids direct water use for heat rejection but may involve efficiency penalties and is not always the most suitable option under all operating conditions.

This means that the choice of cooling configuration does not simply change the total amount of water associated with hydrogen production, but also the nature of the impact itself, shifting the balance between abstraction pressure and consumptive loss. For this reason, **cooling technologies must be assessed not only in terms of thermal performance, but also in terms of how they modify the relation between process demand, total plant water use and local water-resource sensitivity**. As highlighted in the study, this distinction is particularly important because **cooling can become one of the main drivers of the overall water footprint of hydrogen production systems**, even when direct process-water demand remains comparatively limited.

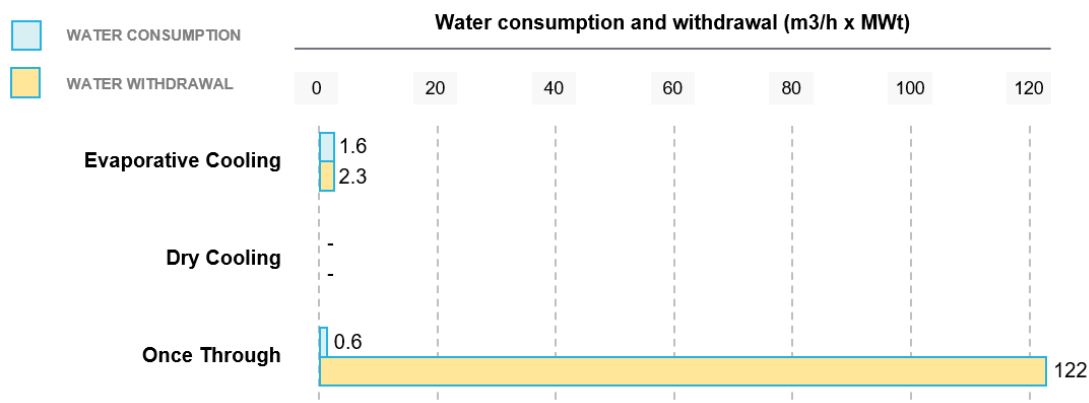


Figure 2-9: Water footprint of main cooling technologies

The impact of cooling on hydrogen-related water use becomes particularly evident when the analysis is extended across different source-water conditions. The graphical comparison developed in the study shows that the same hydrogen production technology may display very **different balances between water withdrawal and water consumption depending on whether the plant relies on freshwater, brackish water or seawater**. This does not mean that all cooling water must be treated to the same purity level required for electrolysis feedwater. Rather, it reflects the fact that the overall plant water balance changes with the selected source water, because source characteristics influence abstraction volumes, treatment needs for process water, reject-stream generation and the way cooling demand translates into system-level water pressure. As a result, the total plant water profile reflects not only the thermal demand of the technology itself, but also the broader interaction between cooling needs and the type of water resource on which the plant is based.

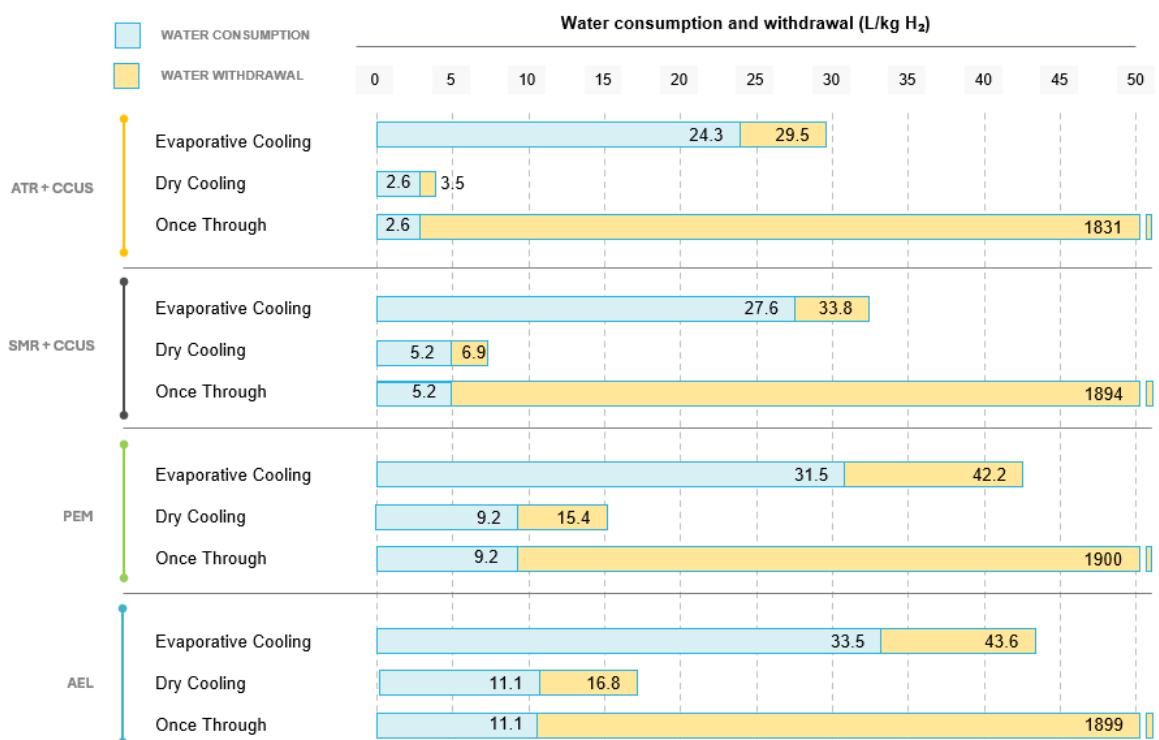


Figure 2-10: Water footprint comparison (L/kg H₂) under different cooling and H₂ production technology layouts (Tap water fed system)

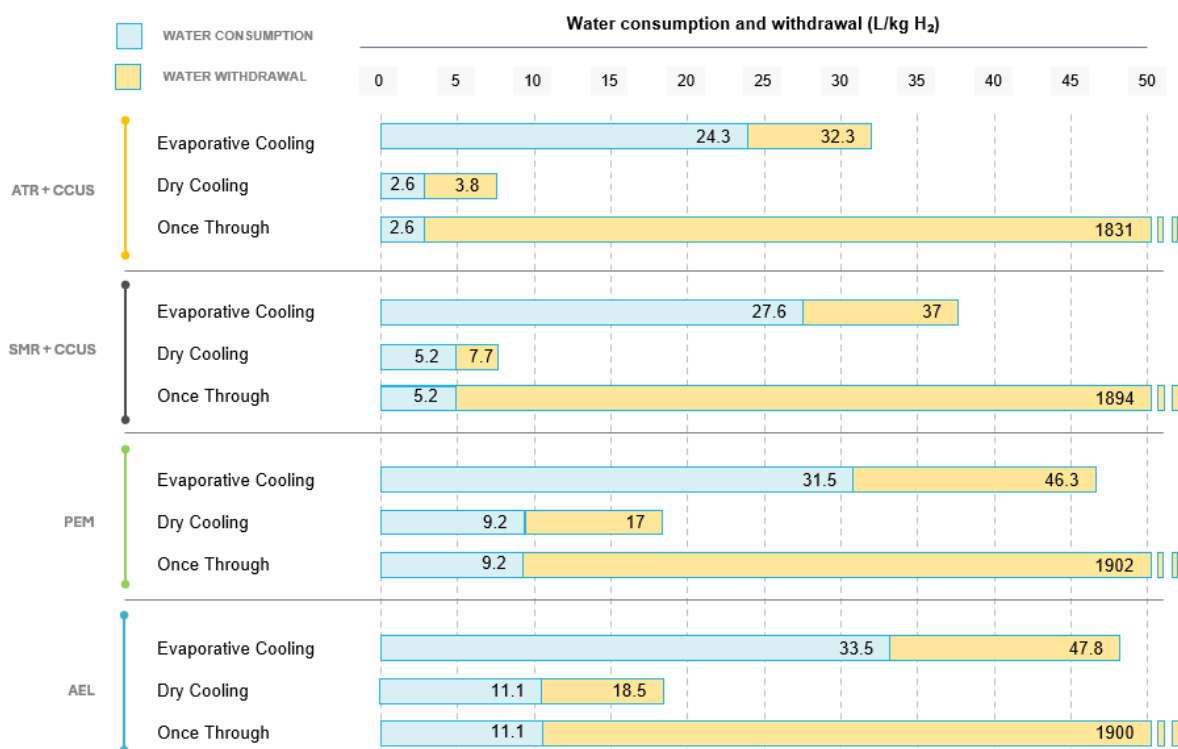


Figure 2-11: Water footprint comparison (L/kg H₂) under different cooling and H₂ production technology layouts (Brackish water fed system)

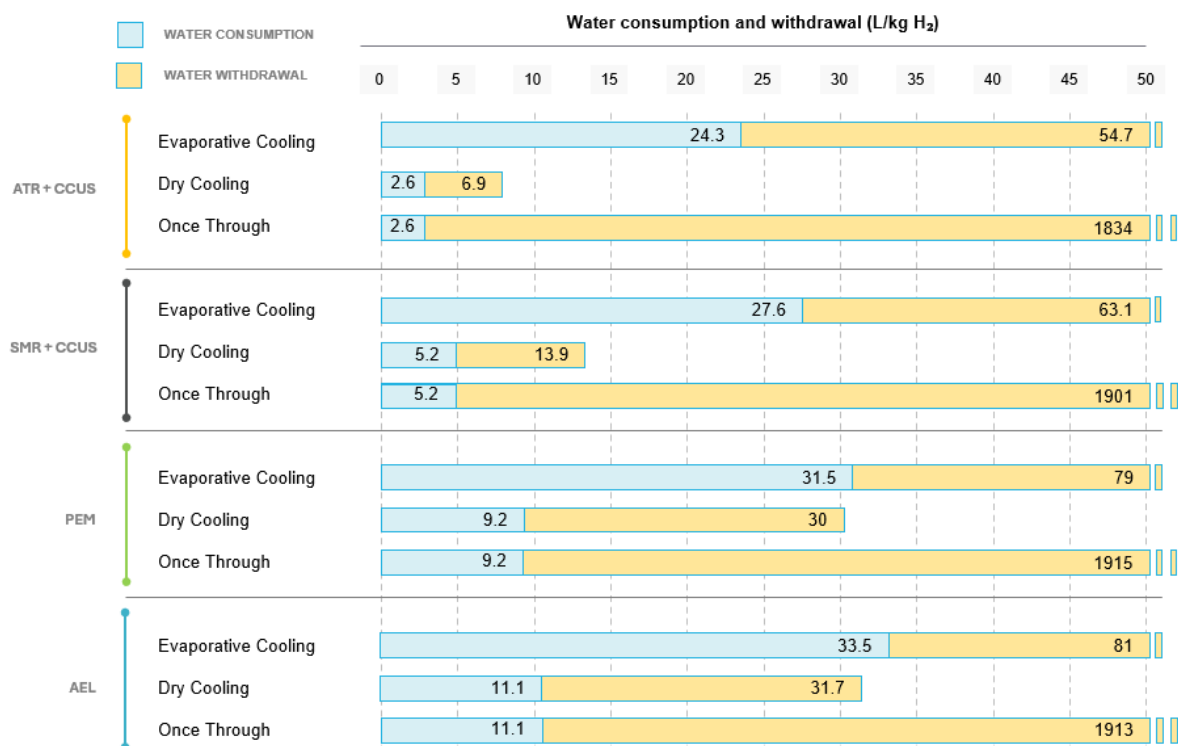


Figure 2-12: Water footprint comparison (L/kg H₂) under different cooling and H₂ production technology layouts (Seawater fed system)

A first common pattern emerging from the three source-specific graphs is that, for a given technology and cooling configuration, **water consumption remains broadly stable**, while **water withdrawal**

increases as the source water becomes more saline. This indicates that the main effect of moving from freshwater to brackish water and then to seawater is not a change in the amount of water effectively consumed by the cooling process itself, but a change in the **amount of source water that must be abstracted upstream** in order to supply the system under increasingly demanding source-water conditions. In other words, the same cooling duty can generate a much higher abstraction burden when the plant relies on more saline water sources.

This pattern is especially visible for **dry cooling** and **evaporative cooling**. In these configurations, the cooling demand is superimposed on a broader plant water balance that already depends on source-water quality and treatment performance. As salinity increases, the system requires more source-water abstraction to deliver the same useful water input to the plant, and this is reflected in the growing gap between **consumption** and **withdrawal**. The graphs therefore suggest that the influence of source water is felt mainly through the **withdrawal side** of the balance, while the consumptive component remains largely driven by the thermal behaviour of the plant and by the cooling configuration itself. This is why the difference between freshwater, brackish water and seawater appears much more strongly in abstraction terms than in net consumptive losses.

A different situation is observed for **once-through cooling**. In this case, the defining feature is the extremely large volume of water abstracted to remove heat, while only a very limited share is effectively consumed. As a result, the withdrawal component becomes so dominant that the effect of source-water type is comparatively marginal in visual terms. The graphs show that, under once-through cooling, the overall water profile is determined far more by the intrinsic logic of the cooling system itself, namely large abstraction and low net loss, than by the differences between freshwater, brackish water and seawater. This confirms that once-through systems primarily exert pressure through **abstraction intensity**, whereas evaporative and dry systems reveal more clearly how source-water conditions shape the overall system balance.

Taken together, the three comparisons show that **cooling does not affect hydrogen-water systems in a uniform way**. Its impact depends on the interaction between the selected cooling method and the water source on which the plant is based. For this reason, cooling should be understood not only as a thermal management issue, but also as a mechanism that determines whether the water burden of hydrogen production is expressed mainly as **higher abstraction volumes** or as **higher consumptive losses**. This distinction is central for evaluating the suitability of different configurations under specific local water conditions, particularly in water-stressed regions where the acceptability of hydrogen deployment may depend on the type of pressure imposed on the resource as much as on its absolute magnitude.

2.1.4 Cost of treatment and cooling

Compared with electricity, electrolyzers and hydrogen transport infrastructure, water-related costs generally represent a relatively small share of total hydrogen production costs. Nevertheless, treatment and cooling requirements can influence project economics, particularly in water-scarce regions where alternative water sources or low-water cooling solutions become necessary. Consequently, decisions on water sourcing and cooling are often driven less by direct cost considerations than by local water availability, environmental constraints and long-term resilience objectives.

The cost of producing process-grade water depends primarily on the initial water quality. Freshwater and tap water typically require only limited conditioning and polishing, while brackish water, seawater and wastewater require increasingly complex treatment trains, including reverse osmosis and final deionisation stages. Typical drinking-water prices in Europe range between **2 and 4 €/m³**, although significant regional differences exist. Even under relatively expensive water supply conditions, however, the direct contribution of feedwater to hydrogen production remains very limited because electrolysis requires only around **9-13 litres of process water per kilogram of hydrogen produced**, as seen in the previous chapters.

The treatment cost increases with feedwater salinity because of higher energy requirements and lower recovery ratios. Reverse osmosis remains the most widely adopted desalination technology due to its favourable balance between efficiency and cost. Typical specific energy consumption for seawater RO is approximately **3–4 kWh/m³**, while brackish-water treatment generally requires less energy and achieves higher recovery rates [9]. Advanced polishing steps, such as ion exchange and

electrodeionisation (EDI), are then used to achieve the ultrapure water quality required by PEM electrolyzers. Even when seawater desalination is necessary, the resulting cost contribution to hydrogen production remains modest. For PEM electrolysis supplied with treated freshwater, at the **average cost of 2-4 €/m³**, water costs are typically in the order of **0.06–0.18 €/kg H₂**, highlighting the limited influence of feedwater costs on the overall hydrogen economics. A similar conclusion emerges for desalination-based systems. Recent studies show that combining RO and EDI can produce ultrapure water (<0.5 ppm dissolved salts) at costs around **0.46 €/m³** [10][11], translating in water costs typically in the order of **0.02–0.06€/kg H₂**, when considering cooling methods as dry cooling – wet cooling, while reaching values up to of **0.89 €/kg H₂** when considering less common and overconsuming methods as once through. Considering the conventional dry cooling and wet cooling methods, and considering the low water demand of electrolysis, the contribution of water purification to the final hydrogen production cost remains nevertheless negligible, even when non-conventional water sources are used. This confirms that the main challenge associated with seawater or brackish-water use is usually not the direct cost of water treatment itself, but rather the broader considerations related to energy consumption, brine management and local environmental conditions. An additional consideration is the potential benefit of **economies of scale and system integration**. Large hydrogen production facilities can share intake structures, desalination units, pumping systems and energy infrastructure across the entire site, reducing the specific cost of treated water. Furthermore, seawater desalination is particularly well suited to integration with renewable-energy-based hydrogen projects located in coastal regions. In these configurations, desalination plants can be coupled directly with solar or wind generation, allowing the production of both process water and hydrogen within an integrated energy–water system. Such synergies can improve asset utilisation, reduce infrastructure duplication and enhance the overall resilience of the project. Consequently, while seawater requires more intensive treatment than freshwater or brackish water, its practically unlimited availability and compatibility with large-scale renewable energy developments make it an attractive option for coastal hydrogen hubs and hydrogen valleys.

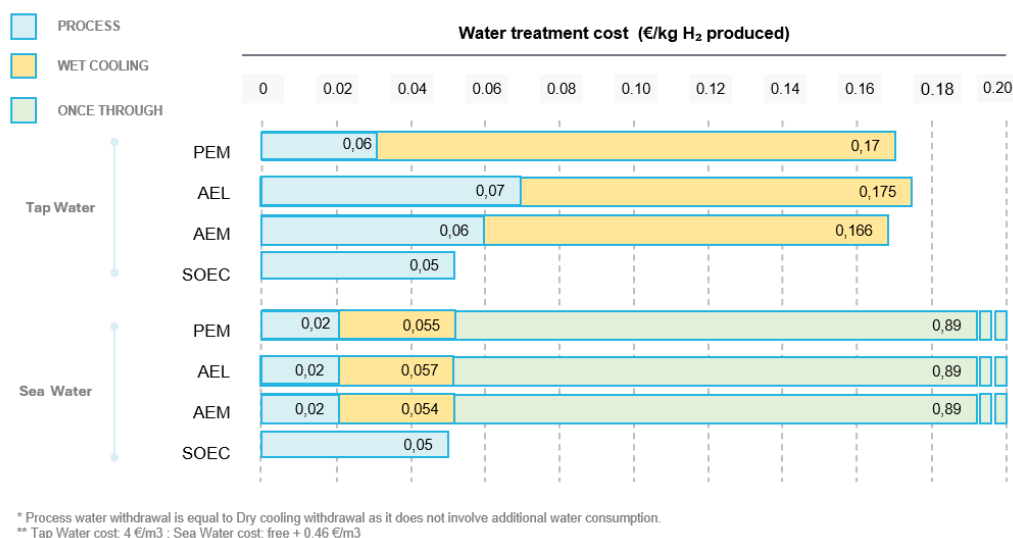


Figure 2-13: Cost comparison for water withdrawal: Tap Water - Sea Water

Cooling configuration has a more visible influence on system performance than feedwater treatment costs. Cooling can account for most of the total water withdrawal of a hydrogen plant and may therefore determine both operational expenditure and local water-resource impacts. Wet or evaporative cooling systems generally offer lower capital costs and high thermal performance, but at the expense of higher water consumption. Dry cooling significantly reduces water use and may be preferable in water-stressed regions; however, it introduces higher capital costs and efficiency penalties due to less effective heat rejection. Once-through systems typically have the lowest consumptive water use but require very large withdrawal volumes and are therefore strongly dependent on local water availability.

The economic trade-off is therefore not simply between different water-treatment technologies, but between **water availability, treatment requirements and cooling configuration**. In regions with

abundant water resources, conventional treatment and wet cooling may provide the lowest cost solution. Conversely, in water-scarce areas, developers may favour reclaimed wastewater, desalinated seawater or dry-cooling systems despite their higher cost, in order to reduce pressure on freshwater resources and improve long-term operational resilience.

Overall, the study confirms that, for PEM electrolysis supplied with freshwater, **water-related costs represent only around 1.5–4.5% of total LCOH** when assuming a conservative lower-bound LCOH of 5 €/kgH₂. Their relative impact becomes even smaller when a realistic average LCOH of 8 €/kgH₂ is considered, reaching values of around 0.8–2% of total LCOH, confirming that water costs remain marginal even under challenging sourcing conditions. **Consequently, water should be considered primarily as a strategic siting and sustainability factor rather than a major economic barrier.** The selection of water source, treatment technology and cooling system should therefore be guided not only by cost minimisation but also by water availability, environmental constraints and long-term resilience objectives.

2.1.5 Efficiency inversion – a key message

When hydrogen production systems are compared under the assumption of **70% electrolysis efficiency**, fossil-based technologies such as SMR + CCUS and ATR + CCUS appear to have a lower overall water footprint than renewable pathways. However, this trend reverses once **higher-efficiency electrolysis (≈ 80%)** is considered. As illustrated in the figure, the improvement in electrolyser performance reduces the total thermal load and, consequently, the **cooling water requirements**.

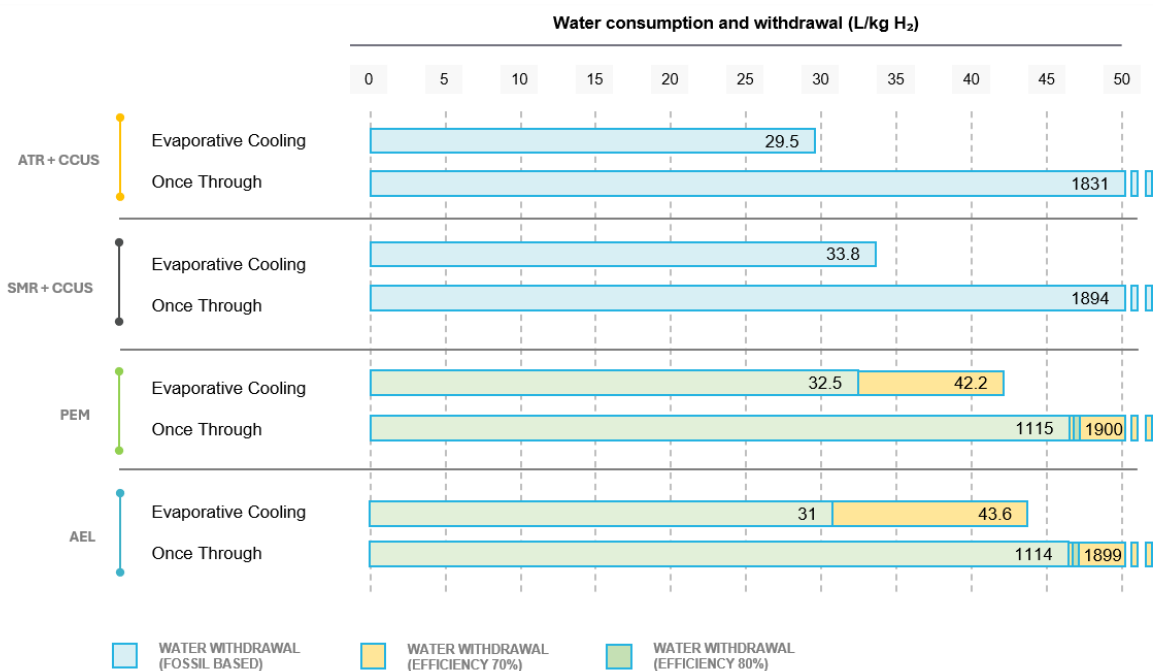


Figure 2-14: Water footprint comparison (L/kg H₂) under 70% and 80% electrolysis efficiency for different cooling and H₂ production technology layouts (Tap water fed system)

Under these conditions, **renewable electrolysis technologies (PEM and Alkaline)** become **more water-efficient than fossil-based routes**, particularly when the once-through cooling layout is applied. This shift occurs because the increased conversion efficiency directly lowers the waste heat to be dissipated, thus decreasing the need for evaporative or recirculating cooling.

In other words, while fossil-based systems remain more water-efficient at lower electrolyser efficiencies, **advancements in electrolysis efficiency narrow and ultimately invert this gap**, making renewable hydrogen production not only the cleaner option in terms of CO₂ emissions but also increasingly **competitive in water use and thermal efficiency**.

KEY TAKEAWAYS



Integrated nature of hydrogen water demand

Taken together, the analysis confirms that the water dimension of hydrogen production cannot be interpreted through **direct process-water demand alone**. The overall water profile of a hydrogen plant is shaped by the interaction between the selected production technology, the **quality and origin of the available water source**, the **treatment intensity** required to reach process specifications, and the management of reject streams and brine. For this reason, the same nominal hydrogen output may correspond to very different system-level water requirements depending on how water is sourced, conditioned and integrated into the plant configuration.

Cooling as a determining system-level factor

The study shows that **cooling is one of the main drivers** through which hydrogen production moves from process-level demand to full system-level impact. Its role is not uniform: depending on the configuration adopted, cooling may primarily increase **water consumption** through evaporative losses or, conversely, impose very high-water **withdrawal** through once-through abstraction. This effect becomes even more relevant when combined with different source-water conditions, since freshwater, brackish water and seawater do not affect the plant in the same way. As a result, the water footprint of hydrogen production must always be assessed through the combined lens of **technology, source water, treatment and cooling design**.

Efficiency improvements and future resilience

Finally, the results indicate that future improvements in **electrolyser efficiency** from 70% to 80% may significantly strengthen the water performance of renewable hydrogen systems by reducing the thermal load to be dissipated and, therefore, the cooling-related contribution to total water use. In this perspective, the most robust solutions are not those that minimise one single parameter in isolation, but those that achieve the best balance between **process efficiency, water quality requirements, treatment burden, cooling needs and local water-resource conditions**. This is particularly important in water-stressed regions, where the acceptability and long-term sustainability of hydrogen deployment depend not only on carbon performance, but also on the type and magnitude of the pressure imposed on local water resources.

Cost of Water

Overall, the study confirms that, for PEM electrolysis supplied with freshwater, **water-related costs represent only around 1.5–4.5% of total LCOH** when assuming a conservative lower-bound LCOH of 5 €/kgH₂. Their relative impact becomes even smaller when a realistic average LCOH of 8 €/kgH₂ is considered, reaching values of around 0.8–2% of total LCOH, confirming that water costs remain marginal even under challenging sourcing conditions. **Consequently, water should be considered primarily as a strategic siting and sustainability factor rather than a major economic barrier.**

3 Geospatial visualisation of water availability and hydrogen potential across Europe

3.1 Method and the clean hydrogen explorer

To evaluate the interaction between water availability, renewable energy resources and hydrogen production capacity across Europe and selected neighbouring regions, an integrated spatial assessment has been developed. The analysis combines harmonised hydro-meteorological, energy and hydrogen datasets and applies a common methodological framework to both historical conditions (2000–2019) and future projections (2026–2055). An overview of the datasets considered for the analysis is provided in Table 3-1.

Table 3-1: Hydro-meteorological, energy, and hydrogen dataset overview.

Dataset/Provider	Data type	Spatial/Temporal coverage
ISIMIP3 <i>Inter-Sectoral Impact Model Intercomparison Project - phase 3a and 3b</i>	Temperature, Precipitation, Runoff, Potential evapotranspiration, consumption	Global (0.5°x0.5° grid) Historical: 1950-2019 Projections: 2015-2100 (SSP1-2.6, 3-7.0, 5-8.5)
PECD <i>Pan-European Climate Database version 4.2</i>	Hydropower production, Wind/Solar capacity factor	Europe/North Africa (0.25°x0.25° grid) Historical: 1950-near present Projections: 2015-2100 (SSP1-2.6, 2-4.5, 3-7.0, 5-8.5)
GEM <i>Global Energy Monitor Global Solar/Wind Power Tracker</i>	Solar/Wind installed capacity	Global (facility-level, point location) 1970–2059 (announced, construction, operation, disuse, and dismantling dates)
IEA <i>International Energy Agency Hydrogen Production Projects Database</i>	Hydrogen production capacity	Global (facility-level data, point location) 1965-2043 (announced, construction, operation, disuse, and dismantling dates)

For the historical analysis, we considered the 20-year period 2000-2019. ISIMIP3a provides reanalysis-based simulations covering the period up to 2019 and thus more recent years have not been considered.

For the future analysis, we consider the 30-year period 2026–2055. This near- to mid-term horizon is commonly adopted in climate impact assessments to characterize emerging trends while limiting the amplification of uncertainties associated with long-term climate divergence, socio-economic pathways, and technological evolution. In addition, the selected time horizon is particularly relevant for infrastructure planning and hydrogen-related investments, broadly coincides with the typical operational lifetime of some of energy and water infrastructures, and is consistent with the main European policy horizons (for instance, the EU 2050 climate neutrality target).

In this context, **SSP scenarios provide the overarching framework linking socio-economic development and climate forcing.** Rather than representing purely physical perturbations of the climate system, they embed alternative trajectories of emissions, technological progress, and adaptive capacity within consistent development pathways.

The analysis is based on SSP3-7.0 and SSP5-8.5. **SSP3-7.0 represents a “regional rivalry” pathway characterized by fragmented governance, limited international cooperation, and slow technological diffusion.** As a result, emissions remain high throughout the century, making SSP3-7.0 broadly consistent with a continuation of current policy trends and often considered close to a business-as-usual trajectory. **SSP5-8.5, by contrast, depicts a fossil-fueled development pathway with very high energy demand and minimal mitigation efforts,** and is widely used as a worst-case or high-end reference scenario to explore upper-bound climate risks.

Among the scenarios commonly adopted in climate impact studies, the intermediate pathway SSP2-4.5 is not currently available within the ISIMIP3b framework. SSP1-2.6 is instead available and could in principle have been included in the analysis. However, SSP1-2.6 assumes rapid and globally coordinated mitigation efforts, early peaking of emissions, and a sustained transition toward low-carbon technologies. Given current emission trajectories and the persistent gap between stated climate targets and implemented policies, this pathway is increasingly regarded as overly optimistic for mid-century assessments. For this reason, SSP1-2.6 was not considered in the present study, which instead prioritizes higher-emission scenarios that are considered more representative of plausible near-term developments and therefore provide a more precautionary assessment of future climate impacts.

Clean Hydrogen Explorer is the web-based visualization tool developed within this study, which allows to explore the interconnections between water availability, renewable energy production, and hydrogen development plans. It provides a structured entry point to data, analyses, and case studies supporting research and decision-making at the water-energy-hydrogen nexus.

Figure 3-1 presents the landing page² of the Clean Hydrogen Explorer, divided into 3 areas:

- **Top menu bar:** to navigate within platform sections
- **Thematic boxes:** provide direct link to Analysis, Water, Energy, Hydrogen sections
- **Case studies map:** provide localization of each Case study and direct link to the results page

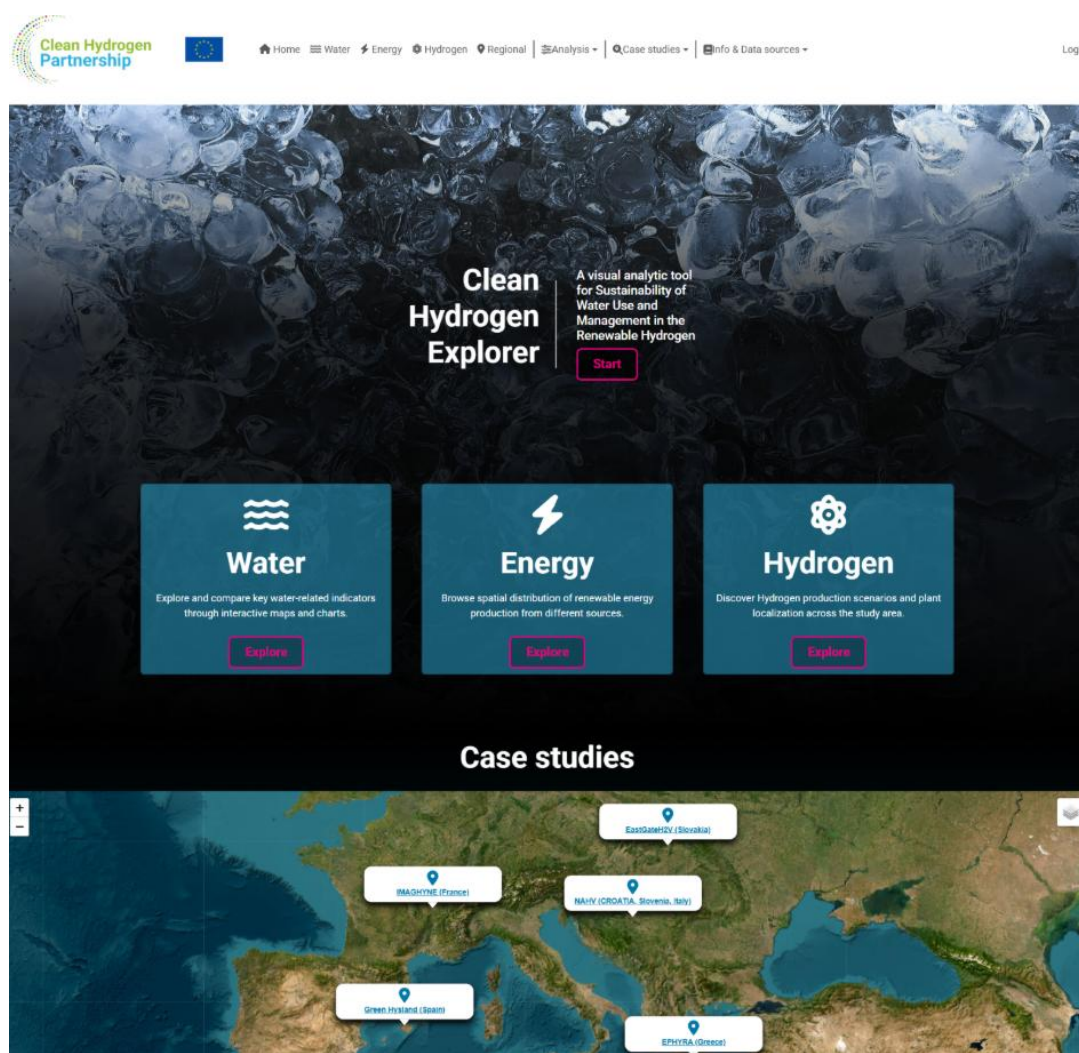


Figure 3-1: Clean Hydrogen Explorer landing page, with top menu

² published at the url: <https://cleanh2.soft-water.it/>

Beyond the continental assessment, the methodology is linked to a basin-scale modelling framework based on the LISFLOOD hydrological model, which is used in the case-study analyses to assess local impacts and seasonal water constraints.

This integrated modelling framework (Figure 3-2) is designed to assess the impacts of current and future hydrogen production on water availability. In particular, it quantifies water consumption and additional water requirements for hydrogen-related processes, such as electrolysis and cooling, and evaluates their implications for other water-using sectors, including municipal supply, agriculture, and industry. The spatially explicit localisation of hydrogen production plants and their associated water demands is a key element of this approach, as it allows these new uses to be consistently integrated alongside existing sectoral water demands.

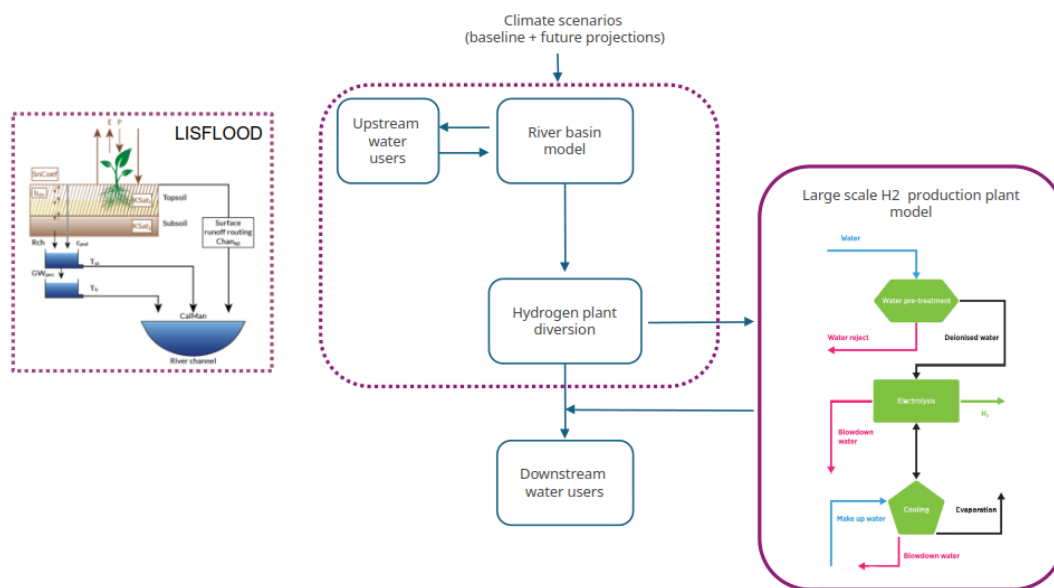


Figure 3-2: Overview of the integrated modelling framework at the basin scale

3.2 Water availability: indices and scenarios

Water resource availability in the different regions of the study domain was assessed based on three widely used literature indices:

- **Aridity Index**, AI (climate background): structural water availability and baseline climatic water balance. AI defines the fundamental climatic context by quantifying the long-term relationship between precipitation supply and atmospheric evaporative demand, establishing whether a region is inherently water-limited or water-abundant.
- **Standardized Precipitation Index**, SPI (climate variability): meteorological drought occurrence, intensity, and duration (anomalies). SPI identifies departures from normal precipitation patterns across multiple timescales, capturing transient climate shocks that represent temporary deviations from the baseline conditions described by AI.
- **Water Exploitation Index Plus**, WEI+ (human–water system): water stress and scarcity resulting from the interaction between natural water availability and anthropogenic demand. WEI+ measures exploitation intensity by comparing total water abstractions against renewable water resources, revealing how human activities modify or exacerbate climatically determined water constraints.

The rationale for this choice is that **the Aridity index (AI) describes long-term climatic constraints** that determine a region's baseline water availability regime, **SPI captures short-term climate shocks** and variability that create episodic drought conditions superimposed on this baseline, and **WEI+ reflects the degree of human pressure on water systems** and society's adaptive capacity to manage resources within these climatic boundaries. Together, these three indicators provide a comprehensive assessment spanning climatic predisposition (AI), climate-driven perturbations (SPI), and socio-

hydrological stress (WEI+), enabling distinction between regions facing chronic water limitations versus those experiencing temporary deficits or unsustainable exploitation patterns.

The historical assessment of water availability reveals a strong north–south contrast. As observed in Figure 3-3, Northern and Western Europe generally exhibit low WEI+ values and humid climatic conditions, indicating abundant water resources relative to demand. In contrast, Mediterranean and North African regions are characterised by higher water exploitation, lower aridity index values and recurrent drought conditions. Severe water stress is already evident in parts of Spain, Italy, Greece and Cyprus.

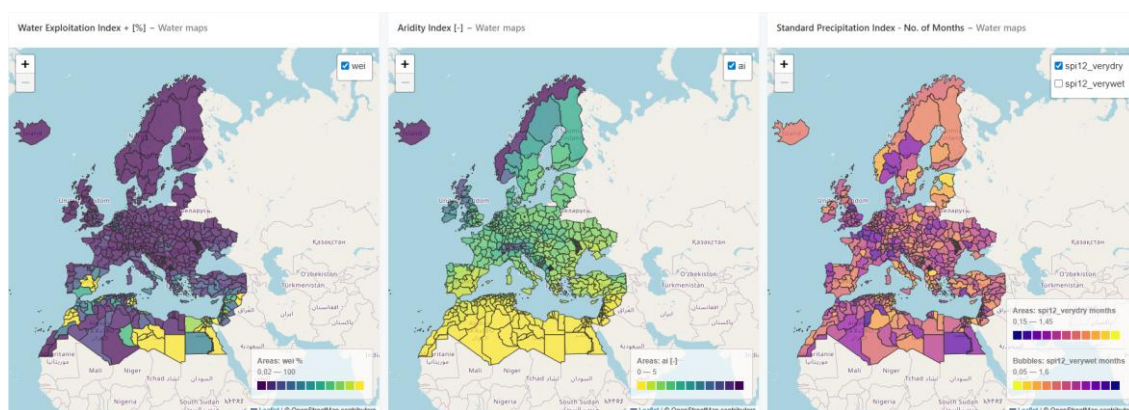


Figure 3-3: Water Exploitation Index Plus (WEI+, left panel), Aridity Index (AI, center panel), and number of very dry average months per year considering the Standard Precipitation Index (SPI12, right panel) under the historical conditions for the 2000-2019 time period.

Future climate projections reinforce these patterns. Under SSP3-7.0, (Figure 3-4) water scarcity intensifies across southern Europe and North Africa, while droughts become more frequent and persistent. Under SSP5-8.5 (Figure 3-5), arid conditions expand further northward, water exploitation increases in additional regions, and drought variability becomes more extreme. The results indicate a shrinking margin of adaptation in already vulnerable regions and increasing water-related risks for future hydrogen deployment.

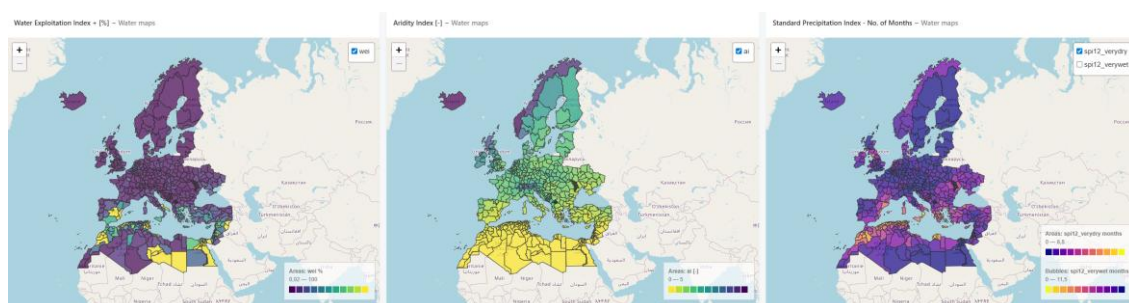


Figure 3-4: Water Exploitation Index plus (WEI+, left panel), Aridity Index (AI, center panel), and number of very dry average months per year considering the Standard Precipitation Index (SPI12, right panel) under SSP3-7.0 climate projections for the 2046-2055 time period.

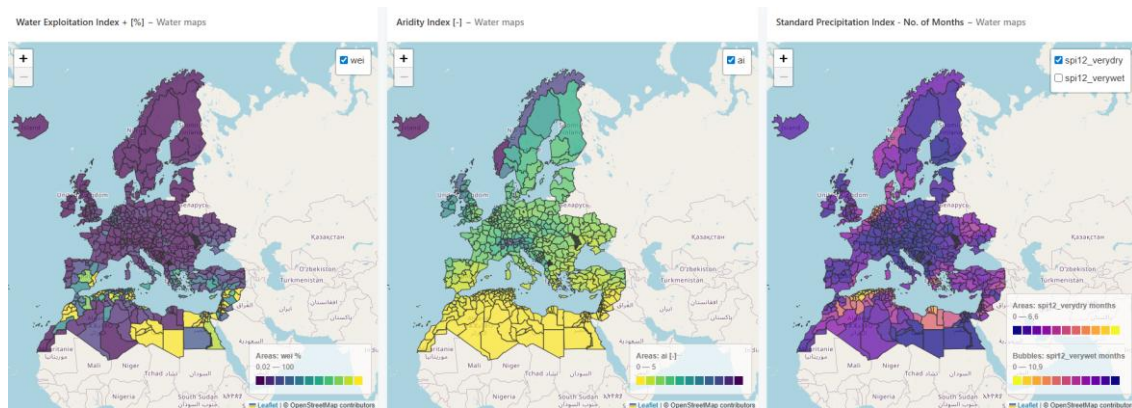


Figure 3-5: Water Exploitation Index Plus (WEI+, left panel), Aridity Index (AI, center panel), and number of very dry average months per year considering the Standard Precipitation Index (SPI12, right panel) under SSP5-8.5 climate projections for the 2046-2055 time period.

3.3 Renewable energy and hydrogen production potential

The analysis of renewable energy resources shows that historically, wind energy has been the largest contributor to renewable electricity production, followed by hydropower and solar power. Future projections indicate substantial growth in renewable generation, particularly for solar and wind technologies. Solar production is expected to expand rapidly across southern Europe and North Africa, while wind remains the dominant renewable source in many northern regions. Hydropower remains comparatively stable and geographically concentrated.

Figure 3-6 shows significant regional differences across Europe and neighbouring regions.

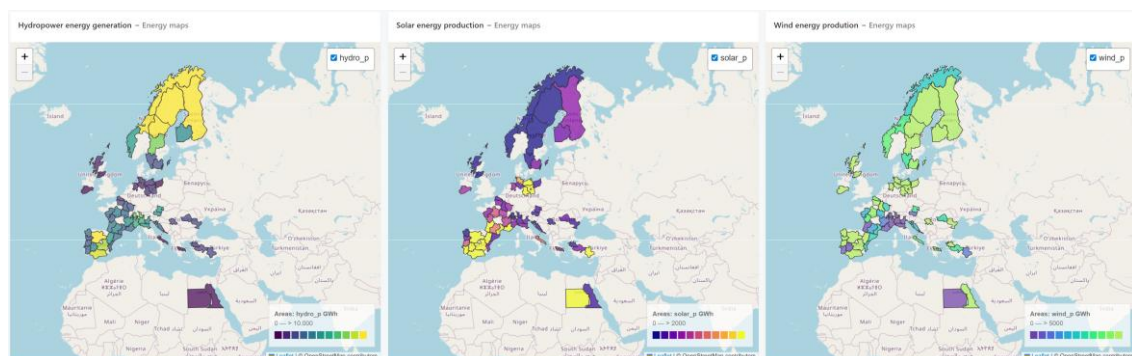


Figure 3-6: Hydropower (left), solar (center), and wind (right) energy production in the historical period (2000-2019). Only regions with total renewable energy production exceeding 5,000 GWh/year are shown.

The most promising areas for renewable energy production are located in the Iberian Peninsula. Many regions in Spain and Portugal show a favourable combination of hydropower, solar, and wind. A similar pattern is observed over large parts of France, although with overall lower production levels. In northern Italy, high production is mainly associated with **hydropower and solar**, while wind plays a more limited role. In contrast, northern Germany is characterised by a combination of strong wind and solar production, with negligible hydropower contribution. Several regions in Scandinavia also stand out in terms of energy production potential. Here, the dominance of hydropower is complemented by significant wind generation, resulting in some of the highest aggregated renewable outputs across the domain. North Africa shows a markedly different profile. Hydropower and wind production remain limited across most regions, while solar energy is much more prominent. Solar production is, however, spatially concentrated, with particularly high values in specific areas rather than being uniformly distributed.

Considering aggregated production levels, wind remains the dominant renewable source across all future horizons, followed by solar and hydropower. Solar shows the strongest relative growth over time, progressively closing the gap with wind, while hydropower remains comparatively stable. This behaviour reflects the different levels of technological maturity and spatial constraints of the three sources. Hydropower has been developed over several decades and, in Europe, most sites with favourable geomorphological and hydrological conditions are already exploited. By contrast, wind and solar are comparatively recent technologies and still offer substantial expansion potential, as they can be deployed over much wider areas and are less strongly constrained by local orography. Differences between the reference scenario (SSP3-7.0) and the worst-case scenario (SSP5-8.5) are small, both in terms of total production and relative contributions of the three sources.

This similarity also extends to spatial patterns (for this reason, only SSP3-7.0 is here reported in Figure 3-7). For all renewable sources, the geographic distribution of production under SSP3-7.0 and SSP5-8.5 is largely consistent, suggesting that long-term deployment patterns and installed capacity play a more important role than scenario-specific climate differences at the regional scale.

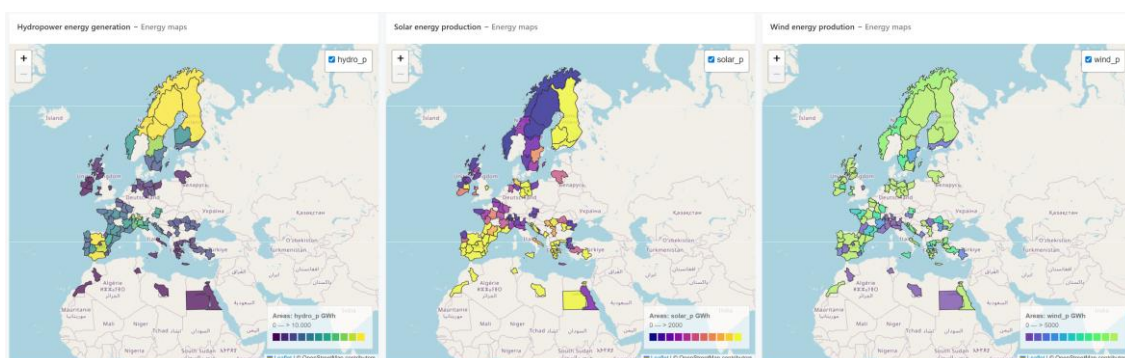


Figure 3-7: Hydropower (left), solar (center), and wind (right) energy production for SSP3-7.0 (2046-2055). Only regions with total renewable energy production exceeding 5,000 GWh/year are shown

Compared to the historical period, future projections show a clear increase in renewable electricity production across large parts of the domain. For hydropower, total production remains nearly constant over time. Nevertheless, moderate increases are visible in specific regions, particularly in the Iberian Peninsula, the Alpine arc, and parts of Scandinavia, where favourable hydro-climatic conditions persist. Solar power exhibits a much stronger increase than hydropower. Significant growth is projected across almost the entire Pan-European domain, with widespread gains in both southern and central Europe, reflecting the strong expansion of installed capacity and the broad availability of solar resources. Wind power also shows substantial increases in many regions. The most pronounced growth is observed in Norway and the United Kingdom, as well as in western Europe, particularly Spain and France. Additional notable increases are projected in Greece and in parts of North Africa, especially Morocco, reinforcing the role of wind as a key contributor to future renewable electricity production.

By enabling stakeholders to immediately identify the most promising locations for renewable energy investments, the tool facilitates strategic resource allocation and prioritized targeting of areas where infrastructure development would yield maximum return, rather than dispersing resources across marginally productive locations.

Hydrogen production capacity is projected to grow rapidly over the coming decades. For the historical period, hydrogen production capacity is defined as all plants with status operational or demo, as well as all plants with a date online up to 2025, regardless of status. Aggregated over the Pan-European domain, the resulting hydrogen production capacity is equal to 298.8 kt H₂ per year. Figure 3-8 provides a spatial overview of hydrogen production plants operating, under construction or planned in 2025. Each point represents a hydrogen production facility, with circle size proportional to the installed capacity and colour indicating the project status (concept, feasibility study, demo, under construction, or operational).

The figure highlights that currently operational plants are relatively few when compared to the number of projects that are planned or under development. Most operational facilities are concentrated in central

and western Europe, reflecting the early-stage deployment of hydrogen technologies and the role of pilot and demonstration projects in these regions.

When future and planned installations are also considered, a much denser distribution of hydrogen production plants emerges. High concentrations are observed in western Europe, including Portugal, Spain, France, Germany, Italy, and Switzerland, as well as in the United Kingdom and along the coastal areas of Scandinavia. In contrast, eastern Europe and extra-European regions within the domain show a markedly lower presence of hydrogen production facilities, even when projects in planning or early development phases are considered. Some regions outside continental Europe, such as Egypt and Jordan, Tunisia, and the coastal areas of Morocco, host a limited number of hydrogen projects. However, the majority of these projects are currently at the concept stage, indicating long-term ambitions rather than near-term production capacity. Notable examples of large-scale projects include concept-level facilities in Spain and Egypt, as well as feasibility-stage projects in the United Kingdom.

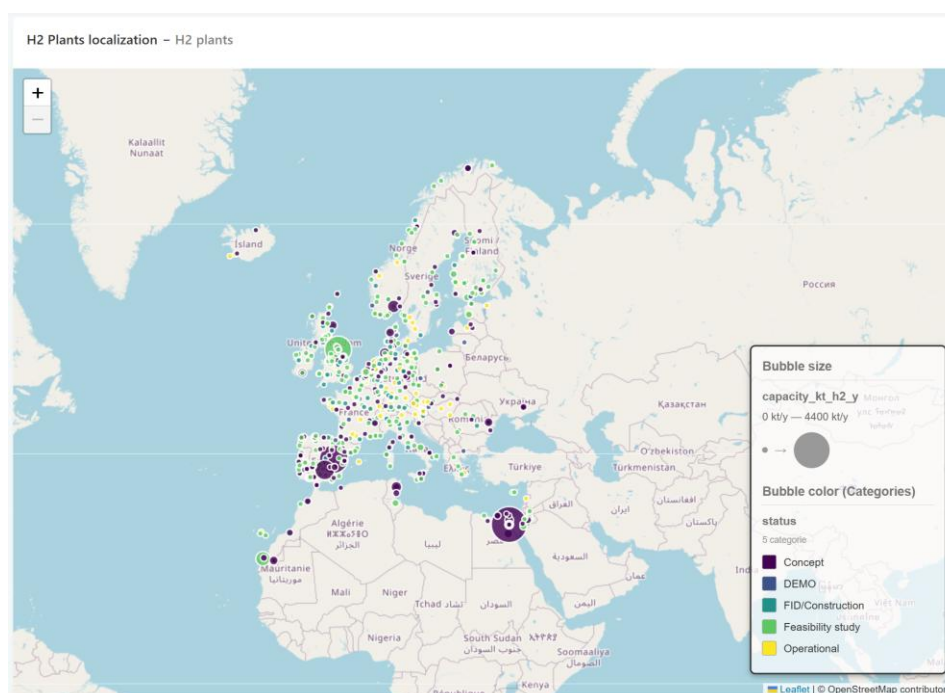


Figure 3-8: Distribution of the hydrogen production plant. Circle size represents the production capacity in kt H₂ per year; color represents the implementation status in 2025.

Figure 3-9 shows the spatial distribution of hydrogen production capacity in 2025, used to represent the historical period. As expected, the geographic pattern of hydrogen capacity closely reflects the distribution of active plants shown in the previous figure. Hydrogen production capacity is mainly located in central and western Europe, the United Kingdom, Scandinavia, and Iceland. By contrast, no hydrogen production capacity is currently present in the eastern parts of the Pan-European domain, nor in North Africa and other Mediterranean areas such as Turkey, Syria, and Israel.

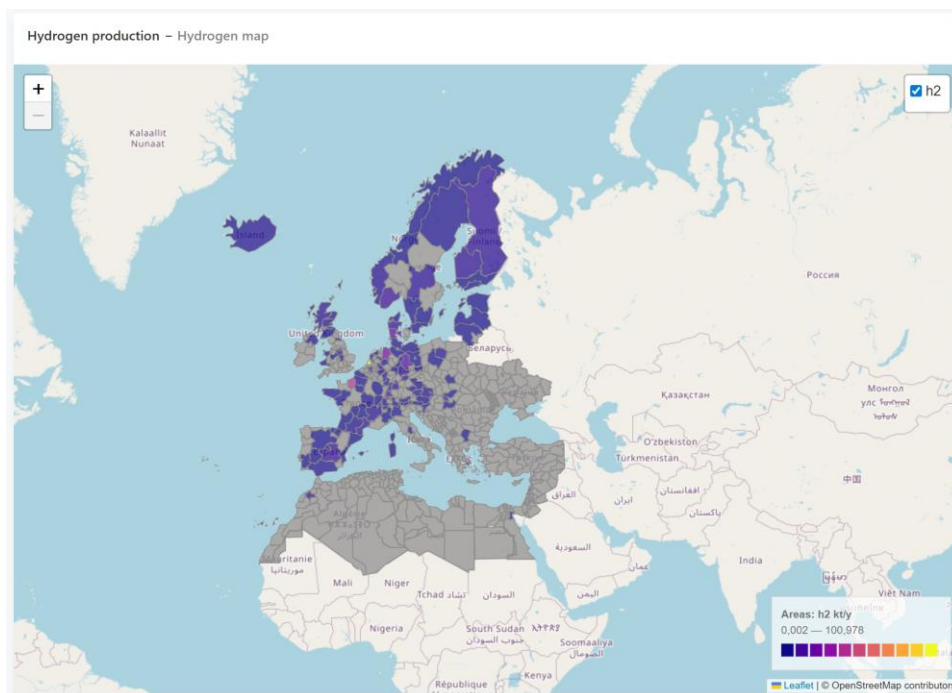


Figure 3-9: Hydrogen production capacity in 2025, used to represent the historical period. Grey areas indicate regions with no installed hydrogen production capacity.

The spatial distribution of the projected evolution of hydrogen production capacity over the next three decades (2050 horizon) is illustrated in Figure 3-10 (note that the upper limit of the colour scale has been increased with respect to Figure 3-9).

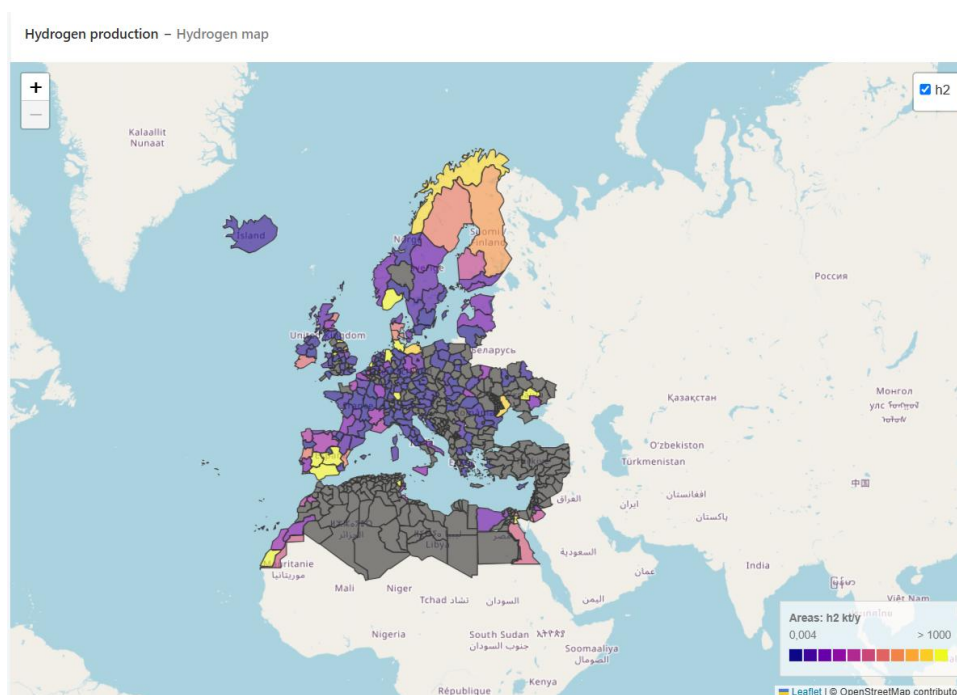


Figure 3-10: Hydrogen production capacity in 2050, used to represent the future period 2046-2055. Grey areas indicate regions with no installed hydrogen production capacity.

Compared to 2025, a clear expansion of hydrogen production capacity is projected across the domain. This expansion involves both an increase in the number of regions hosting hydrogen production facilities and a substantial growth in capacity in regions where hydrogen production is already present in the

historical period. These trends reflect current and planned investments aimed at scaling up hydrogen technologies and supporting their integration into the energy system.

By 2050, hydrogen production evolves from a relatively limited and regionally concentrated system into a widespread Pan-European network, with the main production areas transitioning into mature hydrogen production hubs. The map reveals a nearly continuous belt of high production capacity extending from the Iberian Peninsula through France and Germany to Scandinavia, with strengthened links to eastern European regions. The highest production capacities are concentrated in Scandinavia, particularly Norway and Sweden, where abundant hydropower and wind resources provide favourable conditions for large-scale green hydrogen production. The Iberian Peninsula emerges as another major production hub, benefiting from exceptional solar irradiance and expanding wind capacity, while France, Germany, and the Benelux countries also develop substantial production capacity, reflecting strong policy support and industrial decarbonization strategies. The United Kingdom also emerges as an important production area, particularly in Scotland and coastal regions. Compared with the historical period, the geographic footprint expands considerably towards eastern Europe, where countries such as Poland, Romania, and the Baltic states emerge as important production areas, supported by renewable energy expansion and EU policy frameworks. Outside continental Europe, Morocco and Egypt stand out as the main hydrogen production hubs in North Africa. Morocco combines favourable renewable energy potential with strategic proximity to European markets, while Egypt expands rapidly by leveraging both Mediterranean coastal wind resources and Red Sea solar potential.

Despite this widespread expansion, regional heterogeneity remains evident by mid-century. Large parts of southeastern Europe and the Balkans show more moderate development, while most Mediterranean regions outside Morocco and Egypt continue to display limited hydrogen production capacity. These patterns suggest that, although renewable energy availability is a necessary prerequisite for hydrogen production, it is not sufficient on its own. Infrastructure availability, investment capacity, policy support, and market integration remain key factors shaping the long-term deployment of hydrogen production facilities. Overall, the projected distribution highlights the transition towards a mature, geographically diversified, and capacity-intensive hydrogen production system integrated into a Pan-European low-carbon energy system by 2050.

3.4 Multi-criteria analysis: environmental and socio-economic regional profiles

The Clean Hydrogen Explorer includes a **multi-criteria analysis** module, based on an interactive parallel-coordinates chart, that allows regions to be screened simultaneously against multiple indicators — water availability (WEI+, SPI), renewable energy potential and hydrogen deployment — across different time frames and climate scenarios.

By progressively filtering these axes (for example, selecting regions in the higher energy clusters, with WEI+ below the severe-stress threshold and limited intra-annual scarcity), **the tool identifies the areas that combine favourable water and energy conditions for future hydrogen development**. The full interactive functionality, including the recursive filtering shown in Figure 3-11, is available directly on the [Clean Hydrogen Explorer](#).

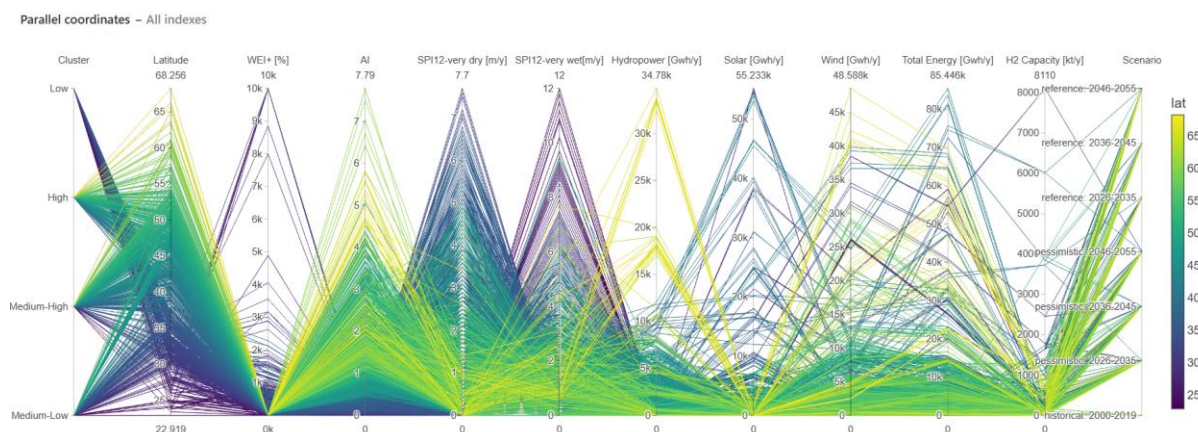


Figure 3-11: Recursive filtering example

Building on this multi-criteria screening, the two subsections below deepen the assessment of the identified regions along two complementary dimensions: their **environmental performance** (energy use, water footprint and greenhouse-gas emissions) and their **socio-economic implications** (water-use pressure and macroeconomic benefits).

Environmental Impacts

The assessment was complemented by an environmental and socio-economic evaluation that examined the performance of representative hydrogen production configurations across seven macro-regions. For each region, three sustainability metrics were considered: Specific Energy Consumption (kWh/kgH₂), Water Footprint (kgH₂O/kgH₂) and greenhouse gas emissions, expressed as Global Warming Potential over a 100-year horizon (GWP100, kgCO₂e/kgH₂).

For every macro-region, the two most feasible production configurations were defined for each electrolyser type (Alkaline – AEL and PEM) by combining technological constraints (water-treatment and cooling systems – dry, wet, once-through) with regional characteristics (water source and availability, renewable electricity mix and climatic conditions). **GHG emissions were then computed on a cradle-to-gate basis for the production of 1 kg of hydrogen**, summing three contributions: the operational phase of the electrolyser, which is the dominant driver (more than 90% of the total and directly proportional to the electricity emission factor); the construction and end-of-life of the electrolyser (about 5–7%); and the water-treatment plant over its construction, operation and end-of-life (about 1%).

Because **electricity is by far the main driver**, the regional differentiation of the results stems essentially from the emission factor of the renewable electricity source. These emission factors were derived from two environmental databases providing technology- and region-specific data: the **EcoQuery database (ecoinvent)**, used for hydropower – distinguishing alpine and non-alpine sources – photovoltaics and wind; **and the IEA PVPS database, adopted as an alternative source for photovoltaics**, since the EcoQuery value was considered excessively high. The renewable share of each region was categorised in accordance with IEA public monitored data as Low (0–20%), Moderate (20–40%), High (40–60%) and Very High (60–100%).

For each region, the best configuration was therefore selected as the one characterised by the lowest GWP100 value among the feasible combinations of renewable source, electrolyser and cooling system. It should be noted that the renewable source with the highest share in a region is not necessarily the one yielding the lowest emissions: for instance, where hydropower dominates the mix, wind electricity can still deliver a lower GWP100 once system efficiencies are taken into account. No other indicator was used for the regional ranking, since GWP100 is the only metric that varies as a function of regionality: Specific Energy Consumption and Water Footprint are much more stable values, being governed by the adopted technology rather than by location.

Table 3-2: Final environmental evaluation for each region

Region	Renewable Share	Water availability	Best Configuration in terms of GHG emissions	Note
Nordic-Baltic	Very High	Very High	Wind Electricity, freshwater	Hydropower is the RES with the highest share. However, the lowest results in terms of GHG emissions are obtained by wind electricity.
Western-Atlantic	Moderate	Moderate	Hydro (alpine) electricity, freshwater	Wind power is the RES with the highest share. However, the lowest results in terms of GHG emissions are obtained by hydro (alpine) electricity
Central-Continental Europe	High	High	Hydro (alpine) electricity, freshwater	Wind power is the RES with the highest share. However, the lowest results in terms of GHG emissions are obtained by hydro (alpine) electricity

Mediterranean Europe	High	Moderate	Hydro (alpine) electricity, freshwater	Water availability is referred to freshwater. However, also seawater has been evaluated as water source. Hydropower has been selected being the RES with the highest share and the lowest GHG emission value
Danube-Black Sea South Caucasus	Moderate	Moderate	Wind electricity, freshwater	Hydropower is the RES with the highest share. However, the lowest results in terms of GHG emissions are obtained by wind electricity.
Western Balkans	High	Moderate	Hydro (non-alpine) electricity, freshwater	Hydro power has been the only RES accounted for this region.
North Africa-Mediterranean	Low	High	Wind electricity, seawater	Water availability is referred to seawater. Low renewables penetration and freshwater scarcity make this region less suitable for sustainable hydrogen production

The data selected show that **greenhouse gas emissions are strongly influenced by the electricity source** used for hydrogen production. Wind-based configurations generally achieved the lowest carbon intensities, typically in the range of 2.0–2.4 kg CO₂e per kg of hydrogen, while hydropower-based configurations also performed favourably in regions with abundant hydroelectric resources. Solar photovoltaic pathways showed higher variability depending on local conditions.

Water sourcing and cooling strategies introduce regional trade-offs. In water-scarce regions, desalinated seawater emerges as a viable solution for maintaining hydrogen production while reducing pressure on freshwater resources. Desalination increases energy consumption compared with freshwater treatment and therefore may affect overall environmental performance depending on the electricity carbon intensity. Dry cooling systems minimise water use but require more energy, whereas wet or once-through cooling options are mainly feasible in water-abundant regions.

At aggregate level, **hydrogen-related water withdrawals remain relatively small compared with overall sectoral demand.** Nevertheless, certain countries and regions already experiencing high levels of industrial water stress may face increased competition for water resources. The analysis highlights Denmark, Morocco, Tunisia, Spain and Ukraine as areas where hydrogen expansion could increase pressure on industrial water use and where integrated water-management planning will be important.

Since hydrogen production falls within the industrial sector, a high over withdrawal in the industrial sector indicates a risk of negative spillovers within the industrial sector, whose infrastructure is under-dimensioned *latu sensu* with respect to the future needs of hydrogen facilities (also called “within” spillovers). Likewise, a high over-withdrawal compared with other sectors indicates that **negative spillovers might arise in other sectors**, in case hydrogen production occurred in spatial adjacent to agricultural or municipal contexts (also called “across” spillovers). Finally, the Table 3-3 includes the percentage shares of hydrogen production capacity (in terms of MW of electricity) with respect to the regional total.

Table 3-3: percentage shares of hydrogen production capacity (in terms of MW of electricity) with respect to the regional total

Macro-region	Share of 2050 hydrogen production	Over-withdrawal of water compared with:		Comment on potential spillovers from over-withdrawal due to 2050 hydrogen production	Assessment of the sectorial pressure effect
		Industrial sector	Other sectors		
Nordic-Baltic	13%	+1.5%	+1.4%	Most (73.8%) of the regional projected hydrogen production capacity will be installed in countries with suitably developed water infrastructure in all available aggregate sectors. However, Denmark and Latvia might raise concerns both in terms of within and across spillover effects	High (due to “within” and “across” spillover effects)

Western-Atlantic	11%	+0.6%	+0.2%	Virtually all the regional projected hydrogen production capacity will be installed in countries with suitably developed water infrastructure in all available aggregate sectors. Marginal concerns for spillovers within the industrial sector in UK (and Ireland)	Moderate (due to “within” only spillover effects)
Central-Continental Europe	14%	+0.3%	+0.4%	Virtually all the regional projected hydrogen production capacity will be installed in countries with suitably developed water infrastructure in all available aggregate sectors	Low
Mediterranean Europe	25%	+0.8%	+0.1%	Virtually all the regional projected hydrogen production capacity will be installed in countries with suitably developed water infrastructure in available aggregate sectors. Marginal concerns for spillovers in Spain	High (due to “within” and “across” spillover effects)
Danube-Black Sea South Caucasus	7%	+0.3%	+0.4%	Virtually all the regional projected hydrogen production capacity will be installed in Ukraine, with some concerns about spillovers within the industrial sector and across aggregate sectors	Low
North Africa-Mediterranean	30%	+3.0%	+0.4%	Most of the productive capacity will be installed in Egypt, that displays very limited concerns for spillovers within the industrial sector and (much less so) for effects across aggregate sectors. However, the rest of the capacity will be located in Morocco and Tunisia, which do raise concerns for both types of spillovers, especially for the ones within the industrial sector	High (due to “within” only spillover effects)

Table 3-3 reports only the macro-regions for which the common methodology identifies a non-null hydrogen production capacity by 2050; regions with no projected hydrogen production capacity at that horizon are therefore not included in the assessment.

Considering water used in industrial contexts, projected hydrogen capacity by 2050 is expected to induce a limited over-withdrawal of +0.6% across regions. Considering water used across other sectors, this number is even lower, standing at +0.2%.

Overall, the multi-criteria assessment shows that suitability for hydrogen production depends not only on renewable energy availability, but also on water-resource conditions, environmental performance, and the broader socio-economic context. Regions with strong renewable resources but severe water limitations may still support hydrogen development, provided that appropriate water management strategies, alternative water sources and efficient technologies are adopted.

Socio-Economic Impacts

The development of hydrogen projects across the analyzed countries yields substantial macroeconomic benefits, with projected GDP impacts by 2050 of about €423-572 billion.

The installation of additional hydrogen capacity by 2050 is expected to increase GDP levels by less than 1.5% in most analysed clusters, especially European ones, at 2025 prices. The North Africa-Mediterranean cluster is among the most promising when comparing projected investments with current GDP. The focus of central governments and the potential for wind and photovoltaic production have promoted this development, but it remains uncertain whether these countries will overcome regulatory, institutional barriers and high funding costs. In this cluster, GDP increases are expected to be significantly higher than 1.5%, although this estimate should be interpreted cautiously.

The overall GDP contribution from additional hydrogen capacity is calculated as the sum of three tiers: direct (economic value generated within the hydrogen value chain), indirect (generated along upstream

supply chains), and induced contributions (arising from household consumption financed by labour income). The breakdown of economic indicators, contribution types and time horizons is detailed below.

Table 3-4: GDP (billion €) by macro-region as overall sum of Direct, Indirect and Induced GDP

GDP by macro-region	Assessment of the effect	2030	2040	2050
Nordic-Baltic	High	26 - 35	38 - 51	45 - 61
Western-Atlantic	Modest	30 - 40	37 - 50	46 - 62
Central-Continental Europe	Modest	24 - 32	36 - 49	47 - 64
Mediterranean Europe	High	62 - 84	78 - 105	106 - 144
Danube-Black Sea South Caucasus	High	0.9 - 1	0.9 - 1.1	23 - 31
North Africa-Mediterranean	Very high	50 - 68	76 - 103	156 - 210
TOTAL ACROSS ALL THE MACRO-REGIONS		193 - 260	266 - 359	423 - 572

The cluster of countries selected that was considered for the GDP and employment analysis included the entities that are projected to possess a non-null production capacity of hydrogen by 2050 according to the common methodology.

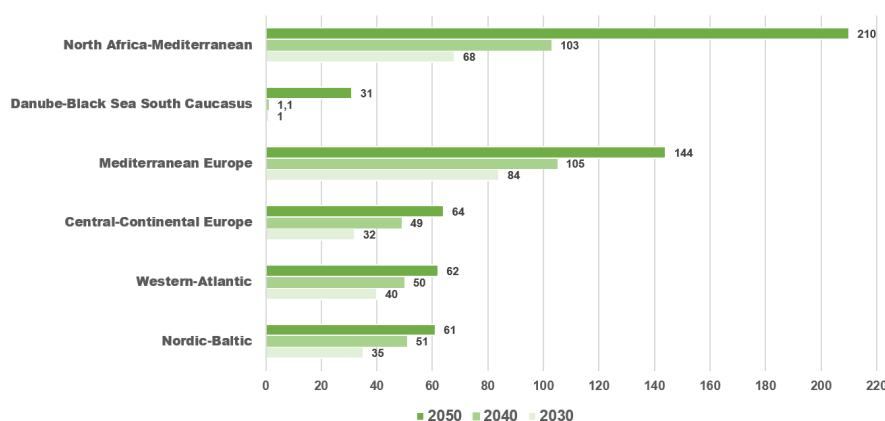


Figure 3-12: Upper-bound GDP (billion €) by macro-region as overall sum of Direct, Indirect and Induced GDP

Full-Time Equivalents (FTE) quantify employment impacts by converting total hours worked into equivalent full-time workers. Employment figures are reported as overall totals, since a breakdown of direct, indirect and induced FTEs cannot be provided with the same reliability as GDP metrics. Table 3-5 shows the FTE employment generated by additional hydrogen capacity over time: for instance, in the Nordic-Baltic macro-region, from 2030 to 2040 the completion of hydrogen production projects will have generated 100k new FTE places of employment.

Table 3-5: Full Time Equivalent (FTE, thousands) employment generated by macro-region

Full Time Equivalent by macro-region	Assessment of the effect	2020-2030	2030-2040	2040-2050
Nordic-Baltic	Very high	105	100	107
Western-Atlantic	Low	100	80	89
Central-Continental Europe	Low	91	90	105
Mediterranean Europe	High	208	168	207
Danube-Black Sea South Caucasus	High	3	2	49
North Africa-Mediterranean	Modest	164	160	292
TOTAL ACROSS ALL THE MACRO-REGIONS		671	600	849

Corresponding employment impacts demonstrate similar regional variance, scaling to 849 thousand FTE by 2050. Together with the corresponding GDP estimates, FTE for the North Africa-Mediterranean

cluster will have to be monitored closely, tracking the evolution of the regulatory landscape and factual commitment from central governments.

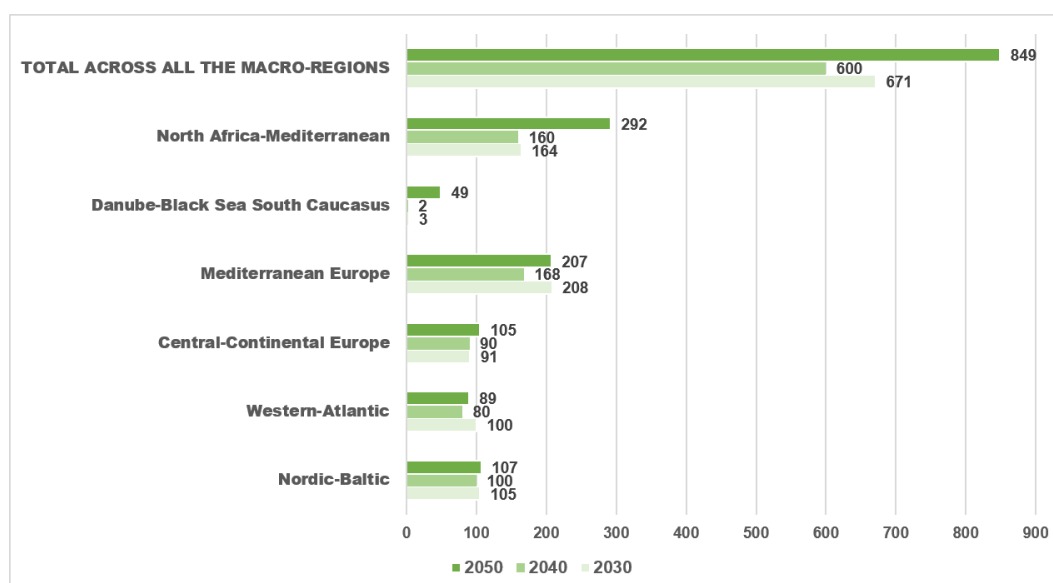


Figure 3-13: Full Time Equivalent (FTE, thousands) employment generated by macro-region

3.5 Preliminary conclusions from the geospatial visualisation

The geospatial visualisation exercise demonstrates that renewable hydrogen development opportunities are not distributed evenly across Europe and neighbouring regions. Future deployment is strongly influenced by the spatial interaction between water availability, renewable energy potential and hydrogen production capacity. Regions with abundant renewable resources do not necessarily coincide with regions characterised by favourable water conditions, making the water–energy nexus a key determinant of future hydrogen deployment.

At the continental scale, the overall impact of hydrogen on water resources remains modest. The assessment shows that hydrogen-related water withdrawals represent only a small fraction of total water demand and do not fundamentally alter the overall balance of water use across Europe. **Projected hydrogen-related over-withdrawal compared with existing sectoral water withdrawals generally remains limited, typically in the range of approximately 0.1–1.5%, while overall water withdrawals associated with hydrogen production are estimated to increase total withdrawals by only around 0.2–0.6%.** These results indicate that hydrogen is unlikely to become a dominant driver of water demand at national or continental scale and does not overwhelm existing water-use patterns.

However, aggregate figures conceal important regional differences. The largest future concentrations of hydrogen production capacity are projected in regions already facing significant water stress, particularly the **North Africa–Mediterranean** and **Mediterranean Europe** macro-regions. By 2050, these two macro-regions are expected to account for the largest shares of hydrogen-related water demand (**30%** and **25%**, respectively). At the same time, these regions already experience chronic water scarcity, high Water Exploitation Index values, recurrent drought conditions and increasing pressure from other water users. Climate change is expected to intensify these challenges through declining freshwater availability and increasing drought frequency.

This reveals a central finding of the geospatial visualisation exercise: **aggregate comfort and local risk point in opposite directions.** While hydrogen represents a relatively small additional demand at European scale, the strongest projected growth in hydrogen production coincides with some of the most water-constrained regions in the study area. In contrast, regions such as the **Nordic–Baltic** and parts of the **Western–Atlantic** macro-region combine abundant water resources, lower water stress and strong renewable energy potential, providing greater capacity to accommodate future hydrogen development with limited additional pressure on water resources.

The geospatial visualisation also highlights that renewable energy availability alone is not sufficient to determine hydrogen suitability. Water availability, drought risk and long-term climate resilience emerge as equally important factors. Several Mediterranean, islands and North African regions display excellent renewable resource potential but face structural water constraints that may limit future deployment unless alternative water sources and dedicated water-management solutions are adopted. Sustainable hydrogen development therefore depends not only on access to renewable electricity but also on the ability to secure reliable water supplies under future climatic conditions.

From a technological perspective, the assessment further confirms that water source selection, treatment requirements, cooling configuration and electrolyser technology play a critical role in determining overall sustainability. In water-stressed regions, desalinated seawater, brackish water and treated wastewater will likely become increasingly important for reducing pressure on freshwater resources. Similarly, cooling-system selection can significantly influence both water consumption and overall environmental performance. These technology choices therefore become particularly important in regions where hydrogen expansion coincides with increasing water scarcity.

An important conclusion emerging from the regional analysis is that large-scale assessments provide a consistent basis for comparing regions and identifying broad development opportunities, but they cannot capture basin-specific constraints, seasonal variability, groundwater dynamics or local competition among users. For this reason, integrated and spatially explicit planning tools such as the **Clean Hydrogen Explorer** provide an essential first screening capability, but detailed basin-scale assessments remain necessary to evaluate actual project feasibility and sustainability.

These findings provide the rationale for the case studies presented in the next chapter. In particular, the analysis identifies water-stressed Mediterranean and island regions, together with locations where ambitious hydrogen deployment overlaps with existing or projected water scarcity, as priority areas for closer investigation. **The selected case studies therefore move beyond the regional perspective developed in this chapter and examine how water availability, seasonal dynamics, competing water uses and climate change affect hydrogen deployment at basin scale.**

KEY TAKEAWAYS



Key messages from the geospatial visualisation

- **Water conditions will influence where renewable hydrogen can expand sustainably**, particularly in Mediterranean and North African regions facing structural water scarcity.
- **Renewable energy availability alone is not sufficient**; water stress and climate resilience must be integrated into hydrogen planning and investment decisions.
- **Technology choices**, including water source, treatment systems, cooling strategy and electrolyser configuration, are critical for minimising environmental impacts and maintaining sustainable operation.
- **Integrated planning tools**, including the Clean Hydrogen Explorer and basin-scale hydrological modelling, are essential to support evidence-based decision-making and align hydrogen development with water security objectives.
- **Regional assessments are a necessary first step, but case-study analysis at basin-scale is indispensable** for understanding local constraints, seasonal water availability and project-level sustainability.

4 CASE STUDIES

4.1 How the case studies were selected – Analytical framework for the case studies selection

The selection of the case studies was designed to move the analysis from a **regional perspective** to a **project-level assessment**. While the regional screening identified broad patterns of water stress, renewable energy potential and water-use efficiency, it could not fully capture the operational implications of hydrogen production at local scale. The case studies were therefore introduced to test how these regional conditions translate into real projects and to provide a focused set of examples reflecting different combinations of water constraints, territorial conditions and hydrogen development opportunities.

The selection process was based on three key indicators: **water stress**, representing the pressure on available water resources; **water-use efficiency**, used as a proxy for the economic value generated per unit of water consumed; and **renewable energy potential**, indicating the technical opportunity for renewable hydrogen deployment. These indicators were assessed together because none of them alone is sufficient to identify representative cases. The analytical value of the framework lies in the combined assessment of **resource pressure**, **economic water productivity** and **renewable deployment potential**.

Countries were initially screened through the relationship between water stress and water-use efficiency, while renewable potential was represented through bubble size. Threshold values of **12.5% for water stress** and **50 USD/m³ for water-use efficiency** were used to distinguish four territorial profiles: high productivity/high stress, high productivity/low stress, low productivity/high stress, and low productivity/low stress. This classification was not intended to rank countries, but to identify different strategic contexts for hydrogen deployment and ensure that the selected case studies captured the diversity of conditions under which hydrogen projects may operate.

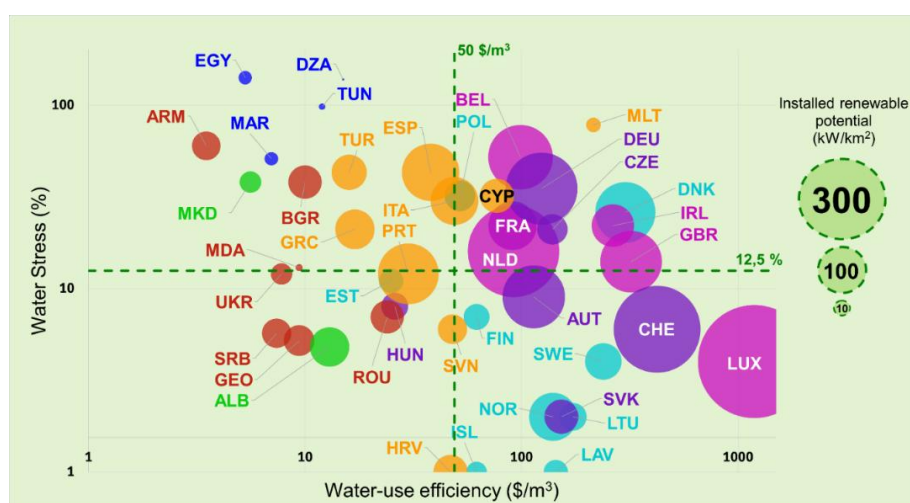


Figure 4-1³: Distribution of countries within the study based on their water stress (%), water use efficiency (\$/m³) and its renewable potential (directly proportional to the size of each country's bubbles) [1] [2][3]

To improve the interpretation of the results, a complementary classification based on the **25th and 75th percentiles** of the three indicators was added. This approach helped distinguish relatively weak, intermediate and strong territorial performance and supported a more systematic identification of broader territorial profiles. The resulting framework provided a robust basis for selecting a balanced set of case studies, ensuring that the analysis covered a wide range of water, energy and development conditions relevant to renewable hydrogen deployment.

³ The acronyms used for each country correlate with the ISO 3166-1 alpha3 standard.

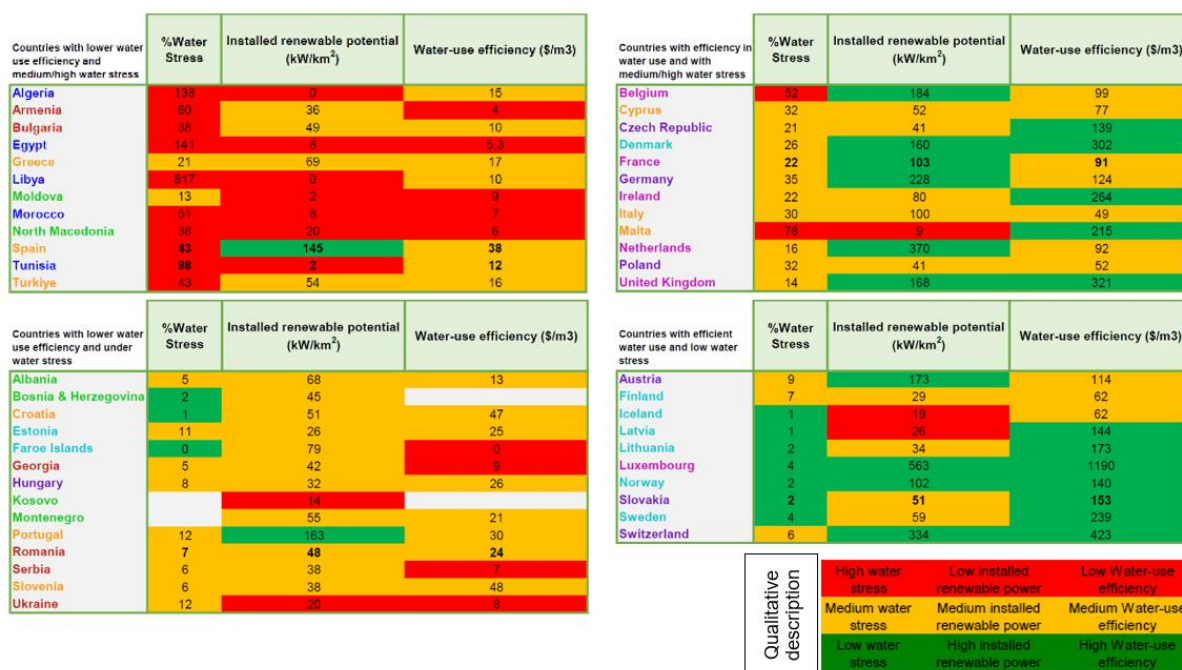


Figure 4-2: Visual representation of the colour classification, based on the 25th and 75th percentiles of the three variables [1], [2], [3]

The five projects

The five case studies were selected through a systematic methodology to ensure a representative range of hydro-climatic, water-resource and renewable hydrogen deployment conditions across Europe. The selection considered regional indicators related to water stress, water-use efficiency and renewable hydrogen production potential, while information from the *Clean Hydrogen Explorer* platform is included to provide additional regional context on climatic, hydrological and energy conditions of each case study. Together, these elements provide a robust basis for comparative analysis and the development of transferable recommendations. The resulting portfolio of case studies coincides with five Hydrogen Valleys⁴ co-funded by the Clean Hydrogen Partnership; together with their representative characteristics and contribution to the comparative assessment, it is summarised in Table 4-1.

Table 4-1: Characteristics and rationale for the selection of the five Hydrogen Valley case studies.

Hydrogen Valley	Regional profile	Main application sectors	Hydro-climatic context	Purpose within the assessment
Green Hysland (Spain)	Mediterranean island	Mobility, power generation	High seasonal water stress	Assess hydrogen deployment under water-constrained conditions.
EPHYRA (Greece)	Mediterranean mainland	Industry, energy	Seasonal variability	Compare different Mediterranean water-management contexts.
IMAGHyNE (France)	Continental	Chemical industry, mobility	Stable hydrological conditions	Represent mature, less water-constrained regions.
EASTGATEH ₂ V (Slovakia)	Continental inland	Industry, transport	Moderate climatic variability	Extend the analysis to inland continental Europe.

⁴ Hydrogen Valleys - Clean Hydrogen Partnership - European Union

NAHV (Croatia)	Coastal transitional	Port operations, transport, industry	Stable coastal water conditions	Improve transferability to coastal regions.
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Together, these case studies provide a representative portfolio of European Hydrogen Valleys, enabling a robust comparison of hydrogen-water interactions across diverse territorial contexts and supporting the identification of transferable recommendations.

The main technical and operational parameters of the analysed electrolyser considered to perform the LCA study are then compiled in Table 4-2.

Table 4-2: Summary of the main features of case studies

	Green Hysland	IMAGHyNE	EPHYRA	EastGateH₂V	NAHV
Country	Spain	France	Greece	Slovakia	Croatia
Location	Lloseta, Mallorca Island	Lyon	Municipality of Agioi Theodoroi	Košice	Vinkovci, Croatia
Electrolyser, size	PEM, 2.5 MW	PEM, 27 MW	ALK, 30 MW	PEM, 2 MW	PEM, 10 MW
Status	Operational	Pre-FID	Under construction	Pre-FID	Pre-FID
H₂ production (ton/year)	300	4,000	4,989	500	315
Electricity (kWh/kg H₂)	55	62.5	53.9	52.5	51.7
Electricity source	Solar PV + PPA	Solar PV + Hydropower	Solar PV + Wind + PPA	Grid	Solar PV + PPA
Water consumption (electrolysis process) (L/kg H₂)	25	9.7	11.11	16.29	9.76
Pre-treatment water before electrolyser	RO+EDI	RO+EDI	RO+EDI	RO+EDI	Filtration+ RO+EDI
Cooling system	Closed circuit/loop	Closed circuit	Closed circuit	Closed circuit	Closed circuit
Water consumption (cooling) (L/kg H₂)	0.21	1.16E-3	9.952E-4	9.91E-2	9.36E-2
Water abstraction (L/kg H₂)	37.03	14.30	16.37	24.10	15.07
Water source	Tap water	Tap water	Tap water + Desalinated	Tap water	Well water

4.2.1 Green Hysland project – Spain

The Green Hysland project, located on the island of Mallorca, was selected as a representative Mediterranean and insular Hydrogen Valley due to the combination of strong renewable energy potential, seasonal water variability and significant competition for available water resources. The island's economy is strongly influenced by tourism, which concentrates population and water demand during the summer months, when water availability is generally lower. These characteristics make Green Hysland particularly relevant for assessing how renewable hydrogen production can be integrated without compromising existing socioeconomic activities and essential water uses [12][13][14].

Green Hysland aims to establish an integrated renewable hydrogen ecosystem covering the entire value chain, from photovoltaic electricity generation and hydrogen production to storage, distribution and end use. Renewable hydrogen is produced in Lloseta using a 2.5 MW PEM electrolyser, with an estimated production capacity of approximately 300 tonnes per year. The system is supplied by photovoltaic plants located in Lloseta and Petra and includes hydrogen distribution by pipeline and road transport for applications in public transport, buildings, tourism facilities, port activities and the local gas network [12][15]

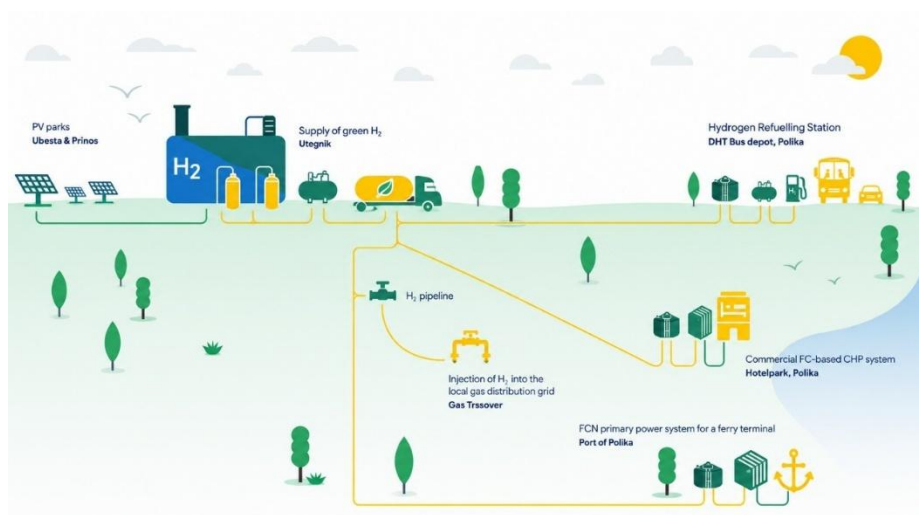


Figure 4-3: Diagram of the Green Hysland Project, showing the various parts of the hydrogen value chain implemented in the project [12]

The project's water demand must be considered within the specific water-resource context of Mallorca. Urban supply accounts for the largest share of water consumption on the island and is closely linked to tourism, followed by agriculture and other uses. Moreover, Mallorca relies predominantly on groundwater, complemented by reclaimed water, desalinated water and a limited contribution from surface resources. This combination of seasonal demand and dependence on groundwater increases the importance of coordinating hydrogen production with existing water uses [13][14]

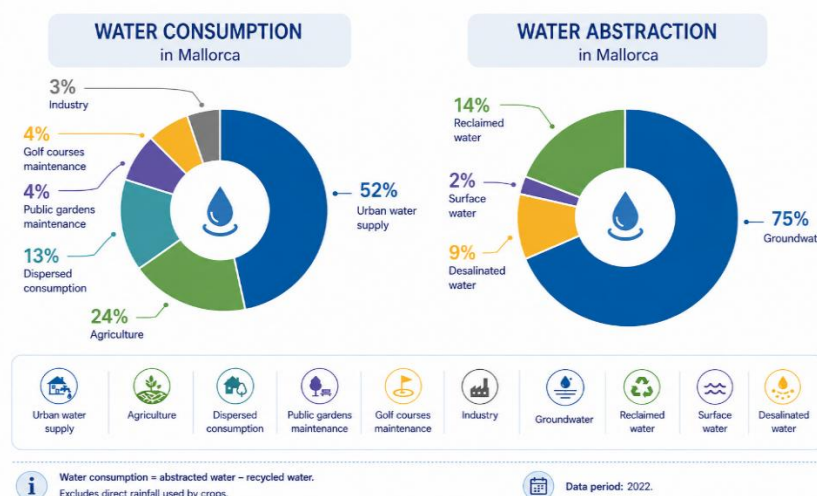


Figure 4-4: Distribution of water consumption and abstraction on the island of Mallorca [13][14]

The regional context was further characterised using information from the *Clean Hydrogen Explorer*. The WEI+ map (Figure 4-5) shows that Mallorca is located within a broader Mediterranean area subject to comparatively high pressure on water resources. This information was used to complement the regional assessment and to identify the potential influence of water stress on electrolysis-based hydrogen production, particularly during periods of reduced availability and increased seasonal demand

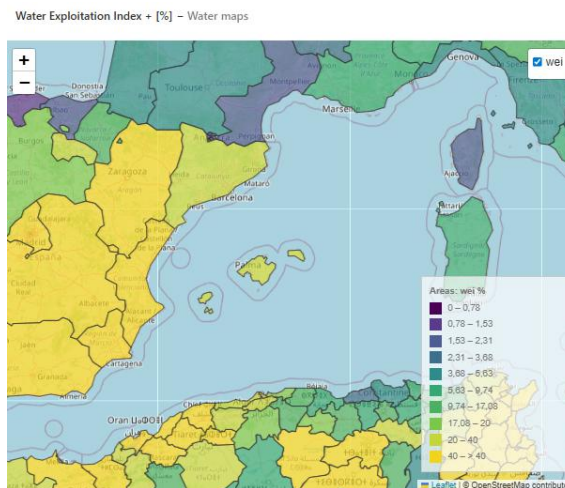


Figure 4-5: WEI+ values for Mallorca's zone obtained from the *Clean Hydrogen Explorer*.

Water consumption recorded during the initial operation of the hydrogen plant is approximately 25 L/kg H₂ for the hydrogen production process, while total water abstraction is estimated at around 37 L/kg H₂ when preliminary treatment requirements are considered. The treatment system includes chlorination and activated-carbon filtration, followed by reverse osmosis and ion-exchange deionisation to achieve the water quality required by the electrolyser. Although hydrogen production represents a relatively limited demand compared with the island's principal water uses, maintaining a reliable water supply throughout the year remains important for continuous operation.

Green Hysland represents one of the most water-sensitive cases included in the comparative assessment. Its insular configuration, seasonal tourism-driven demand, dependence on groundwater and limited surface-water availability provide a valuable basis for evaluating measures such as the use of reclaimed or desalinated water, improved coordination between water users, operational flexibility and water-storage solutions. The project also demonstrates how an integrated Hydrogen Valley can support energy-system decarbonisation while accounting for the constraints of a Mediterranean island environment [12][13][14][16].

4.2.2 IMAGHyNE project – France

The IMAGHyNE project, located in the Auvergne-Rhône-Alpes region, was selected as a representative continental Hydrogen Valley due to its high level of industrial integration and its alignment with the French and European hydrogen strategies. The project covers the complete hydrogen value chain, including renewable hydrogen production through electrolysis, storage, transport and end-use applications across industrial, mobility and energy sectors, making it a suitable case study for assessing the interaction between hydrogen production and water resource availability under mature industrial conditions [17].

The regional context was characterised using the *Clean Hydrogen Explorer*, which provides indicators of water stress and water availability across Europe. As shown in Figure 4-6, France is characterised by generally lower WEI+ values than the Mediterranean case studies, although noticeable regional variability exists. These conditions indicate that water availability is generally not expected to constitute a structural limitation for hydrogen deployment, while local and seasonal constraints associated with industrial activity and competing water uses should still be considered during project planning [18][19]

Water Exploitation Index + [%] – Water maps

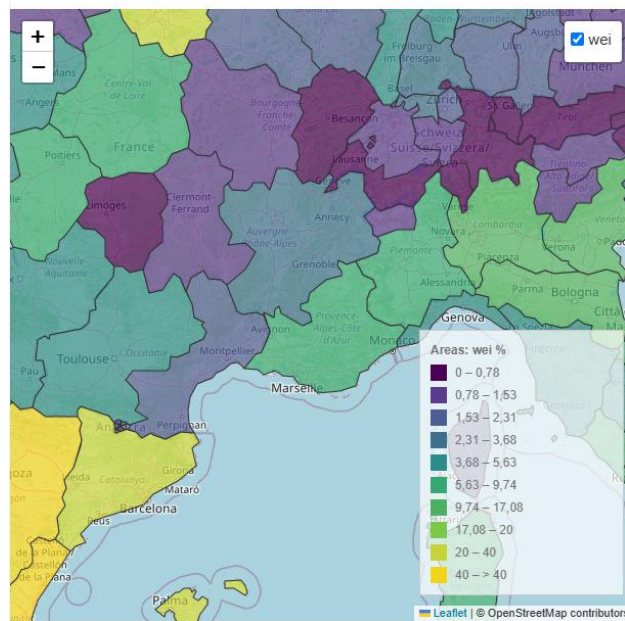


Figure 4-6: WEI+ values obtained from *Clean Hydrogen Explorer*

IMAGHyNE is designed as an integrated hydrogen ecosystem based on multiple distributed electrolysis plants connected through storage, pipeline infrastructure and road-based hydrogen distribution (Figure 4-7). The project aims to deploy up to 57 MW of electrolysis capacity, supplying renewable hydrogen to industrial processes, mobility applications and energy uses while demonstrating the Hydrogen Valley concept at regional scale [20][21][22].

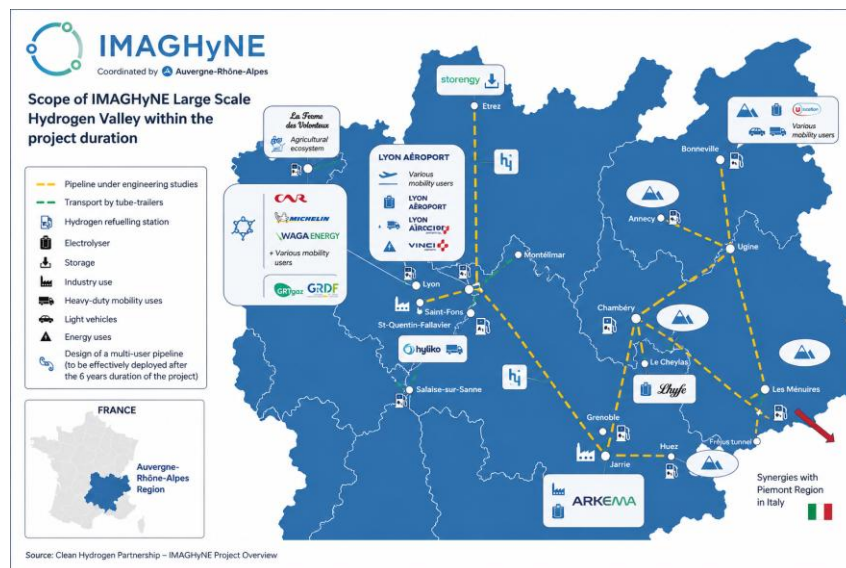


Figure 4-7: Spatial configuration of the IMAGHyNE hydrogen valley, including production, storage, transport and end-use sector.[20]

Although water availability in France is generally sufficient at the national level, competition among sectors remains an important consideration. Irrigation represents the largest share of water consumption, whereas energy production accounts for the highest proportion of water abstraction (Figure 4-8). Consequently, the deployment of electrolysis systems should be assessed within the broader context of regional water allocation and competing demands [23][24][25][26][27].

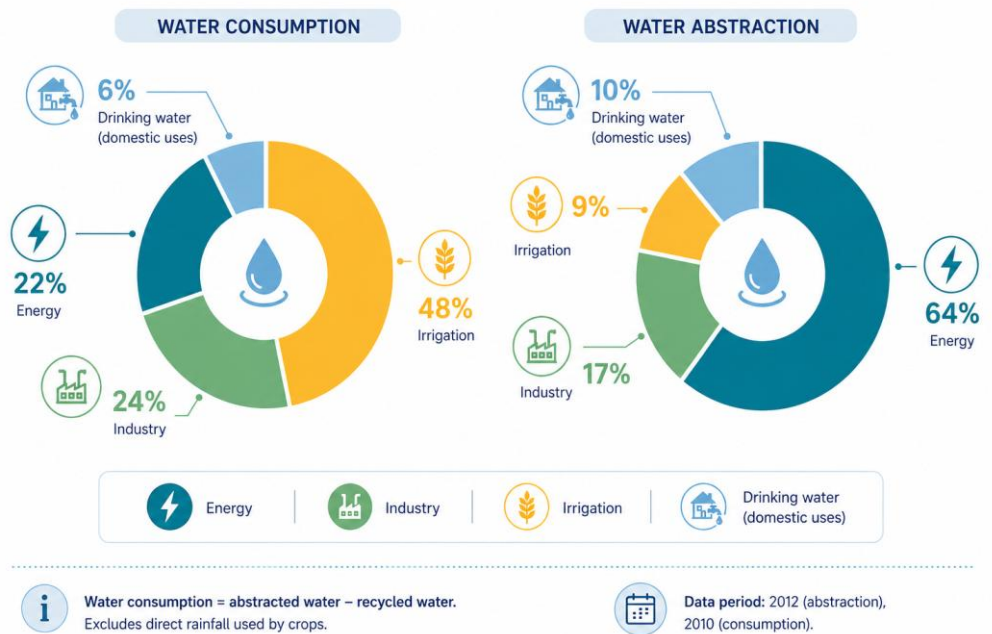


Figure 4-8: Water consumption and abstraction in France by sector [25]

IMAGHyNE complements the Mediterranean Hydrogen Valleys by representing a continental case study where hydrogen deployment is embedded within an established industrial ecosystem and comparatively stable hydrological conditions. This contrast supports the comparative assessment and the development of transferable recommendations for sustainable hydrogen deployment across Europe [17][26][27]

4.2.3 EPHYRA project – Greece

The EPHYRA project, located in Agioi Theodoroi (Corinthia, Greece), was selected as a representative Mediterranean Hydrogen Valley due to the combined challenges of water availability, renewable energy integration and industrial-scale hydrogen production. Developed within the TRIERES Hydrogen Valley framework, the project aims to demonstrate large-scale renewable hydrogen production integrated into the Motor Oil Hellas refinery, supporting the decarbonisation of industrial processes while contributing to the development of the hydrogen economy in South-Eastern Europe [28][29]

The regional context was characterised using the *Clean Hydrogen Explorer*, which provides indicators of water stress across Europe. As shown in Figure 4-9, Greece presents generally higher WEI+ values than the continental case studies, reflecting the greater pressure on water resources typically associated with Mediterranean regions. These conditions, together with pronounced seasonal variability, highlight the importance of considering water availability when planning electrolysis-based hydrogen production.

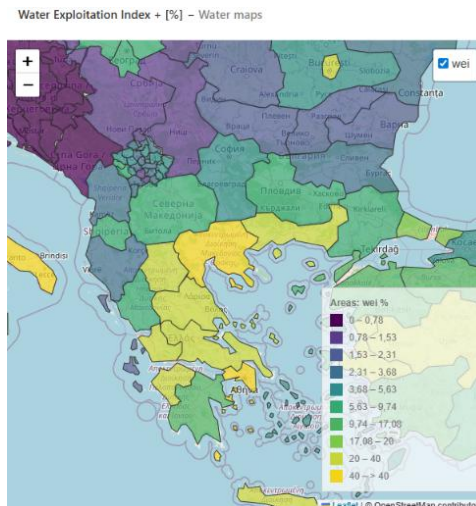


Figure 4-9: WEI+ values obtained from *Clean Hydrogen Explorer*.

The EPHYRA project is based on a 30 MW alkaline electrolyser integrated within an industrial refinery environment. The system is expected to produce approximately 2,400-2,500 tonnes of renewable hydrogen per year under base-case operation, with a potential production of up to 4,900 tonnes per year under full-load conditions. Renewable hydrogen will partially replace fossil-derived hydrogen currently consumed by refinery operations, demonstrating the integration of electrolysis into an existing industrial facility. [28]

The technical configuration combines renewable electricity from solar and wind resources with alkaline electrolysis, requiring approximately 11 L of process water per kilogram of hydrogen, an electricity demand of around 53.9 kWh/kg H₂, and an operational availability close to 91%. These characteristics highlight the close relationship between renewable electricity availability, water consumption and operational flexibility in large-scale hydrogen production systems [28][29][30]

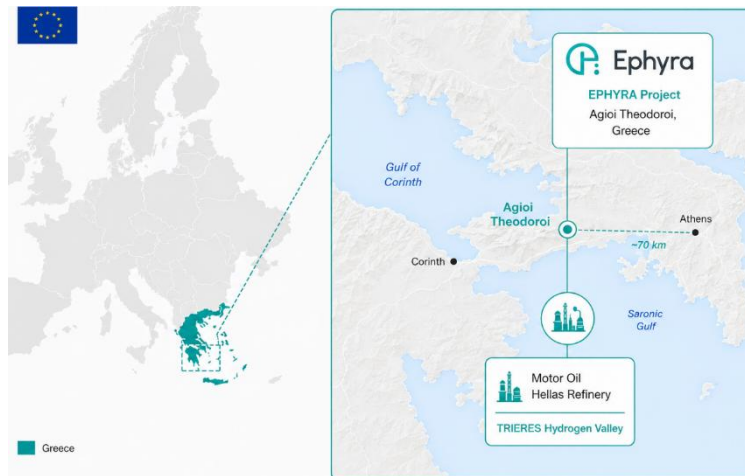


Figure 4-10: Geographical overview of the EPHYRA project in Greece.

Unlike the continental case studies, EPHYRA combines industrial-scale hydrogen production with the water constraints characteristic of the Mediterranean region. The proximity to coastal infrastructure and the potential use of treated wastewater and desalinated water provide opportunities to reduce pressure on conventional freshwater resources while improving the resilience of hydrogen production under future climate conditions. Consequently, EPHYRA represents a valuable case study for assessing adaptive water management strategies in industrial Hydrogen Valleys [28][31]

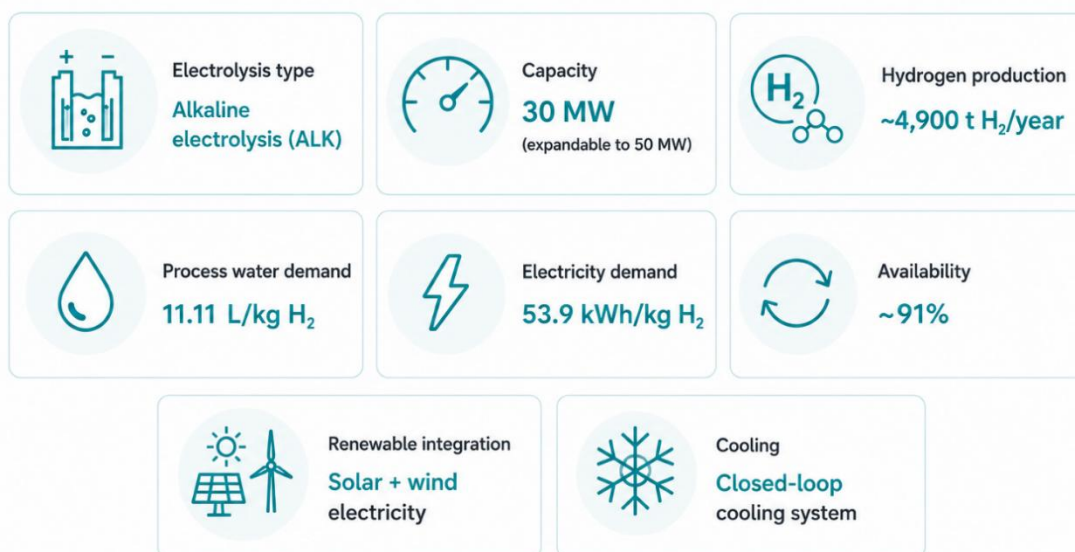


Figure 4-11: Main operational parameters considered for the EPHYRA case study [29]

4.2.4 EASTGATEH₂V project – Slovakia

The EASTGATEH₂V project, located in the Košice region in eastern Slovakia, was selected as a representative continental Hydrogen Valley characterised by relatively low water stress and stable water availability. The project supports the deployment of renewable hydrogen across industrial, mobility and energy applications through an integrated regional hydrogen ecosystem, contributing to the development of hydrogen infrastructure in Central and Eastern Europe and reinforcing cross-border cooperation with neighbouring countries [32][33].

The regional context is complemented by the presentation of *Clean Hydrogen Explorer* (Figure 4-12). These values indicate relatively low levels of water stress in Slovakia compared with the Mediterranean case studies, suggesting that water availability is unlikely to represent a structural limitation for electrolysis-based hydrogen production. Nevertheless, seasonal variability and local hydrological conditions should still be considered during project planning. [34]

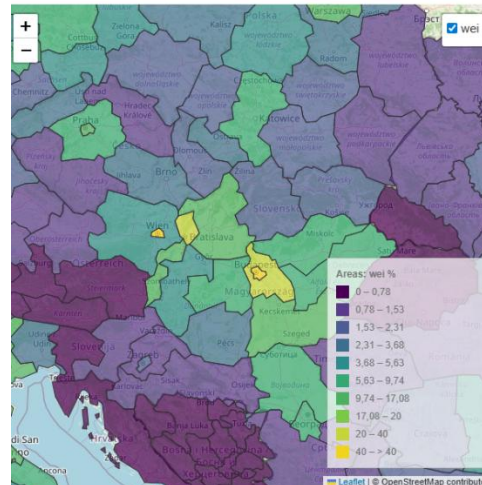


Figure 4-12: WEI+ distribution across Slovakia and surrounding regions based on the *Clean Hydrogen Explorer* assessment framework.

EASTGATEH₂V is being developed as a regional hydrogen ecosystem integrating renewable hydrogen production, trailer-based distribution and multiple end-use applications (Figure 4-13). The project foresees the installation of a 4 MW electrolysis system, combining 2 MW alkaline and 2 MW PEM technologies, with an expected production of approximately 500 t/year of renewable hydrogen. Planned applications include public transport, municipal service vehicles, tourism, aviation demonstrations and industrial hydrogen users [33]

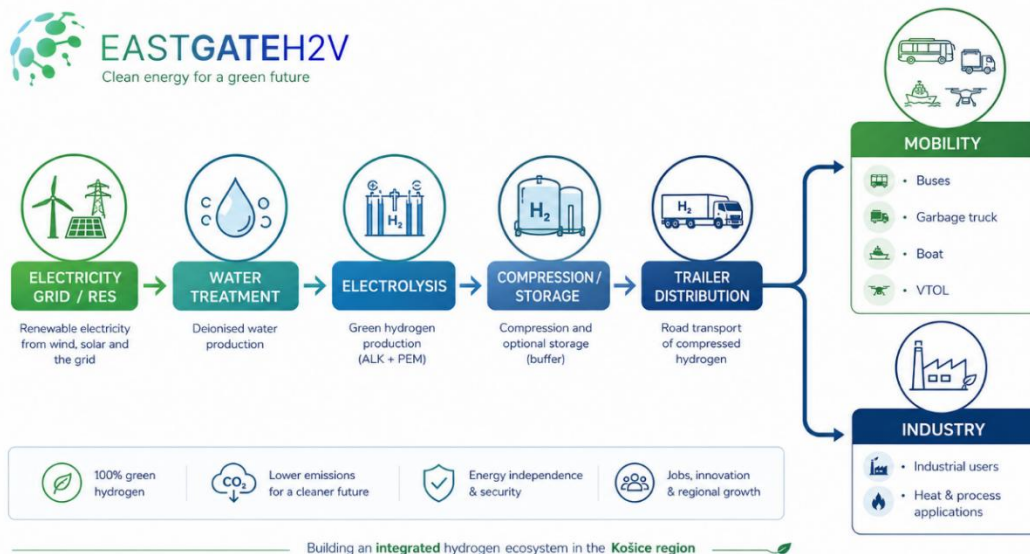


Figure 4-13: Simplified hydrogen value chain and system boundaries considered for the EASTGATEH₂V project [33]

The hydrogen production system is expected to operate around 8,000 hours per year, requiring approximately 9,000-15,000 m³/year of treated water. Water will be supplied by the local utility, treated to ultrapure quality for electrolysis, while the cooling system is designed as a closed-loop configuration, minimising additional water demand beyond the electrolysis process itself. Under these conditions, the projected water demand remains comparatively moderate relative to regional water availability [33]



Figure 4-14: Location of the EASTGATEH₂V project within Slovakia

EASTGATEH₂V provides a representative example of hydrogen deployment in a region where water availability is generally not expected to constrain hydrogen production. This contrasts with the Mediterranean case studies and enables the assessment of operational aspects such as production flexibility, infrastructure integration and long-term hydrogen deployment under comparatively favourable hydrological conditions [32][33][34].

4.2.5 NAHV project – Croatia

The North Adriatic Hydrogen Valley (NAHV) was selected as a representative case study within South-Eastern Europe due to its transnational character and its role in supporting the deployment of renewable hydrogen across Croatia, Slovenia and the Friuli Venezia Giulia region of Italy. The initiative aims to accelerate industrial decarbonisation through coordinated hydrogen production, storage, distribution and end-use applications, demonstrating the Hydrogen Valley concept across multiple industrial sectors and regional energy systems [35][36][37][38].

To provide additional regional context, Figure 4-15 presents the WEI+ values available through the *Clean Hydrogen Explorer* for the Panonska Hrvatska region. The low WEI+ value (approximately 0.96%) is consistent with the favourable water availability conditions identified for this case study, where water is not expected to represent a structural limitation for electrolysis-based hydrogen production under the analysed scenarios.

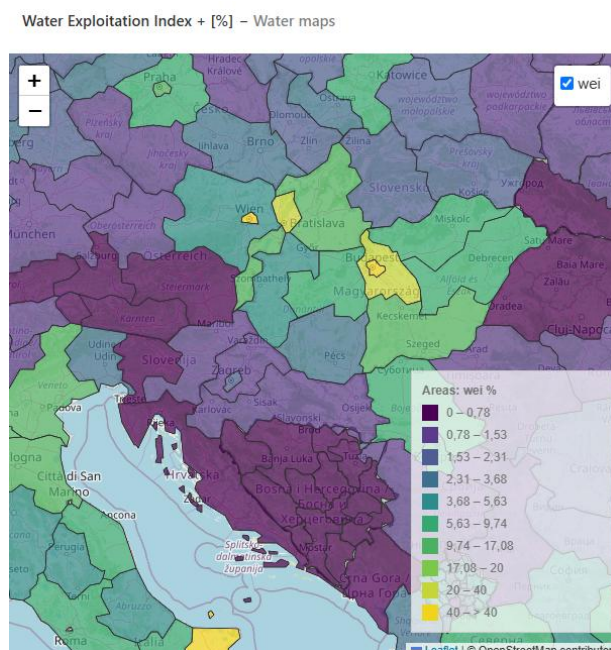


Figure 4-15: WEI+ values obtained from the *Clean Hydrogen Explorer* platform.

Within the Croatian contribution to the NAHV initiative, the Dilj testbed was selected for detailed assessment. The project focuses on the on-site production of renewable hydrogen through a 10 MW PEM electrolyser to partially replace natural gas in tunnel kiln operations within the ceramics industry.

Hydrogen is produced, conditioned and stored on site before being injected into the kiln burners, providing a practical demonstration of hydrogen integration into an existing industrial process [36]

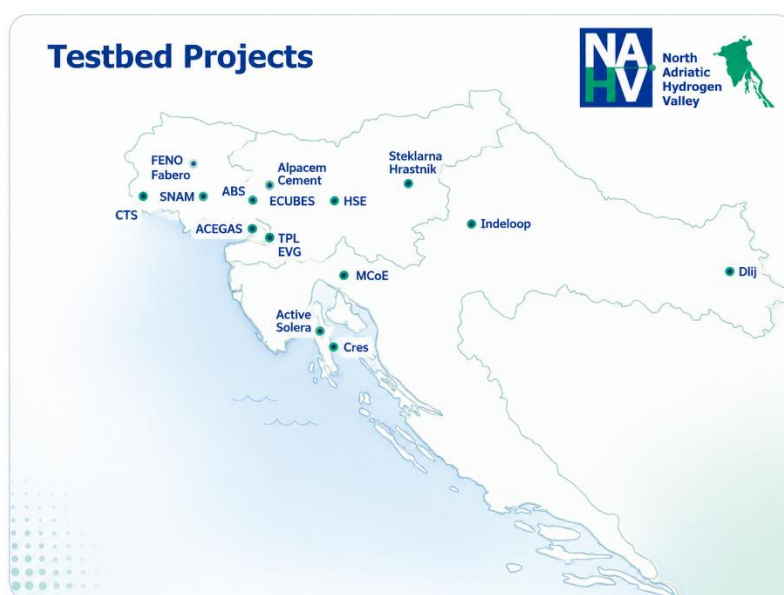


Figure 4-16: Distribution of NAHV testbed projects in Croatia and neighboring regions.
Adapted from [36]

The electrolysis system is expected to produce approximately 315 tonnes of renewable hydrogen per year under around 3,000 operating hours, with an estimated total water demand of approximately 15 L/kg of hydrogen, including process and auxiliary requirements. The project incorporates a closed-loop cooling system, reducing additional cooling water demand and demonstrating the integration of hydrogen production within an industrial facility under favourable regional water conditions (Figure 4-17) [36]

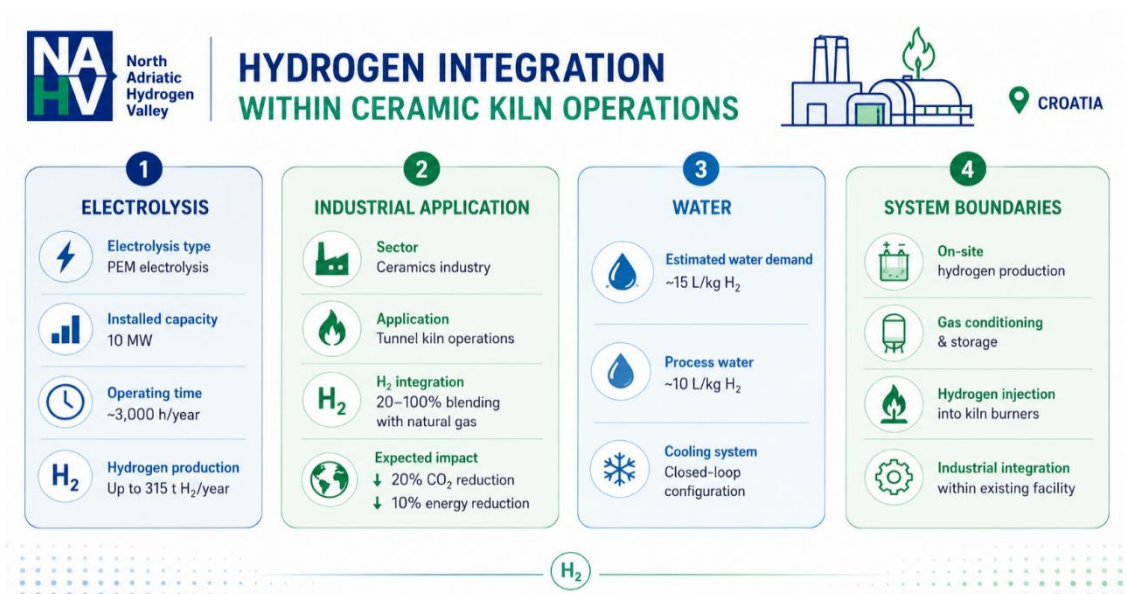


Figure 4-17: Technical overview of hydrogen integration within ceramic kiln operations in the Dilj testbed (NAHV) [36]

The NAHV case study represents a transnational Hydrogen Valley developed under comparatively low water-stress conditions. The assessed indicators show that water availability is unlikely to limit hydrogen deployment in the analysed Croatian context. Its main contribution to the comparative assessment therefore lies in demonstrating how renewable hydrogen can be integrated into existing industrial

processes through coordinated regional cooperation and under generally favourable hydrological conditions [37][38].

KEY TAKEAWAYS



Case studies reveal contrasting water resilience conditions for future hydrogen deployment

- Five representative Hydrogen Valleys were selected to capture contrasting hydrological, climatic and renewable hydrogen deployment conditions across Europe, providing a robust basis for comparative assessment.
- Mediterranean regions generally present greater exposure to seasonal water scarcity and climatic variability, increasing the likelihood of water-related operational constraints for hydrogen production.
- Existing hydrogen strategies, policy frameworks and industrial priorities differ substantially between regions, reinforcing the importance of location-specific planning and resilience measures.
- Although the selected projects differ in scale, sector and technology, their technical characteristics provide a consistent basis for evaluating how local water conditions may influence renewable hydrogen deployment.
- Despite differences in technology and project scale, the selected case studies provide a consistent basis for comparing the influence of regional water conditions on renewable hydrogen deployment.
- The *Clean Hydrogen Explorer* provides complementary information on the regional hydrological context of each Hydrogen Valley through indicators such as the Water Exploitation Index Plus (WEI+).

4.3 Case studies modelling and LCA analysis results

4.3.1 Modeling approach used for the case study

The assessment of water availability and its implications for renewable hydrogen production is based on an integrated modelling framework applied consistently across all case studies. **Historical simulations are used to characterise baseline conditions** over the reference period (2000–2019), while **future changes are evaluated through a top-down, scenario-based modelling approach** that translates climate projections into local hydrological and operational impacts. This enables a consistent comparison between present-day conditions and potential future developments in water availability and hydrogen production performance.

Consistently with the regional analysis, we **consider a historical reference period (2000–2019) and a future assessment period (2026–2055)**. Two climate scenarios for the future timeframes are considered: **SSP3-7.0**, representing a future with limited mitigation and fragmented governance, and **SSP5-8.5**, representing a high-emission pathway associated with continued fossil-fuel-based development. Future climate projections are generated using the **MRI-ESM2 Global Climate Model**, providing daily temperature and precipitation data as inputs for the assessment.

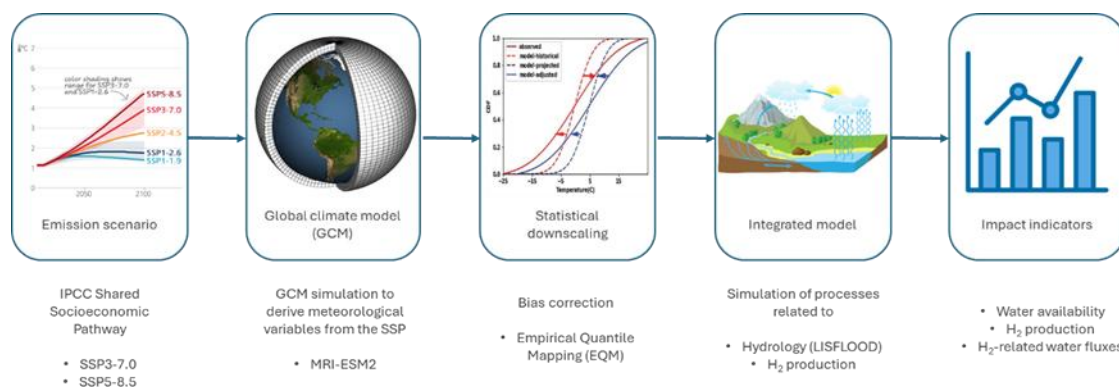


Figure 4-18: Components of the top down, scenario-based framework used to estimate the local impacts of hydrogen production.

To improve their suitability for local analyses, climate projections are statistically downscaled and bias-corrected using historical observations from the **EMO-5** dataset. The corrected climate variables are then used to drive the **LISFLOOD hydrological model**, which simulates key processes of the water cycle, including runoff, soil moisture, evapotranspiration, groundwater storage and river flows. The model also represents water use by major sectors such as agriculture, domestic supply, industry and energy production, while accounting for environmental flow requirements.

Hydrological outputs are then coupled with a dedicated hydrogen-production module that compares the available water resources with the water demand of each facility. When sufficient water is available, plants operate at full capacity; when water becomes limiting, production is proportionally reduced. This approach makes it possible to quantify potential operational constraints caused by changes in water availability. Hydrogen production is assessed specifically in relation to the surface water resources simulated by LISFLOOD: alternative sources such as groundwater, desalinated water, reclaimed water or public water supply are not explicitly represented, so the analysis considers only the share of hydrogen production that can be supported by the available surface water.

Therefore, **the analysis explicitly considers only the share of hydrogen production that can be supported by the available surface water**. The main assumptions of this approach can be summarised as follows:

- in both the historical and future scenarios, the hydrogen plant is assumed to be **fully operational** throughout the entire reference period;
- the hydrogen plant is assumed to have the **lowest priority** among competing water uses within the upstream catchment; the surface water available for hydrogen production is therefore limited to the **residual resource** remaining after existing water demands and environmental flow requirements have been satisfied;
- the plant has a **constant hydrogen production target**, maintained in both current and future scenarios;
- plant-specific **water-intensity coefficients** are assumed to remain constant over time.

The final outputs are aggregated into indicators describing both water resources and hydrogen-production performance, including surface water availability, hydrogen production supported by available resources, water withdrawals and consumption, water deficits, and the number of days affected by partial or insufficient water supply. These indicators provide the basis for comparing baseline and future conditions and for assessing the resilience of hydrogen production systems under changing climate conditions.

4.3.2 Results on water availability and operational performance

A comparative assessment across the five Hydrogen Valleys highlights how differences in hydro-climatic regimes, basin characteristics and plant size shape both the reliability of surface water availability and the hydrogen production that can be supported under historical and future climate conditions. **Two synthetic indicators are reported: the number of days per year in which surface**

water is fully sufficient to meet the hydrogen-related abstraction demand (Figure 4-19), and **the hydrogen production effectively supported by surface water resources** (Figure 4-20). The first indicator reflects the intrinsic reliability of local water availability, whereas the second also incorporates the effect of plant capacity, allowing a more comprehensive comparison across the case studies.⁵

The analysis explicitly accounts for the **environmental flow**, i.e. the minimum amount of water that must be left in the aquatic ecosystem to preserve its regular functioning. The days classified as "fully sufficient" therefore already assume that the environmental flow is preserved: only the water available above this ecological threshold is considered usable for hydrogen production. Second, a day counted as having no (or partial) surface water availability **does not mean that the plant is left without water or must be shut down**. It indicates that surface water alone is not sufficient to cover the demand while preserving the environmental flow; in such cases the plant would need to rely on complementary sources (e.g. groundwater, storage/seasonal buffering or, in coastal contexts, desalinated seawater), with the associated risk that abstracting from surface water beyond the sustainable limit could compromise the environmental flow.

Moreover, the indicators are examined along two complementary dimensions. A **seasonal dimension**, using the standard climatological three-month seasons denoted by the initials of their months: DJF (December–January–February, winter), MAM (March–April–May, spring), JJA (June–July–August, summer) and SON (September–October–November, autumn); this breakdown is essential because water constraints are typically concentrated in specific seasons, most notably summer (JJA). And a **time/scenario dimension**, comparing a historical reference period (2000–2019) with a future period (2026–2055) under two Shared Socioeconomic Pathways: SSP3-7.0 (a fragmented-development, limited-mitigation pathway) and SSP5-8.5 (a high-emission pathway).

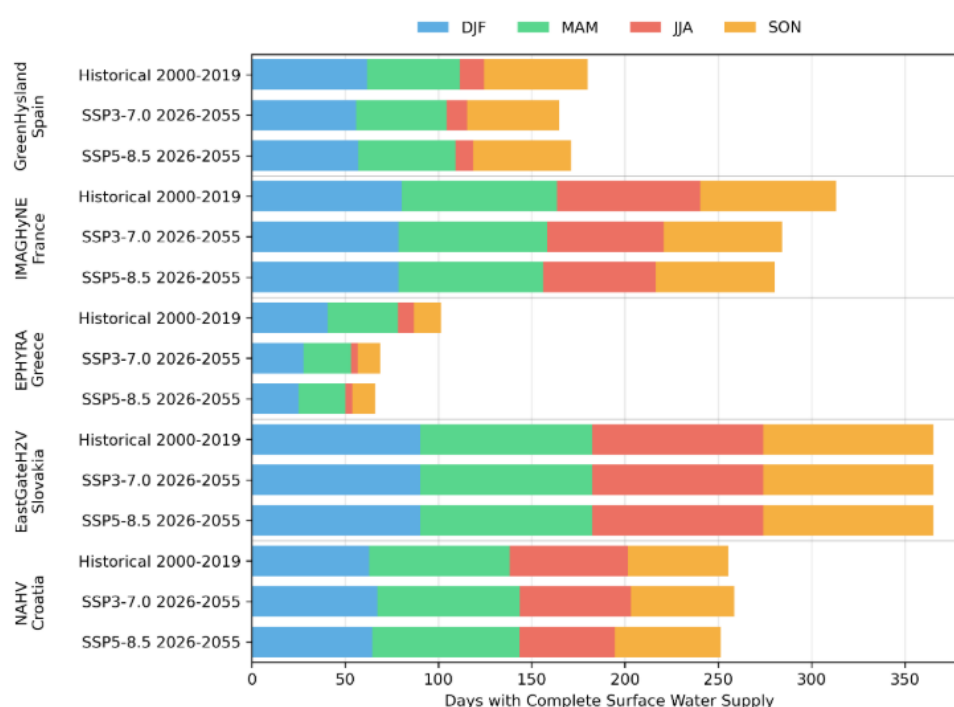


Figure 4-19: Days with complete surface water supply for the five considered Hydrogen Valleys

The **EastGateH₂V** project in **Slovakia** represents the most favourable case, with surface water resources **sufficient to sustain full hydrogen production throughout the entire year**. Under both

⁵ The two indicators are only a synthesis of the assessment: a full set of indicators for each Hydrogen Valley — including water availability, operational efficiency and withdrawal deficits — is available on the Clean Hydrogen Explorer.

historical and future climate conditions, the system maintains essentially 365 days of complete supply, a behaviour that reflects the abundance of water in the basin and the negligible impact of climate change on its hydrological regime. **IMAGHyNE in France follows, with more than 310 days of complete supply under historical conditions.** Future scenarios introduce a moderate reduction, with approximately 285 days under SSP3-7.0 and around 280 under SSP5-8.5, showing an increase in water stress but still preserving a high level of reliability.

Intermediate conditions emerge for the **NAHV** case study in **Croatia**, where historical values range **between 250 and 260 days of complete supply**. Future projections show limited deviations: SSP3-7.0 yields slightly more favourable conditions than the historical baseline, whereas SSP5-8.5 produces a modest reduction. **Green Hysland in Spain shows lower reliability, with roughly 180 days of complete supply** under historical climate conditions and further reductions under both future scenarios, particularly under SSP3-7.0, which reflects the stronger drying tendency projected for this pathway. The most critical situation is observed for **EPHYRA in Greece, where surface water is fully sufficient for only about 100 days per year** under historical conditions, decreasing to 60–70 days under future climates. This scarcity is not evenly distributed across the year: the reduction is especially drastic during the summer season, when surface water is sufficient for only a handful of days and hydrogen production would have to rely on alternative sources for almost the entire period (surface water covers less than about 20 days across summer and early autumn combined). The residual days of full surface-water supply are therefore concentrated in winter and spring. This behaviour is consistent with the strong sensitivity of Mediterranean basins to reduced water availability and increased climatic variability.

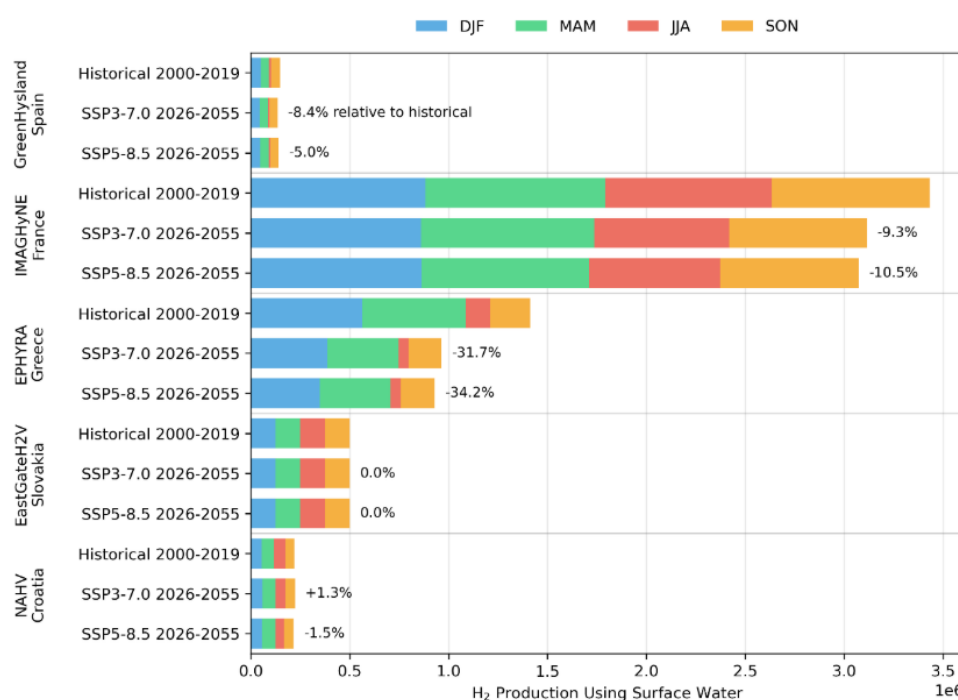


Figure 4-20: Hydrogen production (kg) using surface water for the five considered Hydrogen Valleys

When considering hydrogen production supported by surface water resources, the ranking changes because this indicator also reflects plant size. **IMAGHyNE** shows by far the highest production, with historical values around 3.4 million kg and moderate reductions under future scenarios (-9.3% under SSP3-7.0 and -10.5% under SSP5-8.5). Despite these decreases, the French case study remains the most productive Hydrogen Valley. **EPHYRA** ranks second, with approximately 1.4 million kg under historical conditions, but it also exhibits the strongest climate sensitivity, with reductions of -31.7% and -34.2% under SSP3-7.0 and SSP5-8.5 respectively, confirming the critical role of future water scarcity in the Mediterranean region.

EastGateH₂V maintains constant hydrogen production around **0.5 million kg** across all scenarios, reflecting the complete absence of water limitations and the ability of the plant to operate at full capacity throughout the year. **NAHV** shows **low production levels, around 0.2 million kg**, and an interesting non-linear response: SSP3-7.0 yields a slight increase (+1.3%), whereas SSP5-8.5 produces a small decrease (-1.5%). **Green Hysland** records the **lowest production, around 0.15 million kg** under historical conditions, with further reductions under future climates (-8.4% under SSP3-7.0 and -5.0% under SSP5-8.5), again with SSP3-7.0 representing the most critical scenario.

Overall, the five case studies span a wide gradient of hydro-climatic conditions, from water-abundant northern basins to highly water-constrained Mediterranean systems. The results reveal markedly different responses to climate change: some systems remain largely unaffected, while others experience strong reductions in water availability and hydrogen production potential. These differences highlight how **the sustainability of hydrogen production is fundamentally shaped by local hydrological regimes, the magnitude of competing water uses, and the sensitivity of each basin to future climatic pressures.**

The **Green Hysland** case study highlighted the importance of implementing **adaptive water management strategies** in regions exposed to **pronounced seasonal variability**. The analysis showed that **water deficits** are concentrated during the **summer** months, when reduced surface water availability coincides with increased pressure from competing water uses. Under these conditions, **seasonal buffering** emerged as one of the most effective measures to **increase operational resilience** by reducing the dependence of hydrogen production on short-term fluctuations in water availability. In addition, **desalination** may provide **a complementary water source** capable of supporting hydrogen production during critical periods, particularly in coastal regions where alternative freshwater resources are limited.

The **EPHYRA** case study represents the **most water-constrained environment** among the analysed Hydrogen Valleys and highlights the **challenges that future hydrogen deployment** may face in **Mediterranean regions** under increasing climate pressure. The results showed a substantial reduction in the number of days with sufficient surface water availability under future scenarios, reflecting the **strong sensitivity** of the basin to drought conditions and seasonal variability. To improve long-term operational reliability, the implementation of **seasonal buffering systems** was identified as a priority measure. Furthermore, **desalination** and advanced water treatment technologies may provide additional resilience by diversifying water supply sources and reducing dependence on limited freshwater resources during critical periods. In particular, the adoption of **ASEC-based Zero Liquid Discharge (ZLD) systems** (Figure 4-21) may represent a promising option to maximise water recovery and minimise wastewater generation, further strengthening the sustainability of hydrogen production in water-stressed regions.

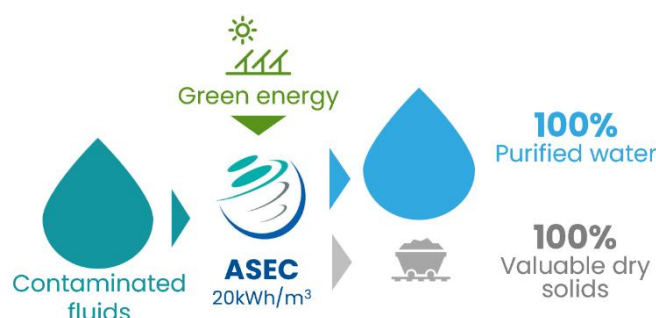


Figure 4-21: ASEC design global working scheme [5]

The **IMAGHyNE** case study demonstrated a comparatively high level of water availability and operational reliability under both historical and future climate conditions. Although future scenarios indicate a moderate reduction in the number of days with complete water supply, the overall impact on hydrogen production remains limited compared to the Mediterranean case studies. As a result, the recommended water management approach is primarily focused on **operational optimisation and resilience enhancement** rather than the development of new water supply infrastructures. In this context, **seasonal buffering** may contribute to improving system flexibility and reducing potential operational disruptions during occasional low-flow periods. Furthermore, the integration of **treated wastewater reuse** may provide an additional complementary water source, increase resource

diversification while reducing pressure on conventional freshwater resources, although its implementation should be evaluated according to local infrastructure and regulatory conditions.

The **EastGateH₂V** case study represents the most robust hydrological context among the analysed Hydrogen Valleys, with surface water resources consistently sufficient to support hydrogen production under both historical and future climate scenarios. The absence of significant water-related constraints suggests that future hydrogen deployment in the region is unlikely to be limited by water availability. Consequently, water management efforts should focus on **maintaining operational efficiency, monitoring future hydrological trends and ensuring sustainable resource use**, rather than implementing additional water supply measures. The results indicate that existing water resources provide a strong basis for long-term hydrogen production, allowing future planning activities to prioritise system optimisation and operational reliability rather than water security interventions.

The **NAHV** case study occupies an **intermediate position between** the highly resilient **Central European** systems and the more **water-constrained Mediterranean regions**. While the analysis identified some seasonal reductions in water availability, the overall impacts on hydrogen production remained relatively limited under both historical and future climate conditions. Consequently, the most appropriate water management approach is based on **adaptive and flexible measures** capable of enhancing resilience without requiring major additional infrastructure investments. In this context, **seasonal buffering** may help mitigate temporary shortages during critical periods, while maintaining operational flexibility to respond to future changes in water availability. The results suggest that a balanced strategy combining efficient resource management and targeted resilience measures can effectively support long-term hydrogen production under the hydrological conditions observed in the region.

Overall, the case studies demonstrate that the suitability of water management strategies **depends strongly on local hydrological conditions, climate vulnerability and project characteristics**. While **Mediterranean regions** may benefit from **buffering, desalination and advanced water recovery technologies**, more **water-abundant regions** can prioritise operational **optimisation and resource efficiency**. These findings confirm that no single solution is universally applicable and highlight the importance of **site-specific approaches** for ensuring the sustainable deployment of renewable hydrogen systems.

4.3.3 LCA comparison of the case studies

This section presents a **cross-comparison of the environmental performance** obtained for the reference scenarios **of the electrolyser of the five case studies assessed through the Life Cycle Assessment (LCA)** approach considering two impact categories: Climate Change (expressed in kg of CO₂ equivalent), and Water Use (expressed in m³ of water world equivalent). The functional unit selected to estimate the potential environmental impacts associated with electrolyzers was 1 kg of hydrogen. The system boundaries were focused on the **materials of electrolyzers, and the electricity and water requirements** (electrolysis process and cooling) in the electrolyzers operation. Inventory data for materials were extracted from literature [39][40] and the stakeholders of the case studies provided the operational data. The inventory data was modelled using the LCA for Experts software and supplemented with the Ecoinvent 3.12 database.

The LCA comparison discloses significant differences among the case studies depending on the electricity source supplying the electrolyser. As shown in Figure 4-22 and Figure 4-23, the **EPHYRA electrolyser presented the best environmental performance** (lowest impacts in both categories) due to the low-medium energy consumption (about 54 kWh/kg H₂) and the electricity source (50-50% solar-wind). The **EastGateH₂V** electrolyser demonstrates the higher environmental impacts associated with grid-connected electricity (Figure 4-22), especially when compared with case study using renewable energy sources such as solar PV, wind energy, hydropower, or combinations thereof. Furthermore, the **IMAGHyNE** electrolyser underlines the drawbacks associated with **hydropower-based electricity systems** (Figure 4-23), which, despite their low greenhouse gas emissions, can have relatively **high impacts** in **Water Use** category due to the significant water requirements associated with hydropower generation

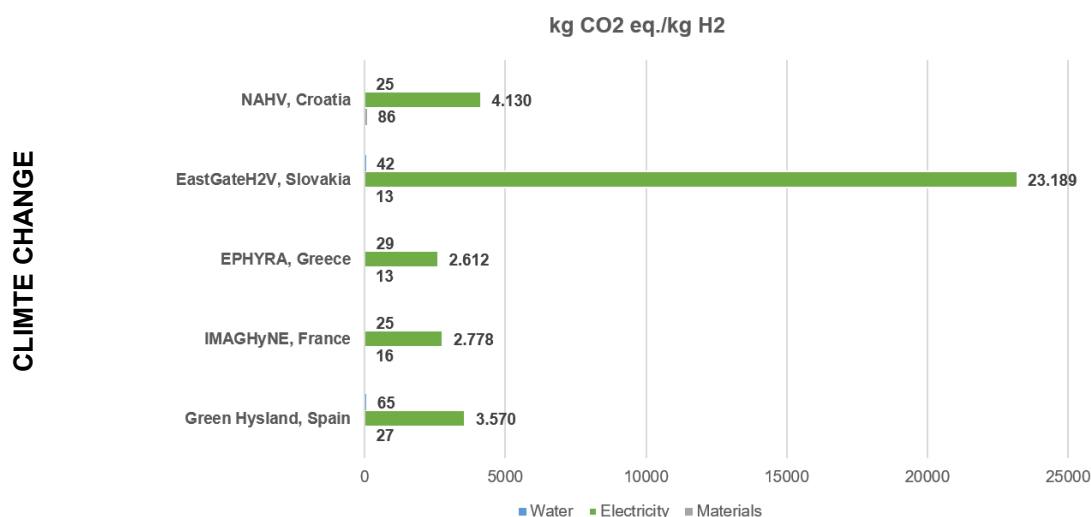


Figure 4-22: Comparative LCA analysis of the different case studies for Climate Change

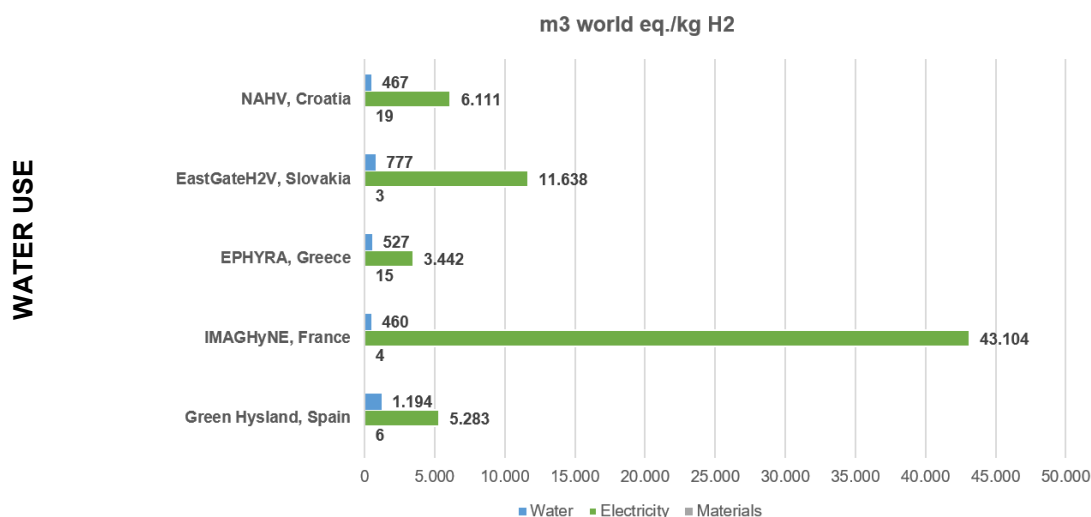


Figure 4-23: Comparative LCA analysis of the different case studies for Water Use

4.4 The five Case studies – comparative synthesis

The five selected case studies provide a comparative overview of how regional hydrological conditions may influence renewable hydrogen deployment across different European contexts. To ensure consistency and facilitate comparison, each case study follows the same structure, presenting the regional and project context, the seasonal water availability patterns under historical (2000-2019) and future (2026-2055) conditions, and the recommended water management strategy. This harmonised approach highlights how differences in climate, water availability and local conditions influence both operational resilience and the suitability of different water management measures.

Green Hysland – Mallorca, Spain

	Water availability - One of the most water-constrained systems, with ~180 days/year of full surface-water availability under historical conditions. - Future scenarios show a further reduction in hydrological reliability, particularly during summer periods, leading to decreased operational stability. Hydrogen production - Hydrogen production is consistently among the lowest across all case studies and further declines under climate change, reflecting strong water limitation. Impact on water - The analyses suggest that potential limitations for hydrogen production in Mallorca are driven primarily by reduced water availability during summer months rather than by overall annual water scarcity. Water management suggestions - Alternative water sources, including reclaimed wastewater and desalination, demonstrated potential to complement seasonal deficits and reduce dependence on conventional freshwater resources during periods of lower availability.
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IMAGHyNE – Auvergne-Rhône-Alpes, Lyon metropolitan area, France	
	Water availability - One of the most productive systems, with >310 days/year of full water supply under historical conditions. - Future scenarios reduce reliability to ~280–285 days/year, indicating severe climate-driven stress. Hydrogen production - Despite the severe climate-driven stress, the system maintains the highest hydrogen production levels across all cases, with only limited relative decline under future climates. Impact on water - The IMAGHyNE case study represents a context with high hydrogen deployment potential and comparatively favourable water availability conditions, reducing the likelihood of major short-term constraints associated with water resources. - Although pronounced accumulated deficits were not consistently observed, seasonal variability may still influence hydrogen production conditions and should not be disregarded in long-term planning. Water management suggestions - Under the analysed scenarios, adaptive approaches centred on operational flexibility and diversified resource management appeared more proportionate than large-scale compensatory strategies.

EPHYRA – Agioi Theodoroi, Greece

	Water availability • The most hydrologically stressed system among the case studies, with ~100 days/year of full supply under historical conditions. • Future climate scenarios reduce reliability further to ~60–70 days/year, indicating strong sensitivity to climate change. Hydrogen production • Hydrogen production shows the largest relative decrease among all cases, reflecting high vulnerability to water scarcity. Impact on water • The EPHYRA case study reflects the challenges of hydrogen deployment under Mediterranean coastal condition, where future production may become increasingly influenced by periods of reduced water availability and competing resource demands. Water management suggestions • Simulated scenarios indicated accumulated deficits approaching 60,000 – 70,000 m3 under the analysed conditions, suggesting that seasonal imbalances may progressively limit operational flexibility without complementary management strategies.
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EastGateH ₂ V – Košice region, Slovakia	
	Water availability • The most hydrologically robust system, with 365 days/year of full surface-water supply across all periods and scenarios. Hydrogen production • No significant climate-driven changes are observed in hydrological reliability or hydrogen production. • Hydrogen production remains constant at maximum operational capacity, indicating no water-related constraints. Impact on water • This case study is characterised by comparatively low water stress conditions and stable hydrological indicators, suggesting a favourable context for future hydrogen deployment. • Simulated scenarios did not indicate persistent severe deficits, while projected hydrogen-related water demands remained limited relative to broader regional water resource availability. Water management suggestions • Under the analysed conditions, long-term monitoring and adaptive planning may be more relevant than extensive compensatory water management strategies.

NAHV – Croatia	
	Water availability • Intermediate hydrological conditions with ~250–260 days/year of full supply under historical period. • Future projections show limited changes, with small differences between SSP3-7.0 and SSP5-8.5. Hydrogen production • Hydrogen production remains low but relatively stable, with minor scenario-dependent variations. Impact on water • The relatively low regional water stress conditions observed for the Croatian case study suggest that hydrogen integration within industrial process may occur without major limitations associated with water availability under current conditions. • Projected hydrogen-related water demands remain modest compared with broader regional resource availability, reinforcing the favourable hydrological context identified for the Dilj testbed. Water management suggestions

- | | |
|--|--|
| | <ul style="list-style-type: none">• Seasonal variability should still be considered in long-term planning, particularly under scenarios involving future expansions of industrial hydrogen deployment. |
|--|--|

5 Conclusions and recommendations

5.1 The overall impact of hydrogen on Europe's water — minor in aggregate, decisive locally

Within the study, future **hydrogen production capacity has been defined for three decadal horizons**, following an approach analogous to that used for solar and wind capacity. It is important to stress that these values represent the potential **hydrogen output that could be achieved, provided that sufficient renewable energy and water resources are available**. Compared to 2025, a clear expansion of hydrogen production capacity is projected across the domain. This expansion involves both an increase in the number of regions hosting hydrogen production facilities and a substantial growth in capacity in regions where hydrogen production is already present in the historical period. These trends reflect current and planned investments aimed at **scaling up hydrogen technologies and supporting their integration into the energy system**.

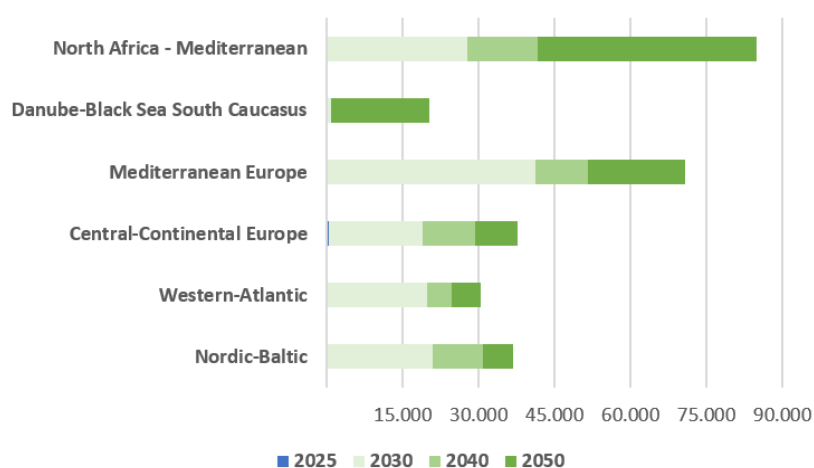


Figure 5-1: Projection of MWel of hydrogen active capacity across all the macro-regions

Looking at projected investments in hydrogen production capabilities, **the countries within the North Africa-Mediterranean cluster are among the most promising**. They are even more promising when comparing project sizes and number with their current GDP.

To convert the hydrogen power capacity (MW) to water demand it is needed to multiply the hydrogen energy output (MWh) by a technology-specific water intensity coefficient (m^3/MWh). Using the literature value of $0.234 \text{ m}^3/\text{MWh}$ for green hydrogen, a **1 MW plant requires 234 litres of water per operating hour, corresponding to about 2,050 m^3 per year** under continuous operation. It is thus straightforwardly computed how many litres of water each country will need to attain the expected hydrogen production in 2030.

By 2050, the largest shares of water demand are expected in **North Africa-Mediterranean** (30% of the total) and **Mediterranean Europe** (25%): a very significant portion of future hydrogen-related water demand is projected precisely in macro-regions that, elsewhere in the report, are identified as the most exposed to structural scarcity, seasonality and climate-related water stress.

As evidenced by the case-studies for Spain and Greece, **Mediterranean contexts** are among the most climate-sensitive and hydrologically constrained, with stronger seasonal deficits, higher competition among users and greater vulnerability to future drought conditions. In regions such as **North Africa-Mediterranean**, future hydrogen expansion will depend heavily on desalination, alternative water sourcing and careful management of local trade-offs.

The **most critical regions are** not necessarily those with the highest demand in absolute terms, but **those where fast hydrogen growth coincides with fragile hydrological conditions**, limited freshwater availability and the need for desalination, wastewater reuse, storage or hybrid water strategies. In that sense, Mediterranean Europe and North Africa-Mediterranean are the priority regions where future hydrogen deployment will need the strongest integration between industrial planning, climate adaptation and water governance.

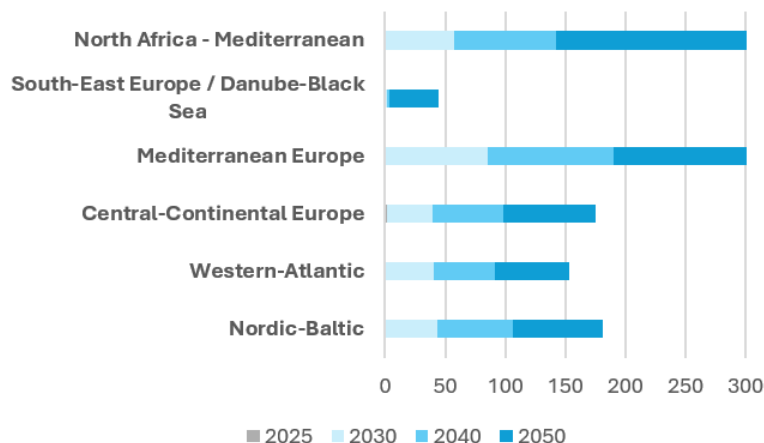
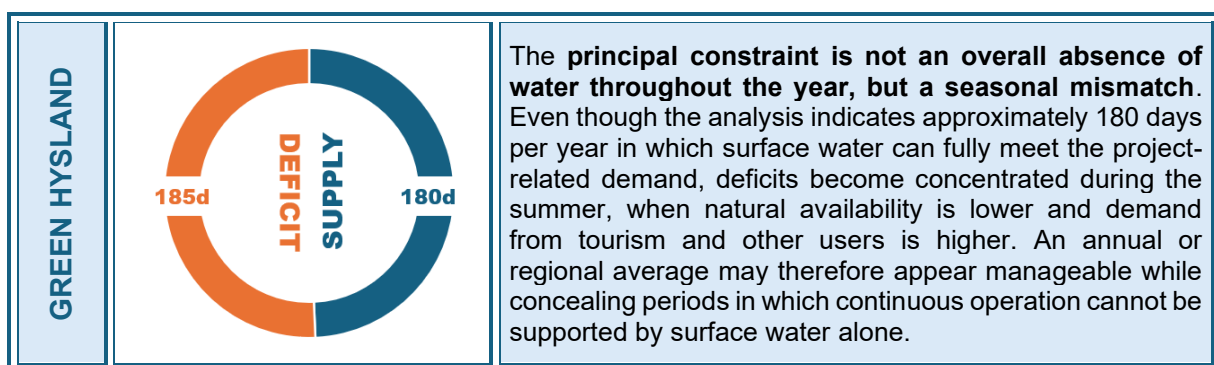
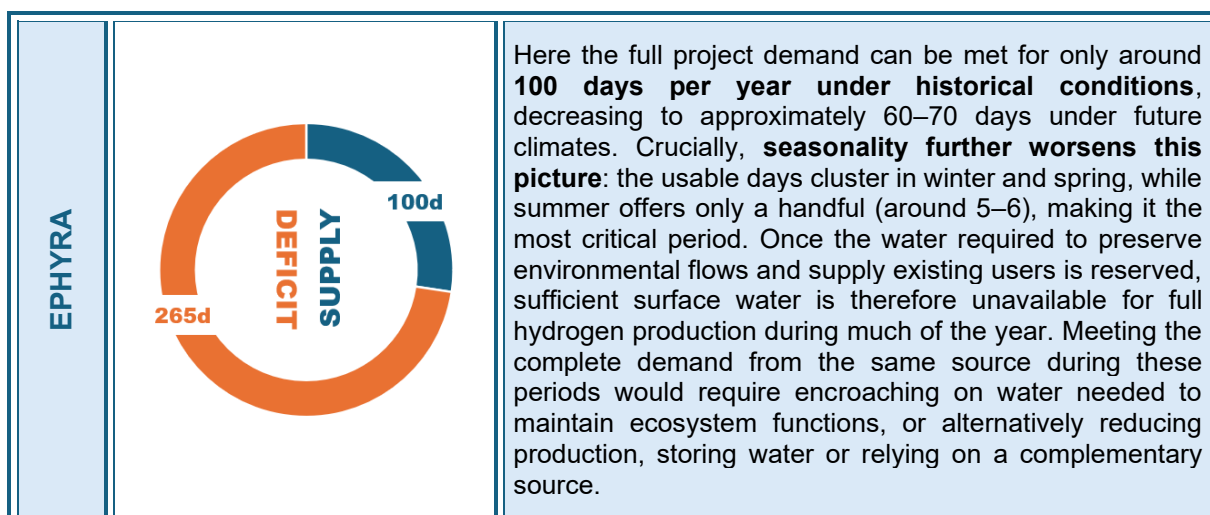


Figure 5-2: Millions of m³/year of water needed to support expected active capacity of hydrogen production

The comparison with the withdrawals already associated with established water-using sectors presented in Table 3-3 shows that, **despite the substantial expansion expected towards 2050**, hydrogen-related demand remains a relatively minor addition at continental and macro-regional scale. Across most of the assessed regions, **the additional withdrawal associated with hydrogen generally remains within approximately 1.5%** of existing sectoral withdrawals. Renewable hydrogen is therefore unlikely to become a dominant driver of water demand or to materially alter Europe's aggregate water balance.

This continent-wide result does not, however, demonstrate that water will be sustainably available for every project. Aggregate indicators compare annual volumes across countries or large macro-regions, whereas actual project feasibility depends on the water available in a specific basin, at a specific time of year, after ecosystem requirements and existing uses have been satisfied. **The same demand that appears marginal in a national balance may therefore become locally critical** when concentrated in a dry basin during its lowest-flow season. Two clear examples illustrating the importance of seasonality are given by the Green Hysland and EPHYRA projects:





In conclusion, this assessment shows that the **environmental performance and sustainability of green hydrogen production are strongly influenced by regional conditions**. Therefore, it is essential to carefully evaluate the technical feasibility of any hydrogen project by analysing the sustainability of the selected site in all dimensions.

Climate change may affect the availability of renewable energy sources in space and time through changes in river discharge for hydropower, reservoir levels, wind patterns and solar radiation. At the same time, increased rainfall, more frequent droughts, higher temperatures and reduced river flow are expected to **decrease the availability of freshwater**, particularly in the Mediterranean and North African regions. This **will make seawater-based systems more relevant**.



Water is neither a general barrier to renewable hydrogen deployment nor a negligible issue. It is a site- and season-dependent variable that may determine project feasibility, environmental compatibility, public acceptability and long-term operational robustness. The appropriate response is not a general cap on hydrogen development, but water-aware siting and planning based on basin-level availability, future climate conditions, environmental-flow requirements and credible water-supply strategies.

5.2 Key findings

This study demonstrates that the large-scale deployment of renewable hydrogen can remain compatible with sustainable water management, provided that water is treated as a strategic planning parameter rather than a marginal operational input. The water footprint of hydrogen is determined not only by the electrolysis process itself, but by the combined influence of technology choice, water source, treatment requirements, cooling systems and local environmental conditions. Across all case studies, water demand emerges as an integrated system issue, with **source water and cooling configuration often representing the main drivers of water-related impacts**.



Hydrogen-related water demand is a system-level issue, not simply a process-water requirement. The water demand of renewable hydrogen cannot be assessed solely on the basis of the water directly consumed by electrolysis. Although mature electrolysis technologies generally require around 9–13 L of process water per kilogram of hydrogen, the actual plant-level water footprint is determined by the interaction between the selected electrolyser technology, the origin and quality of the water source, the treatment chain required to reach feedwater specifications, the cooling system and the management of reject streams. Consequently, plants with similar hydrogen output and comparable direct process demand may generate substantially different levels of water withdrawal and consumption.

	Water source and cooling configuration are the main drivers of the overall water footprint. The selected source determines treatment intensity, recovery efficiency and the volume of raw water that must be abstracted to deliver the required process-grade water. Moving from freshwater to brackish water and seawater generally increases treatment requirements, withdrawal volumes and reject-stream generation. Cooling further changes both the magnitude and the nature of the impact: evaporative systems increase consumptive losses, once-through systems require very large withdrawals, and dry cooling largely avoids direct cooling-water use but may introduce energy and performance penalties. These two choices must therefore be assessed together rather than as independent design options. From an economic standpoint, however, neither the cost of water purchase nor that of purification is a critical factor: given the low water demand of electrolysis, water-related costs remain marginal (broadly in the order of 0.02–0.89 €/kg H₂ even for desalination-based supply), so source selection is driven far more by local availability, energy use and environmental constraints than by cost.
	Efficiency improvements materially strengthen the water performance of renewable hydrogen. Higher electrolyser efficiency reduces the amount of waste heat generated per unit of hydrogen and therefore lowers the cooling duty of the plant. The analysis shows that an increase in electrolysis efficiency from approximately 70% to 80% can significantly reduce system-level water requirements and alter the comparison between renewable electrolysis and fossil-based benchmark routes. Technology development aimed at improving electrical efficiency can therefore deliver a double benefit: lower energy consumption and lower cooling-related water demand. Future water performance will depend not only on water-management measures, but also on continued improvements in electrolyser and balance-of-plant efficiency.
	Geography and seasonality determine whether water demand is manageable. At European and macro-regional scale, the projected water demand associated with hydrogen remains a relatively minor share of existing withdrawals. However, as demonstrated in Section 5.1, this aggregate result does not determine the feasibility of individual projects. Water availability varies strongly between regions, basins and seasons, and the same plant configuration may be sustainable in a water-abundant location but contentious in a drought-prone basin with strong competing uses. The Green Hysland (Mallorca, Spain) and EPHYRA (Agioi Theodoroi, Greece) case studies illustrate this contrast: annual or regional figures may appear manageable, while summer shortages or environmental-flow constraints can prevent the full project demand from being met locally. Water is therefore neither a general barrier to hydrogen deployment nor a negligible issue; it is a site- and season-dependent factor that can determine project feasibility, permitting, public acceptance and long-term operational robustness.
	Water and carbon performance must be optimised together. The Life Cycle Assessment confirms that the carbon footprint of renewable hydrogen is driven primarily by the electricity source used for electrolysis. At the same time, measures adopted to reduce pressure on freshwater resources may create additional energy and emissions burdens. Seawater desalination reduces freshwater dependency but requires additional treatment energy and brine management, while dry cooling limits direct water use but may increase electricity consumption because of lower thermal performance. A configuration that performs better in water-terms is therefore not automatically preferable in climate terms. Sustainable hydrogen design requires the joint optimisation of water use, energy efficiency and greenhouse-gas emissions, rather than the improvement of one indicator in isolation.

Taken together, these findings show that the sustainability of renewable hydrogen depends on matching technology and plant design to the environmental and hydrological conditions of the selected location. Water-related decisions must therefore be integrated from the earliest planning stages and evaluated alongside renewable electricity supply, climate resilience and territorial constraints.

The methodology developed in this study provides a robust and harmonised framework for assessing water–hydrogen interactions across Europe. Future developments could extend the analysis through additional climate scenarios, multi-model climate and hydrological ensembles, longer-term time horizons, and more detailed site-specific operational models. These enhancements would further improve the ability of decision-makers to evaluate the resilience of hydrogen projects under uncertain future conditions.

5.3 Recommendations for sustainable deployment

5.3.1 Mitigation Strategies for Water-Stressed Regions

The case studies show that in water-stressed regions, such as the Mediterranean basin and North Africa, effective water management requires a combination of complementary measures. **Seasonal storage can buffer temporary deficits**, although its economic attractiveness decreases as storage requirements grow. **Reclaimed wastewater provides a stable, climate-independent source** that can significantly reduce reliance on freshwater resources. In coastal and island regions, **desalination offers an additional resilience measure**, but its higher energy demand and environmental impacts make it more suitable as a backup source than as a primary supply. **Wastewater reuse further supports circular-economy objectives**, although additional treatment is generally required to meet electrolyser water-quality standards.

No single solution, concerning the mitigation measures for water-stressed regions, was found to be universally optimal. Instead, hybrid configurations combining moderate storage capacity, reclaimed water and desalination backup consistently offered the highest resilience under future climate scenarios. This is supported by a screening-level trade-off analysis carried out for the most constrained case studies (Green Hysland and EPHYRA), which explored how a fixed share of storage (e.g. ~50% residual) could be complemented by reclaimed wastewater and desalination in varying proportions; no single optimal mix emerged, confirming that the preferable balance is site-dependent. In addition, operational measures such as aligning hydrogen production with periods of greater water availability and integrating projects into regional water-management plans can reduce competition with domestic, agricultural and tourism-related demand.

A key finding is that water-related costs are relatively low, typically accounting for only 0.8–2% of an 8 €/kgH₂ LCOH. Consequently, water should be viewed primarily as a strategic factor influencing project location, scale and long-term resilience rather than as a major economic constraint. The long-term sustainability of renewable hydrogen in water-stressed regions will therefore depend on integrated, adaptive and locally tailored water-management strategies.

5.3.2 Guidance for the Siting of Future Hydrogen Production Plants

Renewable-energy potential alone is an insufficient indicator of the long-term sustainability of hydrogen production. Many regions endowed with excellent solar or wind resources are simultaneously exposed to significant water stress, creating a geographic mismatch between energy and water availability. As a result, robust site selection requires a multi-criteria approach in which water resources are considered alongside renewable-energy potential as a co-equal determinant of project viability.

The regional clustering analysis developed through the *Clean Hydrogen Explorer* illustrates this challenge clearly. When **renewable-energy potential is assessed together with water availability**, only 143 out of 629 European regions are classified as having high suitability for renewable hydrogen deployment. Several existing and planned hydrogen projects are located in regions characterised as medium-low or low suitability, highlighting the importance of incorporating water considerations into early-stage planning decisions.

To support informed site selection, seven different dimensions should be systematically assessed before committing to a project location:

1

Renewable-energy resources. The quality, availability, and complementarity of solar, wind, and hydropower resources remain the essential starting point for hydrogen production, although they do not alone guarantee sustainability.

2	Water availability and baseline water stress. Site screening should incorporate established indicators such as the Water Exploitation Index Plus (WEI+), Aridity Index, and Standardised Precipitation Index (SPI) to ensure that additional water demand remains compatible with long-term resource availability.
3	Seasonality and temporal variability. Annual water balances can conceal critical seasonal shortages. Evaluating intra-annual availability is therefore essential, as dry-season deficits ultimately determine storage requirements and the need for supplementary water sources.
4	Competition among water users. Existing and projected demand from domestic, agricultural, industrial, and tourism sectors should be considered, particularly in Mediterranean regions where seasonal peaks can significantly intensify pressure on available resources.
5	Access to alternative water sources. Proximity to wastewater treatment plants, desalination facilities, or reusable industrial water streams can substantially enhance project feasibility and resilience by reducing dependence on conventional freshwater resources.
6	Infrastructure and regulatory context. The availability of electricity-grid connections, water transport infrastructure, desalination brine-management options, and a supportive permitting framework can strongly influence both project costs and implementation timelines.
7	Climate resilience. Site assessments should incorporate future climate projections, given the expected intensification of water stress across southern Europe and North Africa during the coming decades.

Regional-scale screening tools provide an essential first step for identifying priority areas for hydrogen development. However, by their nature, they average out local hydrological and socio-economic conditions. Consequently, basin-scale assessments and site-specific water-resource studies should always be undertaken before investment decisions are finalised. The case studies presented in this work demonstrate that local competition for water and seasonal availability constraints frequently become more restrictive than the aggregate water volumes suggested by regional-scale analyses.

5.3.3 Best Practices for Water Management in Large-Scale Hydrogen Plants

For large-scale hydrogen projects, a central lesson emerging from this study is that water management must be integrated into project development from the earliest design stages rather than treated as a secondary consideration once the electrolyser technology has been selected. Early integration of water considerations influences key decisions regarding water sourcing, treatment requirements, cooling strategies, infrastructure needs, and permitting pathways. Incorporating these elements from the outset is considerably more cost-effective than retrofitting solutions later in the project lifecycle.

The findings of the case studies translate into the following practical design principles:

- **Select water sources according to local conditions.** In regions experiencing water stress, reliance on tap water should be minimised wherever possible. Alternative sources such as reclaimed wastewater, brackish water, or desalinated seawater can often provide more sustainable long-term solutions when aligned with regional water-management strategies and planning frameworks.
- **Adapt the treatment train to source-water quality.** Lower-quality feedwater requires progressively more advanced treatment processes to meet the ultrapure water specifications demanded by electrolyser systems. Typical treatment configurations may include pre-treatment, reverse osmosis (often implemented in two-pass arrangements), and final polishing technologies such as electrodeionization or mixed-bed ion exchange.
- **Optimise cooling-system design.** Cooling requirements can represent a major share of total water withdrawals. Closed-loop cooling systems and air-cooled (dry-cooling) configurations can substantially reduce water consumption compared with conventional open wet-cooling systems. Although these approaches may involve efficiency penalties or higher capital costs, the trade-off should be evaluated explicitly in the context of local climatic and water-resource conditions.

- **Maximise internal water recovery and reuse.** Water streams rejected during reverse osmosis and deionisation processes can often be reused for auxiliary purposes such as cooling or subjected to additional treatment for further recovery. In parallel, waste heat generated by electrolyzers may be utilised to support thermal desalination technologies, such as multi-effect distillation (MED), thereby reducing overall freshwater demand.
- **Implement continuous monitoring and adaptive management.** Real-time monitoring of water withdrawals, water quality, treatment performance, and recovery rates enables operational strategies to be adjusted in response to seasonal variations in resource availability and changing site conditions.
- **Integrate water considerations into permitting from the outset.** Early engagement with permitting authorities and alignment with regional water-management plans, environmental regulations, and relevant sustainability frameworks (including EU Taxonomy requirements) can reduce project-development risks, facilitate approvals, and strengthen social acceptance.

5.3.4 Feasibility of Seawater and Low-quality waters as a Water Source

Seawater, brackish water and reclaimed wastewater can provide **viable alternatives to freshwater for renewable hydrogen production**, particularly in coastal regions and areas affected by structural or seasonal water scarcity. Their main advantage is the possibility of reducing competition with conventional freshwater users. However, their feasibility depends on the treatment required to reach electrolyser-grade water quality and on the management of the resulting reject streams.

Despite growing research interest, direct seawater electrolysis is not yet a commercially mature option. Chloride-induced side reactions, corrosion, scaling, membrane degradation and limited long-term stability continue to prevent its industrial deployment. Current practice therefore relies on treating seawater, brackish water or reclaimed wastewater through conventional purification trains, generally including pretreatment, desalination or membrane separation, and final polishing to produce ultrapure feedwater.

The main system-level consequence of **using lower-quality water is an increase in raw-water withdrawal** rather than a substantial change in the amount of water ultimately consumed by hydrogen production. Lower treatment recovery means that larger volumes must be abstracted to deliver the same quantity of process-grade water. As an example, in the wet-cooled alkaline electrolyser configuration assessed in this study, **total withdrawal increases from approximately 17 L/kg H₂ with tap water to around 48 L/kg H₂ with seawater**. Brackish water and reclaimed wastewater generally occupy an intermediate position, although their actual performance depends on salinity, contaminant load and pretreatment requirements. Reverse osmosis (RO) is currently the main desalination technology considered for hydrogen applications. Seawater RO typically achieves recovery rates of approximately 40–50% and requires around 3–4 kWh per cubic metre of treated water.

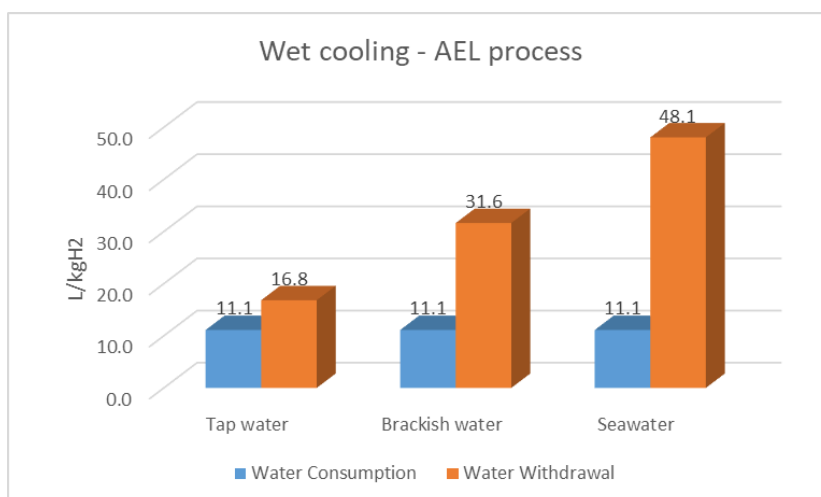


Figure 5-3: Effect of water source on water consumption and withdrawal (wet-cooled AEL).

Thermal desalination technologies such as multi-effect distillation and multi-stage flash distillation typically require approximately 5.5–16 kWh/m³ and are therefore more energy-intensive than reverse

osmosis. Nevertheless, they offer greater tolerance to variations in feedwater quality and may become attractive where low-grade waste heat from the hydrogen plant or neighbouring industrial processes can be recovered.



Brine and other concentrated residual streams must be considered as an integral part of the water-supply strategy. Conventional options such as marine or sewer discharge offer comparatively low costs but may create local salinity, temperature and ecological impacts. Evaporation ponds are simple but land-intensive and suitable mainly for limited volumes in arid environments. More advanced minimal- or zero-liquid-discharge systems can recover additional water and substantially reduce liquid waste, although they require higher capital expenditure and energy consumption. Resource-recovery pathways may additionally valorise salts, acids, bases or minerals, but their technical maturity and market viability remain limited.

Where marine discharge is selected, environmental safeguards should include site-specific impact assessment, engineered diffusers, appropriate discharge-location design and continuous monitoring of receiving ecosystems. These measures are especially important in semi-enclosed marine environments such as the Mediterranean Sea, where limited water exchange reduces the capacity to disperse concentrated saline effluents.

Alternatively to seawater, **brackish water and municipal wastewater can generally achieve higher recovery rates** because of their lower salinity, but wastewater may require more extensive pretreatment and monitoring to manage variable organic, biological and chemical contamination. Its feasibility therefore depends not only on treatment performance, but also on the continuity of the available effluent, regulatory requirements and operator confidence in water-quality reliability.

Overall, alternative water sources can provide a robust basis for hydrogen deployment where freshwater is scarce or subject to significant seasonal variability. However, **they are not impact-free substitutes**. Water treatment requirements, additional energy consumption, increased withdrawals, and brine-management obligations must all be incorporated into system design and economic evaluation. When these factors are properly accounted for, alternative water sources can provide a robust and resilient foundation for expanding hydrogen production while minimising pressure on already stressed freshwater resources.

5.3.5 Circular Approaches for Water Reuse

While the strategies discussed so far focus primarily on securing water supply, the next step is a broader conceptual shift: moving from water sourcing to water circularity. In this framework, water is no longer treated as a one-way input to the hydrogen production process but as a resource to be continuously recovered, reused, and optimised throughout the facility. Circularity therefore represents more than an environmental improvement; it is a resilience strategy. Every cubic metre of water recovered on-site reduces dependence on external resources, lowers exposure to seasonal shortages, and alleviates pressure on already stressed water basins.

Several complementary approaches can support the transition towards circular water management in hydrogen projects:

- **Internal water reuse and recycling.** Recirculating process water, recovering cooling-water streams, and reusing treatment reject flows can significantly reduce both freshwater demand and operational costs. Improved recovery rates also decrease the volume of residual waste streams requiring disposal.
- **Integration with wastewater treatment infrastructure.** The use of reclaimed effluent from WWTPs provides a relatively climate-independent water source that is less vulnerable to seasonal fluctuations than conventional surface-water resources. The case-study analysis showed that the volumes required for hydrogen production represent only a small fraction of the reclaimed-water resources currently available in many regions.
- **Industrial symbiosis and resource integration.** Co-location with industrial facilities such as refineries, food and beverage plants, municipal WWTP facilities, or desalination plants can create mutually beneficial exchanges of water, energy, and heat. Such integrated

configurations can improve overall resource efficiency while reducing infrastructure costs and environmental impacts across multiple sectors.

- **Resource recovery from residual streams.** Brine and other concentrated treatment by-products may contain recoverable salts, acids, bases, or valuable minerals. Although the commercial maturity of these recovery pathways varies, they offer the potential to transform waste-management costs into value-generating co-products while advancing circular-economy objectives.
- **Advanced water-recovery concepts.** Emerging technologies, including ZLD and minimal-liquid-discharge (MLD) systems, aim to maximise water recovery and minimise residual waste streams. Innovative approaches such as modular evaporation and crystallisation technologies, including the ASEC sonic evaporation/crystallisation concept highlighted in the case studies, demonstrate the potential for near-complete on-site water recovery, particularly in highly water-constrained environments.

Taken together, these approaches point towards a future in which hydrogen valleys and large-scale electrolysis facilities move beyond the traditional linear model of water use (abstract, consume, and discharge) and instead adopt circular and adaptive resource-management strategies. In such systems, diversified water sources, resource recovery, operational flexibility, and industrial integration become integral components of long-term planning. When designed according to these principles, hydrogen production can enhance regional resilience and contribute positively to water security, rather than competing with other sectors for increasingly constrained water resources.

5.4 Practical insights from the Advisory Board

To complement the quantitative assessment of water availability and hydrogen production potential, stakeholder consultations were conducted across the selected **Hydrogen Valleys**. These discussions aimed at validating the study findings, identifying practical constraints not fully captured by the modelling framework, and gathering insights on **local conditions influencing hydrogen deployment**. While stakeholders generally acknowledged the importance of water resource management, the consultations highlighted that water availability is often only **one element within a broader set of technical, environmental, economic and social factors** shaping project development.

GREEN HYSLAND	GREEN HYSLAND stakeholders stressed that hydrogen deployment in Mallorca must be assessed within a broader territorial context . Tourism-related land use, biodiversity protection, seasonal pressure on infrastructure and competing resource demands may be as relevant as process-water availability. Concerns were also raised regarding wastewater-treatment capacity, renewable electricity availability and the development of sufficient local hydrogen demand. The main lesson is that project feasibility cannot be determined through water requirements alone . Infrastructure limitations, permitting, public acceptance, market conditions and interactions with existing territorial priorities must be considered together. For large-scale deployment, water planning should therefore be integrated with land-use, energy and infrastructure strategies from the outset , with particular attention to seasonal peaks associated with tourism and to the capacity of local systems to support additional industrial demand.
IMAGHyNE	IMAGHyNE stakeholders emphasised the need to distinguish regional water-resource screening from project-specific water management . Water availability is already considered during early site selection, together with renewable electricity, industrial integration, infrastructure and permitting, allowing potential risks to be addressed before implementation. Developers are also increasingly evaluating alternative sources , including industrial water, seawater and other non-conventional supplies, to reduce dependence on freshwater where appropriate. Particular attention should be paid to how regional results are communicated: broad assessments are valuable for comparing locations and supporting policy, but should not imply that every hydrogen project creates significant local water pressure. The recommended approach is to use regional analysis as an initial decision-support tool and complement it with detailed engineering , basin-level information and local feasibility studies before drawing conclusions on project sustainability.

EPHYRA	EPHYRA stakeholders clarified that the project is expected to rely primarily on desalinated seawater rather than surface water. Consequently, the deficits identified in the modelling describe the limitations of a hypothetical surface-water supply strategy, but do not necessarily represent an operational constraint for the project as designed. Desalination is considered a reliable and established option capable of reducing exposure to seasonal freshwater variability. Treated wastewater was also considered, but concerns over water-quality consistency, operational reliability, permitting and industrial risk perception currently make it less attractive than desalination. The main recommendation is to distinguish resource availability from the actual supply configuration selected by the project. Wider uptake of reclaimed wastewater will require demonstration projects, clearer regulatory pathways and operational evidence capable of increasing confidence among industrial operators and reducing perceived continuity and quality risks.
EASTGATEH ₂ V	EASTGATEH₂V stakeholders confirmed that water availability is not currently expected to constrain hydrogen deployment in the region. However, increasing climate variability remains relevant, particularly the alternation of longer dry periods with more intense rainfall events. Regional authorities are already responding through water-retention measures, stormwater management and flood-mitigation initiatives aimed at strengthening long-term resilience. The Advisory Board therefore recommended avoiding complacency in water-abundant contexts: the absence of an immediate scarcity constraint does not remove the need for forward-looking water planning. Hydrogen projects should incorporate water-demand assessments, efficiency measures and climate-resilience considerations from the earliest development and permitting stages. Continuous monitoring of hydrological trends and coordination with regional adaptation plans can help preserve environmental sustainability, reduce future operational risks and support local acceptance as hydrogen production capacity expands.
NAHV	NAHV stakeholders broadly confirmed that water quantity is not expected to represent a major limitation under the project conditions currently envisaged. Local resources appear sufficient to meet future hydrogen-production needs, and the assumptions used in the assessment were considered consistent with the regional context. The more relevant operational issue is water quality: appropriate conditioning, purification and demineralisation are required to protect electrolyser performance, durability and reliability. The discussion also showed that the principal barrier to large-scale deployment is currently economic rather than hydrological. Hydrogen production costs, electricity-related charges and the availability of adequate support mechanisms remain central to investment decisions. The main recommendation is therefore to focus water planning on treatment reliability and quality control, while addressing project viability through improved economic conditions, energy-cost management and stable policy support for hydrogen deployment.

The stakeholder consultations provided an important practical perspective that complements the quantitative assessment presented throughout this study. Rather than validating or challenging individual modelling results, the discussions helped place them within the broader context of real project development, highlighting aspects that cannot be fully captured through water availability modelling alone.

As shown in Figure 5-4, each Hydrogen Valley identified different priorities according to its regional context and project maturity. While **Green Hysland** highlighted **tourism, land-use constraints** and **biodiversity protection**, **EPHYRA** focused on the **role of desalination** and the practical limitations associated with wastewater reuse. **EASTGATEH₂V** emphasised **climate resilience and long-term planning**, **NAHV** identified **water quality** and **economic viability** as the main operational concerns, whereas **IMAGHyNE** stressed the importance of **considering water management from the earliest planning stages** and **communicating water-related** results carefully.

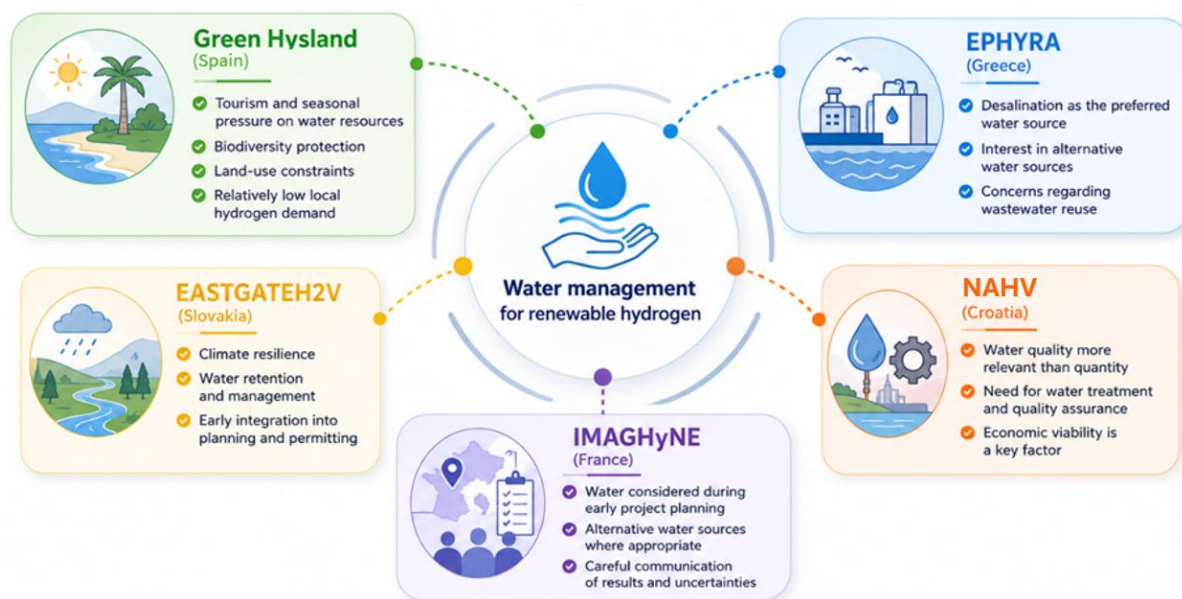


Figure 5-4: Summary of the main insights obtained during stakeholder consultations across the five Hydrogen Valleys.



Although these priorities differ considerably, a common message emerged across all stakeholder consultations: **water should not be considered in isolation**. The successful deployment of renewable hydrogen depends on **integrating water management with technical design, economic feasibility, environmental protection, regulatory requirements and regional planning**. Consequently, the modelling framework developed in this study should be understood **as a strategic decision-support tool** capable of identifying potential water-related challenges at the regional level, while recognising that **project-specific solutions** will ultimately depend on **local conditions and engineering decisions**.

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