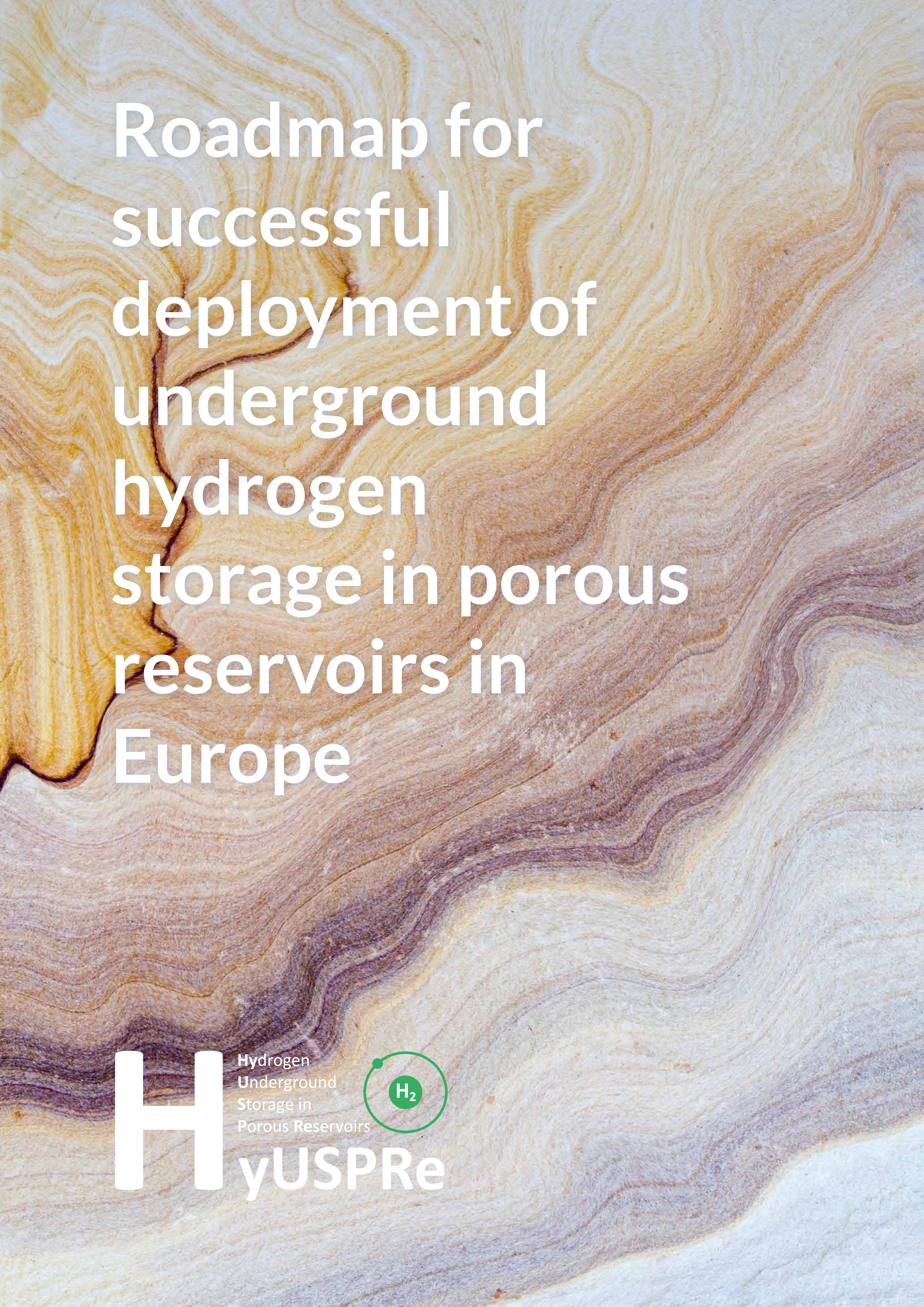


Roadmap for successful deployment of underground hydrogen storage in porous reservoirs in Europe

Hydrogen
Underground
Storage in
Porous **Re**servoirs
HyUSPRe

Acknowledgement

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under grant agreement No 101006632. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme, Hydrogen Europe and Hydrogen Europe Research.

Disclaimer

This document reflects the views of the authors and does not necessarily reflect the views or policy of the European Commission. Whilst efforts have been made to ensure the accuracy and completeness of this document, the HyUSPRe consortium shall not be liable for any errors or omissions, however caused.

This roadmap constitutes a collective view of the HyUSPRe consortium. The consortium partners endorse the general thrust of the arguments made in this roadmap but should not be taken as agreeing with every single finding or recommendation. The consortium partners have not been asked to formally endorse the report.

Funded by

Clean Hydrogen Partnership

Co-funded by the European Union

The HyUSPRe consortium

TNO innovation for life

ENERGIE INSTITUT an der Johannes Kepler Universität Linz

FONDAZIONE BRUNO KESSLER CENTER FOR SUSTAINABLE ENERGY

JÜLICH Forschungszentrum

THE UNIVERSITY of EDINBURGH

TU Clausthal Clausthal University of Technology

WAGENINGEN UNIVERSITY & RESEARCH

centrica energy storage+

ebn

HGS / Powered by MVM

nafta

rag AUSTRIA AG Renewables and Gas

snam

equinor

eni

uniper

About HyUSPRe

The HyUSPRe project researches the feasibility and potential of implementing large-scale underground geological storage for renewable and low-carbon hydrogen in Europe. This includes the identification of suitable porous reservoirs for hydrogen storage, and technical and economic assessments of the feasibility of implementing large-scale storage in these reservoirs to support the European energy transition to net zero emissions by 2050. The project will address specific technical issues and risks regarding storage in porous reservoirs and conduct an economic analysis to facilitate the decision-making process regarding the development of a portfolio of potential field pilots. A techno-economic assessment, accompanied by environmental, social, and regulatory perspectives on implementation will allow for the development of a roadmap for widespread hydrogen storage by 2050, indicating the role of large-scale hydrogen storage in achieving a zero-emissions energy system in the EU by 2050.

This project has two specific objectives.

Objective 1 concerns the assessment of the technical feasibility, associated risks, and the potential of large-scale UHS in porous reservoirs for Europe. HyUSPRe will establish the important geochemical, microbiological, flow, and transport processes in porous reservoirs in the presence of hydrogen via a combination of laboratory-scale experiments and integrated modelling; and establish more accurate cost estimates to identify the potential business case for hydrogen storage in porous reservoirs. Suitable storage sites will be identified, and their hydrogen storage potential will be assessed.

Objective 2 concerns the development of a roadmap for the deployment of geological hydrogen storage up to 2050. The proximity of underground storage sites to large renewable energy production, transport and import infrastructure and the amount of renewable energy that can be buffered to meet time varying demands will be evaluated. This will form a basis for developing future scenario roadmaps and preparing for demonstrations.

Hydrogen
Underground
Storage in
Porous Reservoirs
HyUSPRe

Executive summary

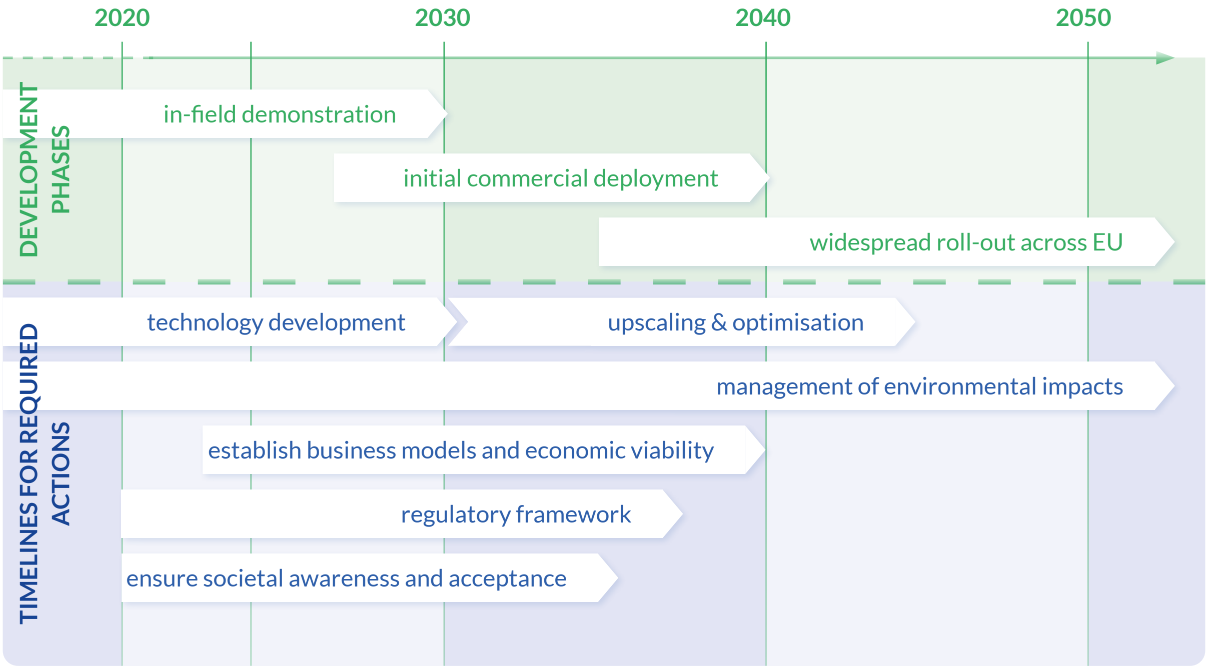
Renewable hydrogen is one of the key elements for Europe to enable the transition to a fully decarbonised energy system in 2050. It is a versatile molecular energy carrier that can be produced from renewable electricity such as wind or solar energy. Hydrogen will be crucial to decarbonise hard-to-abate sectors that rely on renewable hydrogen to be able to reach their sustainability goals, and to produce power and heat in periods of low supply.

The European Union has set ambitious targets for domestic hydrogen production and imports for 2030 to kick-start the development of a hydrogen energy economy. Moreover, in anticipation of a rapidly growing hydrogen demand in the period after 2030, the transport and storage of hydrogen become critical aspects to match the intermittent production of hydrogen from renewables with varying demand in space and time.

A unique advantage of hydrogen is that it can be stored in large quantities. Suitable sites in the subsurface include salt caverns and porous reservoirs such as (depleted) gas fields and aquifers, where hydrogen can be stored for longer periods ranging from days to seasons. In this way, stored hydrogen can offer essential services to society in the form of strategic energy reserves and as balancing solution for unavoidable intra-seasonal to inter-seasonal variations in energy supply and demand. Salt cavern storage is considered a promising solution that is nearing commercial deployment. Storage of hydrogen in porous reservoirs offers the advantage of even larger storage capacities and balances the geographic distribution of subsurface storage potential across Europe as cavern storage is geographically limited. Natural gas is since many decades stored in large quantities in porous reservoirs in the subsurface in many countries in Europe. While the expectation is that hydrogen can also be safely, reliably and affordably stored in porous reservoirs, this technology is not yet fully established. Various projects across Europe are ongoing and planned to progress the technology towards maturity.

The HyUSPRe project[1] was initiated to study the feasibility and techno-economic potential of implementing hydrogen storage in porous reservoirs in Europe to support the energy transition to net-zero emissions by 2050. Storage in porous reservoirs and caverns are complimentary, providing essential system services at competitive costs compared to aboveground alternatives. Underground hydrogen storage (UHS) is expected to become a key enabler for the decarbonisation of the European energy system, with an estimated potential of 500 TWh[2] in porous reservoirs and salt caverns that are currently being used or planned to be used for storing natural gas. The existing potential in underground gas storage (UGS) reservoirs, well-connected to the existing natural gas infrastructure that is to be partly reused for hydrogen, far exceeds the storage demand, which is currently projected to reach up to 270[3,4] TWh by 2050, with porous reservoir storage accounting for more than half of the capacity by that time. Should additional capacity be required, this could be developed in gasfields that are not currently used for storage or in newly developed salt caverns, as was exemplified in HyUSPRe for a scenario with a high storage demand and a low percentage of conversion

Anticipated timelines and required actions for upscaling UHS from its current readiness level at TRL 6 (reduced-scale in-field demonstrations) to TRL 8 (initial commercial deployment at full-scale) making it ready for widespread roll-out across the EU (TRL 9).



of existing storages requiring 1000 TWh additional capacity.

Concrete actions required to develop UHS in porous media

To realise the projected potential of UHS and accelerate its deployment in Europe, the HyUSPRe consortium developed a roadmap with concrete actions and execution timelines for five themes, as illustrated by the visual on page 4. In the following, the key actions per theme that need to be taken to successfully implement UHS in porous reservoirs in Europe are summarised.

To advance UHS in porous reservoirs from a **technical perspective** in the next 5-10 years, research and development efforts should focus on improving materials, wells, and surface technologies, while promoting circularity and sustainability of the infrastructure. In addition, research to upscale modelling and experimental testing to accurately predict fluid behaviour, improve data sharing, and expand global databases is a priority. Specific standards for materials, well design, operational practices and the development of monitoring, measurement, and verification technologies are essential for safe and effective implementation and should be established by the early 2030s.

To ensure active management of **potential environmental impacts,** monitoring thresholds for UHS should be established based on existing studies, with a global exchange of monitoring experience, which is essential to ensure long-term integrity and safety. Operational practices from UGS should be adopted to minimise emissions during construction and operation, supported by comprehensive best practices to mitigate hydrogen leakage risks. In addition, spatial planning for suitable sites should include local stakeholder engagement and international calls for land allocation, guided by robust regulatory standards and environmental assessments to ensure compliance within Europe.

> ‘ UHS is expected to become a key enabler for the decarbonisation of the European energy system.’

Looking at **the economic perspective,** the use of UHS in porous reservoirs can save billions of euros annually in our future energy system. However, realising the full potential of UHS requires overcoming cost challenges and developing robust and optimized business models in the coming decade. Actions include establishing appropriate financing incentives for pioneer UHS projects, sustainable remuneration schemes, shaping

Uniper HyStorage project at Bierwang, Germany. Source: Uniper Energy Storage, used with permission.

market conditions for assured revenues, promoting market transparency, and encouraging innovative business models. Addressing these issues will enable the successful deployment of UHS and contribute to the development of a sustainable hydrogen market in Europe's future energy system.

The establishment of a **regulatory framework** at European and national levels is essential for initial commercial deployment of UHS in the period between 2030 and 2040. Actions to achieve this should outline transition pathways towards the storage of pure hydrogen, harmonise international gas quality standards and introduce subsidies across the hydrogen value chain. Clear permitting requirements, regulatory frameworks and hydrogen-specific technical standards are essential to address regulatory uncertainties. In this context, it is important to realize that regulators are dealing with a novel technology for which not all the rules e.g., norms, standards and procedures have been defined.Regulators have to gain a large amount of (new) knowledge as well, in particular on how to establish well-informed decision procedures, and how to establish the public dialogue and build trust. A continuous exchange of experiences from demonstration sites will help to identify and adapt regulatory challenges. Stronger consideration of the interplay between the electricity, gas, heat, and transport sectors, and a better coordination when it comes to infrastructure planning for different energy sources, would enhance effective development of the hydrogen energy economy.

Efforts to increase **awareness and acceptance** of the energy transition, and the key enabling role of hydrogen including storage in achieving decarbonisation targets, should focus on improving public knowledge, gaining public trust and political support and, stronger involvement or even economic participation of stakeholders and communities. Information campaigns through various media platforms are recommended to

Call to Action

The transition to a sustainable energy future is upon us, and hydrogen holds the key to unlocking its great potential. Underground hydrogen storage is a crucial element in this transition. Embracing this technology is not merely an option but a necessity for achieving our sustainability goals. Now is the time to act and drive this transformative initiative forward.

We would urge policy makers, industry leaders, researchers, and citizens to unite in this ambitious endeavour. Policy makers must enact supportive legislation and provide funding to accelerate the deployment of underground hydrogen storage projects. By creating a conducive regulatory environment, they can foster innovation and investment, ensuring that the necessary infrastructure is in place.

Industry leaders, your expertise and resources are crucial. Augment your investments in research and development to refine underground storage technologies and integrate them into existing energy systems. Collaborate across sectors to share knowledge, streamline processes, and drive down costs. By committing to sustainable practices, you not only contribute to environmental preservation but also position your businesses at the forefront of a nascent market.

Researchers, your discoveries will pave the way for groundbreaking advancements. Focus on overcoming the technical challenges associated with hydrogen storage, such as material durability, safety, and efficiency. By pushing the boundaries of science and engineering, you can develop solutions that make underground hydrogen storage a viable and reliable option.

Citizens, your voice matters. Advocate for clean energy initiatives and support policies that prioritise sustainability. Educate yourself and others about the benefits of hydrogen as a renewable energy carrier. By demanding change and adopting eco-friendly practices in your daily lives, you become catalysts for a larger transformation.

Together, we can build a resilient energy infrastructure that harnesses the power of hydrogen to meet our future needs. This underground hydrogen storage roadmap is not just a vision—it is a call to action. Let us embrace this challenge with determination and collaboration, ensuring a brighter, cleaner, and more sustainable world for generations to come.

highlight the technical feasibility and safety of hydrogen, supported by independent research. Educational initiatives such as energy transition lessons in schools and associations as well as visits to hydrogen storage sites are supportive for integrating hydrogen as an energy carrier into the wider public thinking. Specific campaigns targeting policy makers and the appointment of authorities in charge for energy transition are essential to drive political support, together with stakeholder engagement through surveys and advisory boards aligned with business and community interests.

> ‘This underground hydrogen storage roadmap is not just a vision—it is a call to action.’

Initiatives to advance the technology readiness of UHS in porous reservoirs and salt caverns are currently gaining momentum in Europe, often with support of national governments and the European Union, reflecting commitment by governments and industry to establish a hydrogen economy. Ongoing pilot and demonstration projects, as for example Underground Sun Storage 2030[5] and HyStorage[6], mostly leverage existing infrastructure, while also developing innovative solutions to optimise storage capacity, efficiency, and safety. In the next decade, the UHS project portfolio is expected to expand significantly to realise the required TWh-scale storage capacities within Europe. By implementing the actions formulated in this roadmap the chance of successful and timely UHS deployment will be greatly increased.

Call to Action

Environmental impact and spatial planning

- Ensure integrity and mitigate leakage risk
- Implement monitoring plans for UHS in porous reservoirs
- Demonstrate safety and minimise environmental impact
- Develop a land use plan in line with the energy transition
- Develop appropriate regulations and standards for UHS in porous reservoirs

Technology development

- Develop UHS-tailored technologies for compression, gas cleaning, wells and materials
- Continue R&D on subsurface processes and development of reservoir models and software
- Develop UHS-specific monitoring technologies

Economics and market

- Facilitate development of a hydrogen market
- Overcome cost-related challenges
- Develop positive business cases with innovative business models

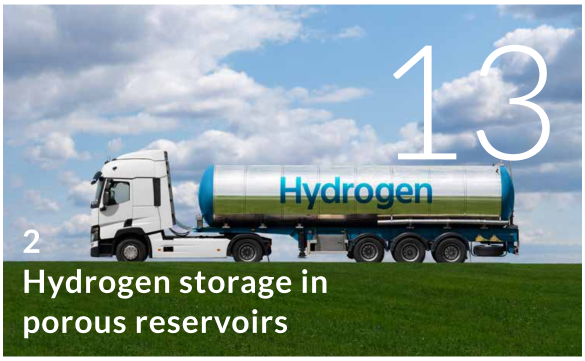
Societal awareness and acceptance

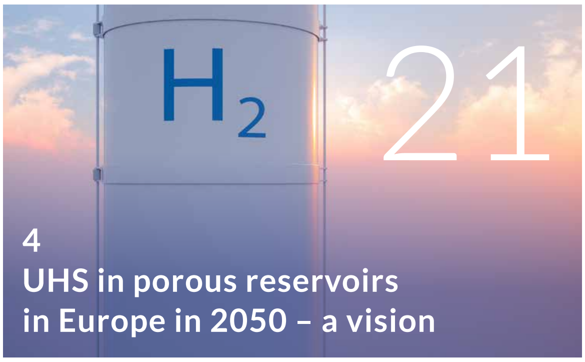
- Increase public awareness
- Develop educational measures for use in schools
- Develop information measures from local to European politics
- Learn from stakeholder perspectives to improve design, planning and operation
- Facilitate engagement of direct neighbours and energy communities

Policy and regulation

- Develop strategic goals, policy and legal framework
- Remove legal insecurities
- Implement longer hydrogen storage periods and adjust certification framework
- Use this roadmap to develop a step-wise-plan for transitioning from natural gas to hydrogen

Underground hydrogen storage demonstration facility Rubensdorf, Austria. *Photo by kind permission of RAG.*





Contents

About HyUSPre 3

Executive summary 4

1. Introduction 11

2. Hydrogen storage in porous reservoirs 13
2.1 Concept of underground hydrogen storage (UHS) 13
2.2 Hydrogen storage in the future energy system 13

3. Status and future potential of UHS in Europe 17
3.1 Status of development 17
3.2 Future technical and market potential 18

4. UHS in porous reservoirs in Europe in 2050 – a vision 21

5. Actions needed to successfully implement UHS in porous reservoirs 25
5.1 Technology development 25
5.2 Environmental impact and spatial planning 29
5.3 Economics and market 32
5.4 Policy and regulation 35
5.5 Societal awareness and acceptance 38

Bibliography 41

1. Introduction

In pursuit of a greener and more sustainable future, the EU has set its sights on leveraging the transformative power of hydrogen. Recognising its pivotal role in decarbonisation and energy security, the EU has embarked on a journey towards establishing a hydrogen economy. With RePowerEU[7], ambitious targets have been set to scale up domestic production of renewable hydrogen to 10 million tonnes (333 TWh[8]) and to import an additional 10 million tonnes by 2030, doubling FitFor55[9] targets as set forth in the context of the Green Deal[10]. After 2030, energy system studies[11,12] project rapid growth of renewable hydrogen demand, the majority of which is expected to be produced within Europe. By establishing ambitious targets for 2030, and in anticipation of a rapidly growing demand in the period between 2030 and 2050, the transport and storage of hydrogen emerges as a critical aspect to match intermittent production from renewables (wind, solar) with varying European demand in space and time.

A key advantage of hydrogen is that it can be stored in large quantities in the underground thereby offering essential services to society in the form of strategic energy reserves and balancing solutions for unavoidable intra- to inter-seasonal variations in energy supply and demand. Storage in salt caverns is considered a promising solution that is nearing commercial deployment. However, a very large number of salt caverns would need to be developed to fulfil projected future storage needs. This would be a technically challenging endeavour and is further aggravated by the unequal geographical distribution of salt deposits across Europe.

Storage of hydrogen in porous reservoirs e.g., in depleted gas fields or aquifers, is an attractive complementary solution. Recognising this, the HyUSPRe project was initiated to establish the feasibility and techno-economic potential of implementing hydrogen storage in porous reservoirs in Europe. Over a period of almost three years, the consortium conducted research in the form of techno-economic assessments, and provided environmental, social, and regulatory perspectives on implementing this technology in Europe.

In this roadmap, the key findings of HyUSPRe are highlighted, knowledge gaps and challenges for hydrogen storage in porous reservoirs are identified, and concrete actions are formulated to advance its readiness towards implementation. It paints a vision of the future role of UHS in porous reservoirs in achieving a zero-emissions energy system in the EU by 2050 and outlines the concrete steps towards commercial deployment. In chapters 2 and 3, we explain how hydrogen storage in porous reservoirs works, why we need it, and what the current state-of-the-art and potential is. In chapter 4, we outline our 2050 vision of what a fully mature hydrogen storage ecosystem could look like. Chapter 5 summarises the key findings of HyUSPRe, and outlines actions that must be taken to realise this vision.

Underground hydrogen storage demonstration facility Rubensdorf, Austria. Photo by kind permission of RAG.


Hydrogen

2. Hydrogen storage in porous reservoirs

2.1 Concept of underground hydrogen storage (UHS)

In UHS, hydrogen is stored as a compressed gas in reservoirs located beneath the Earth's surface (Figure 1). Those reservoirs can be salt caverns (artificial man-made cavities in salt layers), depleted oil and gas fields (layers of porous rock that were exploited to produce oil or gas), or aquifers (water-bearing layer of porous rock). While salt caverns are inherently leak-tight due to the fact that salt is impermeable, depleted oil and gas fields and aquifers require an overlying caprock that is tight so that the gas is contained within the reservoir. The process of storing hydrogen typically involves injecting hydrogen into these reservoirs during periods of excess production or low demand of hydrogen and withdrawing it when required to meet demand at times of low production or low hydrogen import flows.

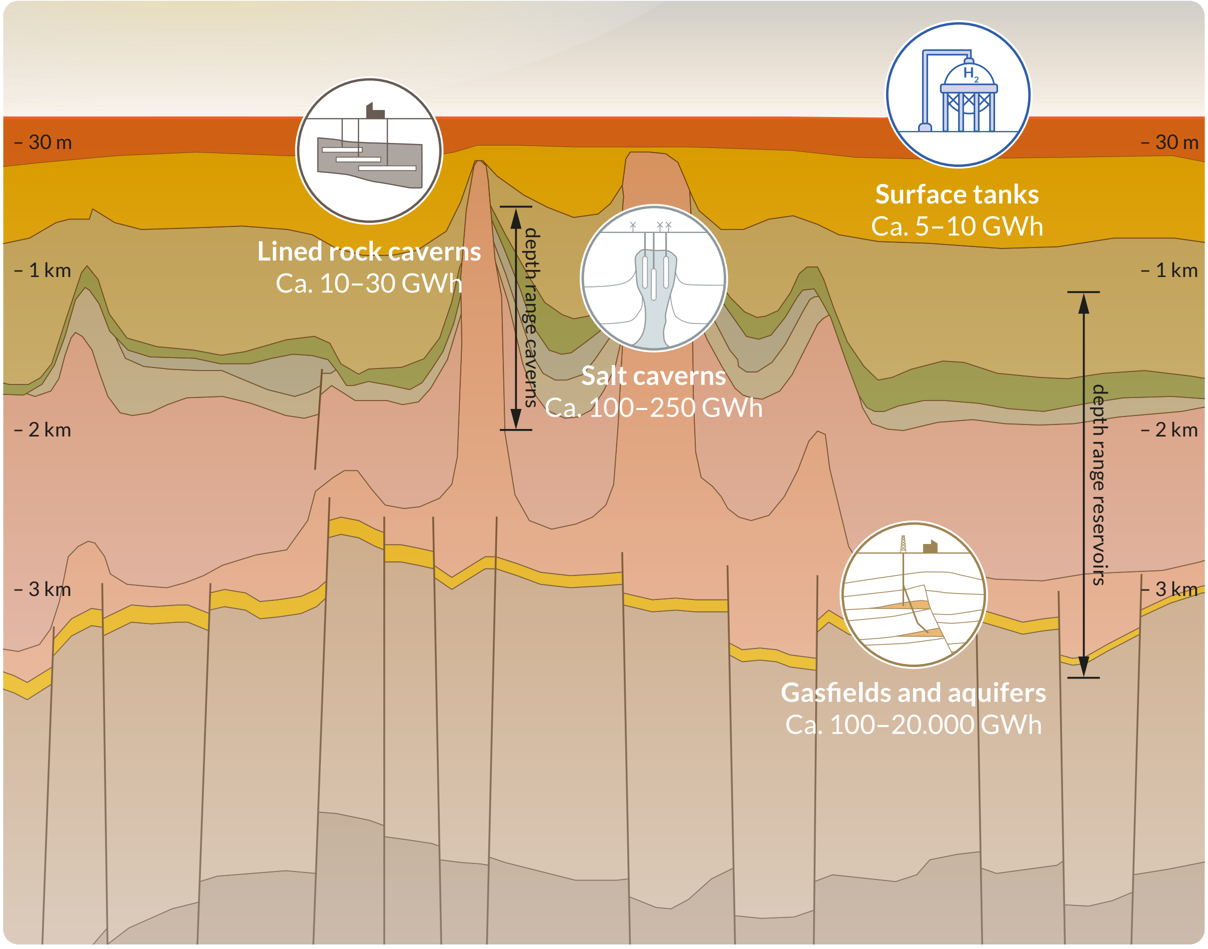
2.2 Hydrogen storage in the future energy system

Our future energy system will be characterised by a larger share of intermittent renewables (wind, solar). Energy storage will play a pivotal role in providing the needed flexibility to balance energy supply and demand in the integrated system, from low power and fast response solutions for short duration (< 1kW; <1s) to longer-term balancing of the grid (>1GW; hours to days, weeks and beyond). For the longer-term balancing needs, large-scale, centralised underground storage of energy is an attractive and cost-effective solution. It can provide flexible bulk power management services for electricity, gas and heat commodities, and offers essential services to society in the form of strategic energy reserves, energy system adequacy[13] and balancing solutions for unavoidable seasonal variations in supply and demand.

Today, many of these services are provided by the storage of natural gas which is already safely stored in large quantities in depleted gas fields and salt caverns in the subsurface of many countries in Europe. Natural gas storage balances supply and demand on a daily basis and secures supply during cold winters and supply disruptions. As the role of natural gas declines, a different non-fossil energy carrier is needed to provide large scale storage possibilities within a renewable energy system. This role can be fulfilled by hydrogen storage.

Figure 1: *Technologies for large-scale hydrogen storage including typical ranges for storage capacities.*

Figure modified from UHS Technology Monitor Report, H2-TCP Task 42 (IEA), 2023.[14]



Hydrogen is foreseen to play an important role in our future energy system. It is a versatile energy carrier that can be produced from renewable electricity (power-to-gas), and then used, for example, to generate electricity and heat, for mobility, or as feedstock for several industry sectors. A key advantage of hydrogen is that it can be stored in large quantities underground, like natural gas today, potentially offering similar services to society. It is also a key enabler for the emerging power-to-gas value chain i.e., the large-scale conversion of renewable electricity into hydrogen molecules. The unique feature of underground hydrogen storage in porous reservoirs is that the storage capacity exceeds that of any other storage option (Figure 2).

UHS storage technologies are particularly efficient for seasonal storage providing balancing services over various timeframes but dominantly with a relative low number of annual cycles complementing shorter cycled energy storage and flexibility options in the energy system.

UHS can play several important roles in the future European energy system. Firstly, by enabling the use of renewable electricity for hydrogen production, the decarbonisation of hard-to-abate sectors is facilitated, by offering a stable hydrogen supply during the whole year. Secondly, by storing excess renewable electricity during periods of surplus, in form of hydrogen, and using it for electricity production during times of high demand, curtailment is reduced, and a consistent electricity supply is ensured (Figure 3). Thirdly, Europe's energy independence is increased by allowing strategic reserves to be stored within Europe, including storing imported hydrogen to enhance regional stability and resilience amid global energy challenges.

UHS is a crucial element in the hydrogen infrastructure, enabling the full potential of hydrogen as a clean and sustainable energy carrier, and contributing to supply and price stability, two important boundary conditions for growth of the emerging hydrogen value chain.

***Figure 2:** Storage capacities and withdrawal times of different storage types, highlighting the uniqueness of UHS in spanning a wide range of capacity and withdrawal time. Note that axes are at logarithmic scale, and that the size of ellipses indicate storage capacities of the respective storage types.*

Figure modified from Artelys and Frontier Economics, 2024.[15]

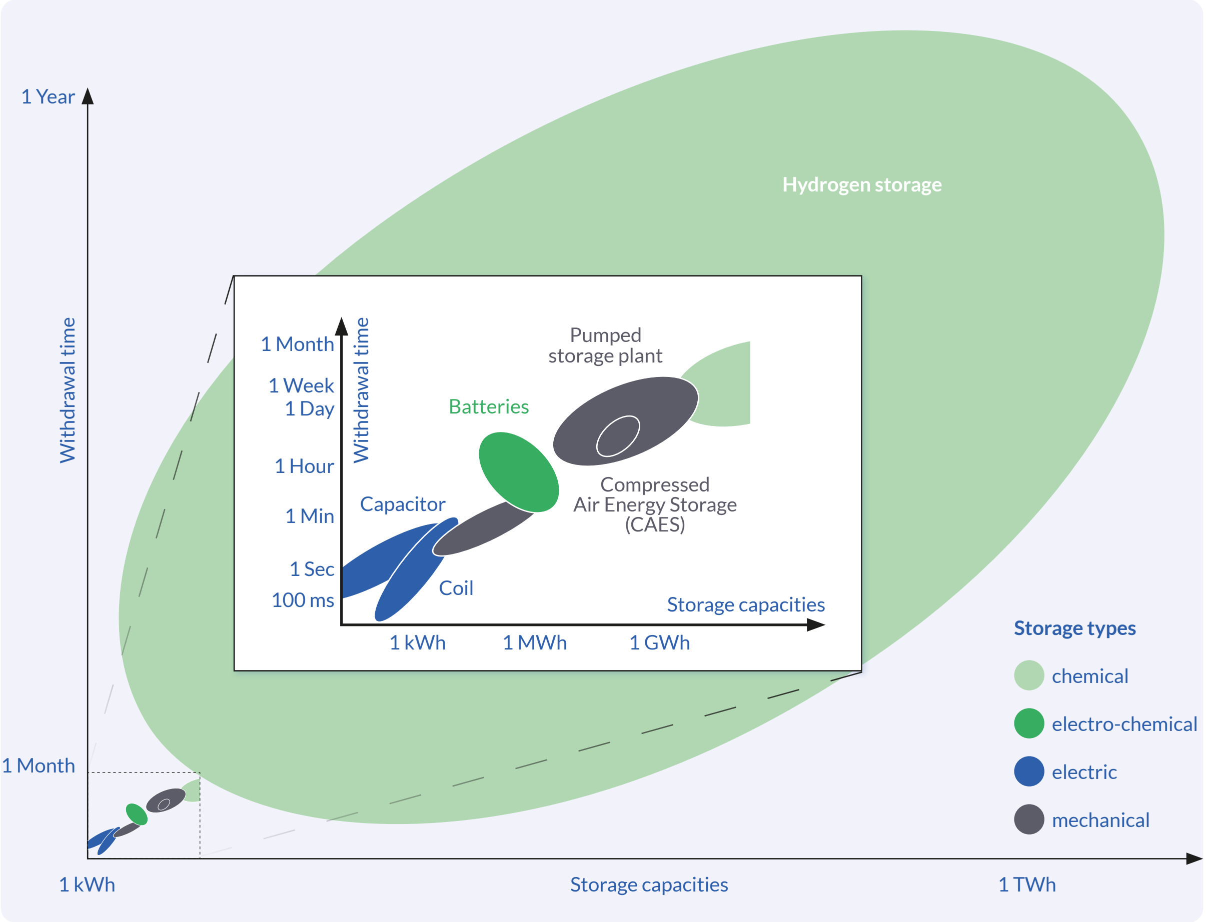
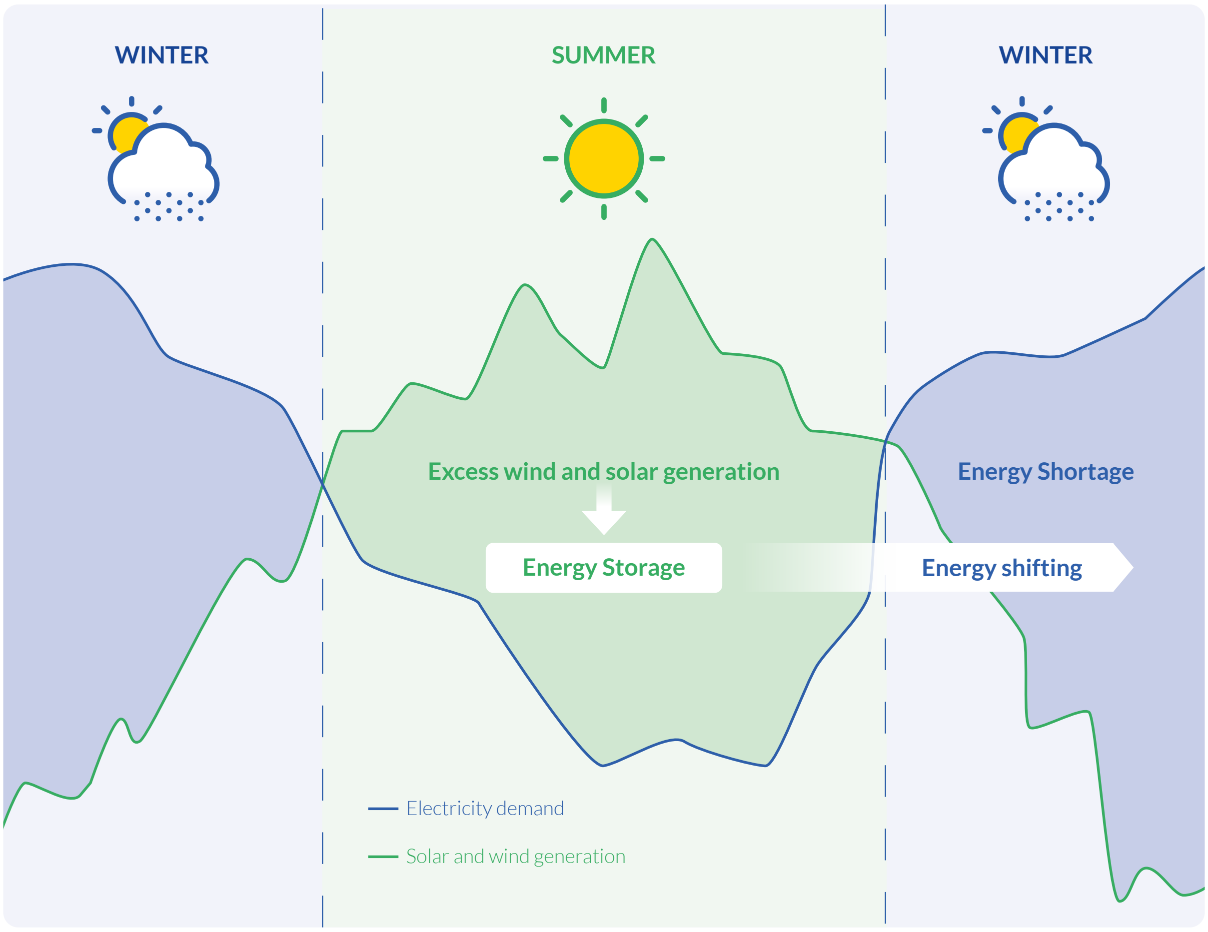


Figure 3: *Illustration of the need for seasonal storage, showing a graph with electricity demand (blue line) and solar generation (green line) for Europe over a single year. Green-shaded area indicates excess solar generation. Solar energy is stored using storage technologies to 'shift" its use in time and thus, to meet high demand in winter.* *Figure modified from EASE, 2022.*[16]



Centrica's Rough gas storage facility. *Photo by kind permission of Centrica.*

3. Status and future potential of UHS in Europe

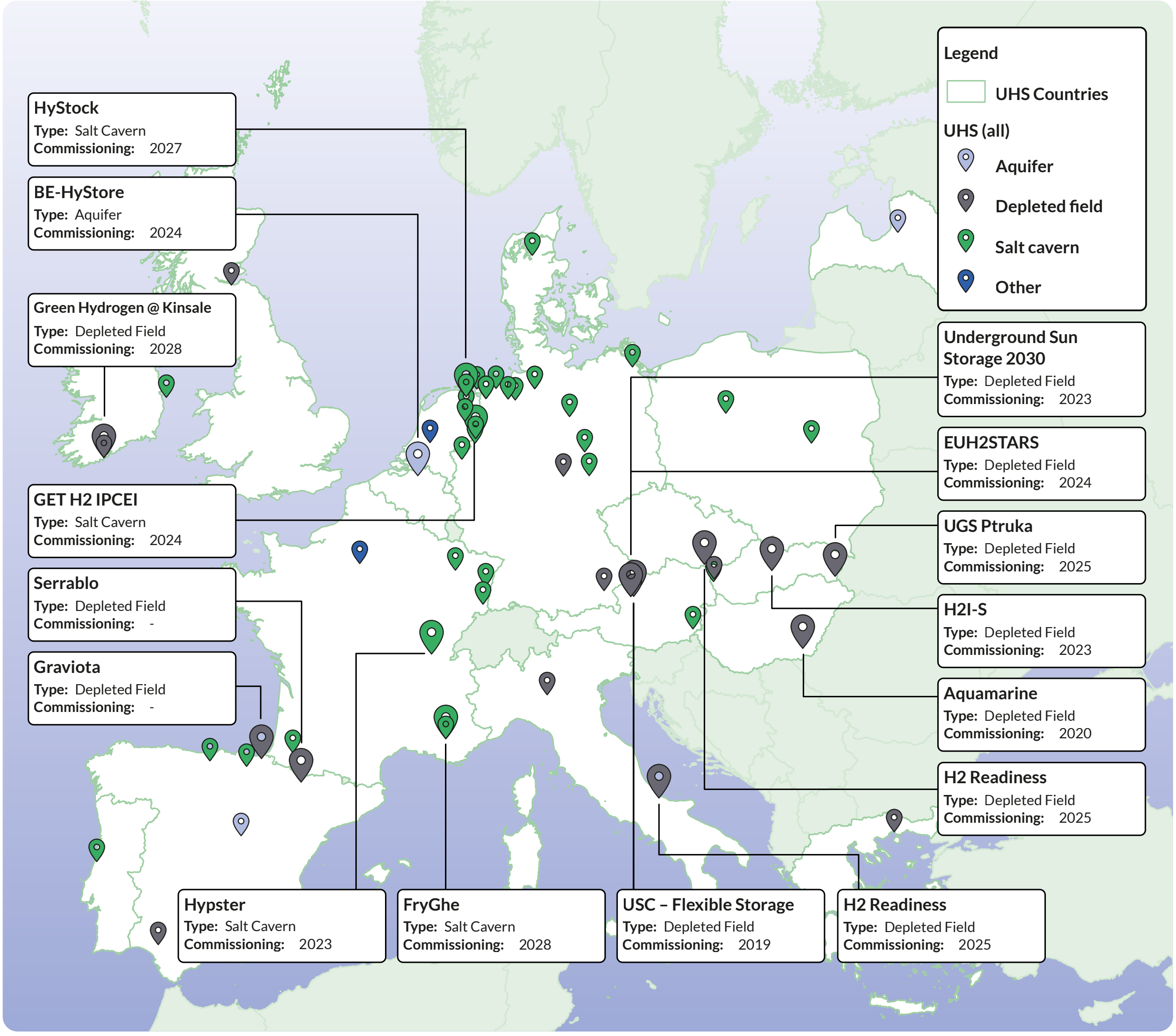
3.1 Status of development

Initiatives to advance the technology readiness of UHS in porous reservoirs and salt caverns are gaining momentum in Europe, often with support of national governments and the European Union. This reflects commitment by governments and industry to establishing a hydrogen economy. The map below (Figure 4) shows ongoing and planned pilot- and demonstration projects in Europe confirming this commitment. These initiatives leverage existing infrastructure such as depleted gas reservoirs, salt caverns, and aquifers for hydrogen storage, while also developing innovative solutions to optimise storage capacity, efficiency, and safety.

By the early 2030s, the expectation is that roughly 9 TWh of storage capacity will be operational, provided by 25-30 sites, of which the majority in number (80%) is in salt caverns[17]. This reflects the higher technical readiness level of this technology (TRL 6-7) currently, compared to porous rock storage (TRL 5-6)[18].

In terms of total storage capacity available in 2030 though, the five sites that will store hydrogen in porous reservoirs represent about 40% of the 9 TWh, highlighting that porous reservoirs have larger storage capacities. Although pilot projects have been storing hydrogen-rich gas mixtures in gas reservoirs in Europe[19,20] pure hydrogen has not been stored in any of these projects. In 2023, a first pilot project injecting pure hydrogen started in Austria, aiming to store at GWh-scale. This will raise the TRL to 6 once successfully completed. Further upscaling of this pilot to demonstration-scale is planned for the period 2025-2030 (to reach TRL 8).

Figure 4: Ongoing and planned underground hydrogen storage projects in Europe.



It is expected that these pilot- and demonstration projects, complemented by fundamental and applied research that is underway across various European countries, will establish the feasibility and scalability of UHS in porous reservoirs and salt caverns, and prepare them for commercial deployment from the 2030s onwards. Ongoing collaborations between research institutions, industry stakeholders, and government bodies result in significant improvement of the readiness level, with a focus on addressing technical challenges, regulatory frameworks, and investment requirements. Other challenges such as cost-effectiveness, scalability, and public acceptance need to be addressed to realise the full potential of UHS in Europe to enable the transition towards a sustainable and societally supported hydrogen energy economy.

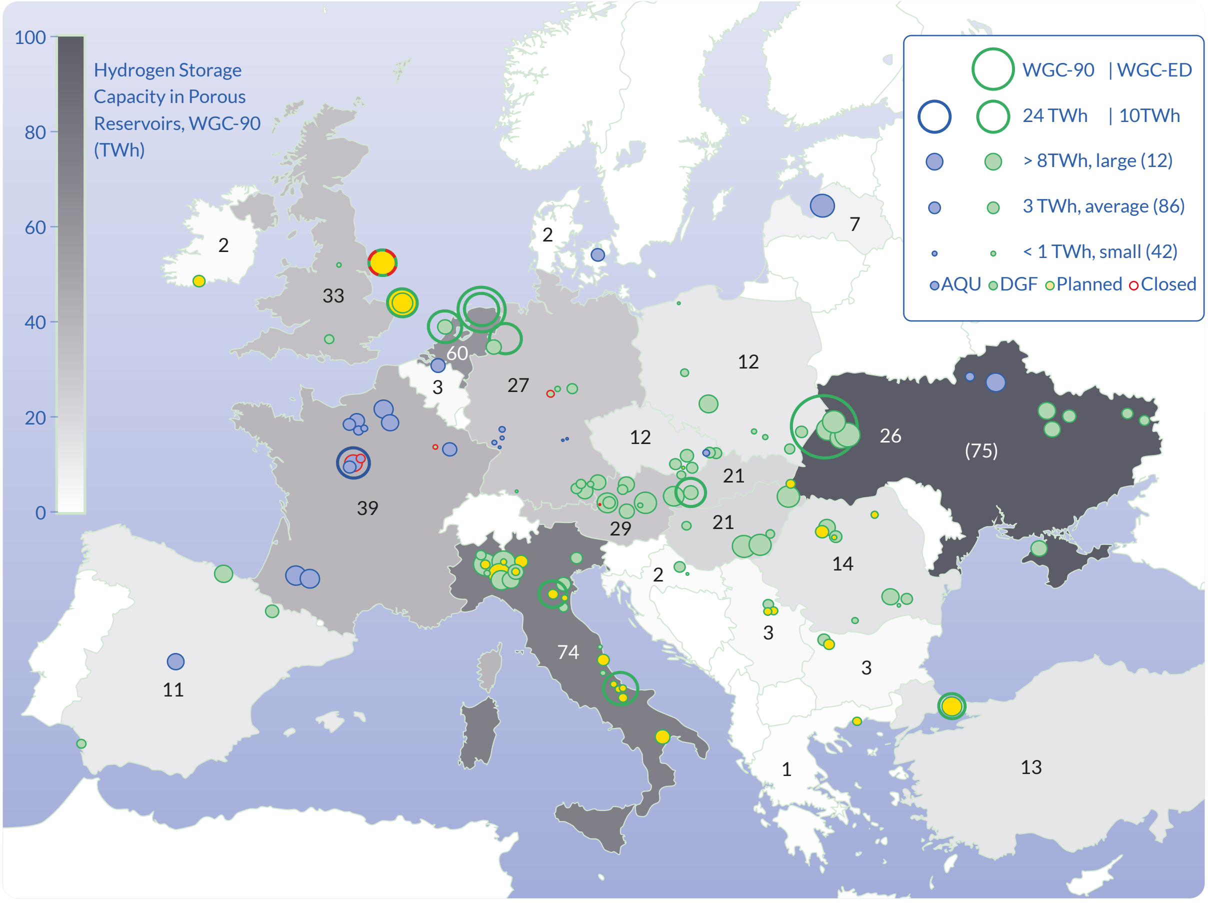
3.2 Future technical and market potential

The HyUSPRe project reveals that underground hydrogen storages are valuable assets for the near future energy system in Europe. Both subsurface storage in porous reservoirs and salt caverns provide key complementary system services at anticipated competitive costs compared to its surface storage alternatives. HyUSPRe estimates the technical potential for hydrogen storage in operational and planned natural gas storage sites in porous reservoirs at 415 TWh (Figure 5). Together with an estimate for storage in reused salt caverns of 50 TWh the total capacity is 465 TWh.[21,22]

Energy system models are used to explore the value of underground storage in the future energy system and test robustness of the latter in different future market contexts. The results from a HyUSPRe study by Groß et al. 2024.[23] give a first outlook for the future market potential for UHS in porous media and caverns. The analysis affirms that hydrogen storage in porous reservoirs and caverns does play a complementary and pivotal role in balancing the supply and demand dynamics of the evolving European energy system.

In 2030, about 50 TWh of hydrogen storage capacity will be required according to the HyUSPRe study by Groß et al. 2024, which in the early phase of UHS deployment will primarily rely on the use of repurposed salt caverns. This is notably in considerable contrast with the 9 TWh of storage capacity that is expected to be operational in the same timeframe according to a recent study by Artelys and Frontier Economics for Gas Infrastructure Europe.[24]

__Figure 5:__ Underground hydrogen storage potential in existing gas storages in porous reservoirs in Europe. The potential hydrogen storage capacity for natural gas storage assets in porous reservoirs is 415 TWh. 86% of the inventory consists of depleted gas fields that are currently natural gas storage sites (green circles). 14% are aquifer sites (blue circles); 11% of the inventory represents planned sites, all depleted gas fields (yellow circles). Very large sites are represented by hollow rings (N=12), all other sites are solid circles. Closed sites are ringed in red. Values centred in countries represent the potential hydrogen capacity identified for that country. Ukraine's exceptionally high value appears in brackets as it exceeds the grey scale maximum of 125 TWh. Map reused and modified from Cavanagh et al., 2023[25]



As hydrogen demand and electricity supply by variable renewable energy supply options increase, the need for storage capacity also will increase significantly after 2030, reaching about 160 TWh in 2040, of which almost half will be provided by repurposed porous natural gas storages (Groß et al. 2024).

In 2050, storage in porous reservoirs will account for almost 65% of the storage capacity for hydrogen as hydrogen storage in porous reservoirs is widely available across Europe and will be realised in a very large share of countries with pore storage potential. Depending on the wind and solar conditions, the system cost-optimal UHS capacity ranges between 80 TWh and 270 TWh in 2050 (Groß et al. 2024). This shows that implementing pore storage capacities complements cavern storage potential and results in a more distributed deployment of UHS across Europe. This enhances resilience and accessibility within the hydrogen infrastructure while reducing the need for the implementation of new salt caverns as hydrogen storage.

Hydrogen storage in porous reservoirs would leverage total annual energy system cost savings of approximately 0.4% (€2 bn per year).[26] From a study by Caglayan[27] it was already indicated that not having underground storage of hydrogen available in the European energy system could increase systems costs by 8%.[28] Morales et al.[29] estimate system cost savings at 10 billion euro while the recent study by Artelys and Frontier Economics[30] mentions annual cost savings at ca. 2.5 billion euro per year.

> ‘Depending on the wind and solar conditions, the system cost-optimal UHS capacity ranges between 80 TWh and 270 TWh in 2050.’

Centrica's Rough gas storage facility. Photo by kind permission of Centrica.


H_2

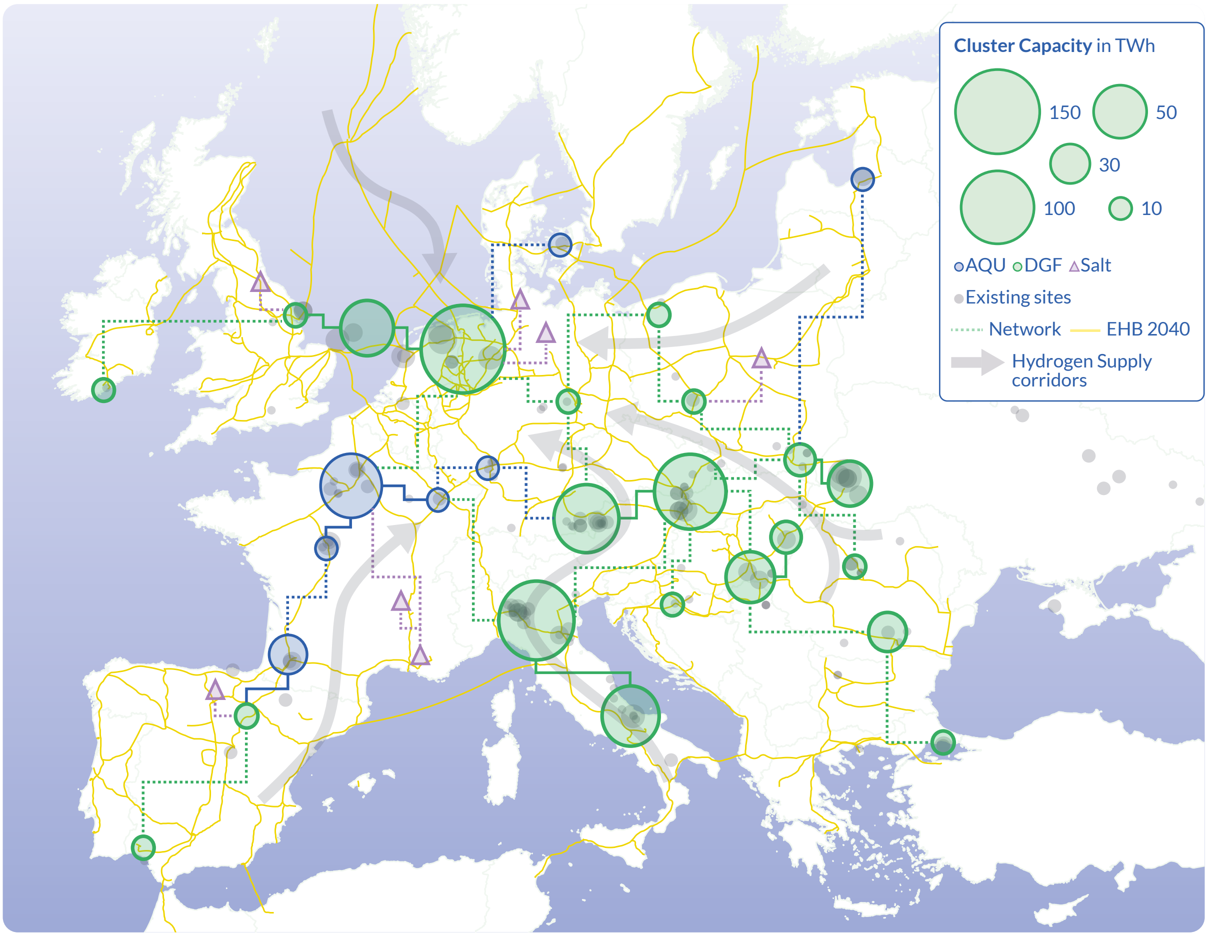
4. UHS in porous reservoirs in Europe in 2050 – a vision

Underground hydrogen storage in porous reservoirs will become an important element of Europe's decarbonised energy system towards 2050, providing essential services to society in the form of strategic energy reserves, energy system adequacy, and balancing solutions for unavoidable intra- and inter-seasonal demand and supply variations. As part of a pan-European hydrogen transport and storage infrastructure, porous reservoir storages will support a well-functioning hydrogen commodity market and contribute to energy security and energy system stability similar to underground gas storage today.

By 2050, the production of renewable electricity and the development of electricity transmission infrastructure in Europe are expected to be drastically increased[31], enabling the widespread use of renewable electricity for the domestic production of renewable hydrogen. Domestic production of renewable hydrogen will have increased significantly[32], and the development of hydrogen import routes[33] will be fully established, creating a high demand for hydrogen storage to balance the system. Across Europe, hydrogen demand centres, concentrated around but not limited to industry, will develop, and will be connected to supply regions and storage sites by an extensive hydrogen transport infrastructure[34] supporting a secure and reliable energy system. Storage in porous reservoirs and salt caverns, offshore and onshore, will support this system by balancing fluctuations in hydrogen supply and demand over timescales ranging from days and weeks to seasons, supporting offtake and fair pricing for hydrogen producers and importers.

The gradual phase-out of the natural gas infrastructure and the parallel development of a dedicated transport and storage infrastructure for pure hydrogen will progress significantly between 2030 and 2050 with careful planning and coordination between countries and sectors. Underground storages will likely be primarily built at or close to existing gas storage facilities, by reusing or adding porous reservoirs and caverns for storage of hydrogen. Deployment of storage capacity will happen at a pace required to meet storage demand and will match the development pace of renewable electricity and hydrogen production and transport infrastructure and import corridors.

Figure 6: *Illustrative vision of a hydrogen storage infrastructure in 2050 that would include storage in porous reservoirs at 400 sites to fulfill a high storage demand of 1,000 TWh. Mid-demand and low demand scenarios of 500 and 250 TWh have the same distribution for 200 and 100 pore storage sites respectively.*[35] *Hydrogen supply corridors and transport pipelines, as envisioned by the European Hydrogen Backbone initiative*[33,34] *are depicted resp. as arrows and yellow lines in the background.* Map from Cavanagh et al., 2023[2].



By 2050 there will be a highly developed hydrogen market and the price of hydrogen is expected to decline because of the intensification of production, the upscaling of electrolysers and multiple import routes. Pore storages will have been widely deployed (Figure 6) and this will help to stabilise prices and create a liquid and transparent market thus, providing favourable conditions for establishing businesses and a good basis for the European industry to stay in Europe and be competitive on the global market. The feasibility and affordability of the storage technologies will depend on continued investment in research and development of different types of UHS, coupled with an increased number of large-scale demonstration sites across Europe in the decades before 2050.

The feasibility and affordability of the storage technologies will depend on continued investment in research and development of different types of UHS, coupled with an increased number of large-scale demonstration sites across Europe in the decades before 2050. A particular success will be the intensified sharing of knowledge on the development of UHS between the stakeholders involved, allowing the replication and application of knowledge across Europe, despite significant differences in local geological conditions. This will enable rapid learning and early de-risking of technologies to become fully commercial much faster.

Successful pilots and demonstrations in the 2020s to 2030s will be very important for public perception and trust in the technology, likewise for the development of a dedicated normative and regulatory framework, and for technical standards. Stakeholder engagement programmes will be developed with the aim to increase knowledge and confidence in the safety of operations, and the learnings from stakeholder perspectives are included into better design, construction, planning, and operation of UHS sites in Europe. For example, learning campaigns about energy transition technologies including hydrogen underground storage can be organised at different educational levels and from local politics to national governments. Public awareness and engagement on hydrogen in general and storage in particular will become a fundamental part of the energy transition education. In addition, engagement programmes for direct neighbours of underground hydrogen storage facilities will prove very effective in finding solutions to local challenges and benefits of UHS developments. Local energy communities will be empowered to co-determine the development of UHS and will become customers of UHS for storing their self-produced energy as well as share additional benefits of UHS, including positive employment effects. Potential challenges related to land and sea use conflicts

> ‘In 2050, porous reservoir hydrogen storages will support a well-functioning hydrogen commodity market and contribute to Europe's energy security and energy system.’

Underground hydrogen storage demonstration facility Rubensdorf, Austria. *Photo by kind permission of RAG.*

associated with UHS will have been addressed through regulation and the participatory processes mentioned above.

While storage sites are deployed extensively across Europe, minimising environmental, health and safety risks will stay a top priority. Continuous improvements in risk mitigation measures and means to minimise potential environmental impacts such as emissions, noise, light and visual pollution, and the effects of potentially induced seismicity will be very important. That is why sophisticated fit-for-purpose risk management and monitoring will be implemented very early in the development process and during the demonstration phase. Microbiological and geochemical reactions in reservoirs will be monitored using established technologies to predict their occurrence, quantify their impact, and develop mitigating measures for site-specific conditions. With the aid of state-of-the-art reservoir modelling software tailored for UHS, reservoir development and operation will be optimised, and impurity levels predicted. Additionally, the best available purification technologies will be developed. Standards for materials used in hydrogen storage will be based partially on available standards for gas storage and adapted for hydrogen by leveraging experiences gained during demonstration projects.

Harmonised regulations on hydrogen including hydrogen storage will be established across Europe and their roles will be clearly defined in the relevant directives and regulations. There will be a clear and unified certification system for hydrogen production and use, with the EU and relevant third countries acting as a single entity for future energy markets. Permit requirements and compliance rules will be clearly defined, and long-term policy and regulatory frameworks will ensure the necessary investment and subsequent development of UHS in Europe. Technical regulators will be in place to ensure efficient and straightforward planning, licensing, and operation of UHS. In addition to a pan-European vision, each European country will include geographical locations and performance characteristics for hydrogen storage in its strategic space planning. National governments will decide individually and in partnership with other countries on their strategic energy buffers and energy storage levels to ensure stable markets and security of supply. Due to the strategic and societal value of storage in the energy system, innovative business models will be developed. This will include, for example, cases of regulated support schemes to stimulate early investment in storage projects. Uncertainties regrading the cost bearers of hydrogen storage (producer, off-taker, grid operator, government) will be addressed in the respective regulatory frameworks. This will also provide clarity on the third-party access regime, regulated or negotiated, for storage in the European Union. European, regional, and local authorities supported by the respective industries will recognise their role as drivers of UHS development and will proceed in a cooperative and coordinated manner to successfully integrate UHS into the European gas, electricity, and heating sectors.

While the vision sketches a future in which UHS is fully established as a mature, commercial, and societally accepted technology, it's realization will not come by itself. Intensive, pro-active, short, medium, and long-term measures will be important for the development and establishment of hydrogen storage in porous reservoirs in Europe. Actions required will be interdependent and extend to several areas at the same time: eliminating the challenges on the technological side, monitoring of the environmental impacts, establishing the hydrogen market, deployment of demonstration sites, elevating public awareness to facilitate societal embedding and development of required standards and regulations. For the successful establishment of UHS, the early involvement of policy makers at European and regional level will be essential to ensure legal certainty for relevant stakeholders.


H2
GREEN HYDROGEN

5. Actions needed to successfully implement UHS in porous reservoirs

The HyUSPRe project investigated the feasibility and potential of implementing large-scale underground geological storage of renewable hydrogen in porous reservoirs in Europe. It addressed specific technical challenges and possible risks related to geological storage of hydrogen, quantified, and mapped the European potential for storage, and conducted techno-economic assessments of the costs, benefits, and implementation pathways of UHS to support the European energy transition to net zero emissions by 2050. In doing so, the project has produced significant insights and identified crucial actions required to accelerate the readiness level of porous reservoirs to enable commercial-scale deployment from the 2030s onwards. In this chapter, the main insights of HyUSPRe and crucial actions required are summarised for five themes that govern successful deployment of UHS in porous reservoirs:

- Technology development
- Environmental impact and spatial planning
- Economics and market
- Policy and regulation
- Societal awareness and acceptance

5.1 Technology development

A lot of hydrogen storage-related experimental studies have been conducted at laboratory scale and in the context of pilot projects in recent years, determining the suitability of steel grades, elastomers and cements regarding their resilience on hydrogen induced modifications. Furthermore, microbial and geochemical reactions, thermodynamic and fluid flow behaviour and geomechanical reactions have been

Figure 7: *Illustration showing the research approach followed within the HyUSPRe project to link subsurface processes to project risks by conducting laboratory-scale research and extrapolating observations to field scale with numerical models.* Figure modified from Corina et al., 2023.[36]

experimentally investigated. Studies are typically carried out in international and national research programs, where the knowledge and tools are developed to mature UHS on a commercial scale. Within projects like HyUnder[37], Underground Sun Storage 2030[38], HyStorPor[39], Hystories[40] and HyUSPRe, relevant research has commenced and has been published for the wider public. The results of these laboratory- and pilot-scale research projects have provided a tremendous amount of insight, but also taught us that further research initiatives will be necessary in the next decades, progressing insights from laboratory-scale experiments into field-scale modelling capabilities and from pilot projects to demonstration projects (Figure 7).

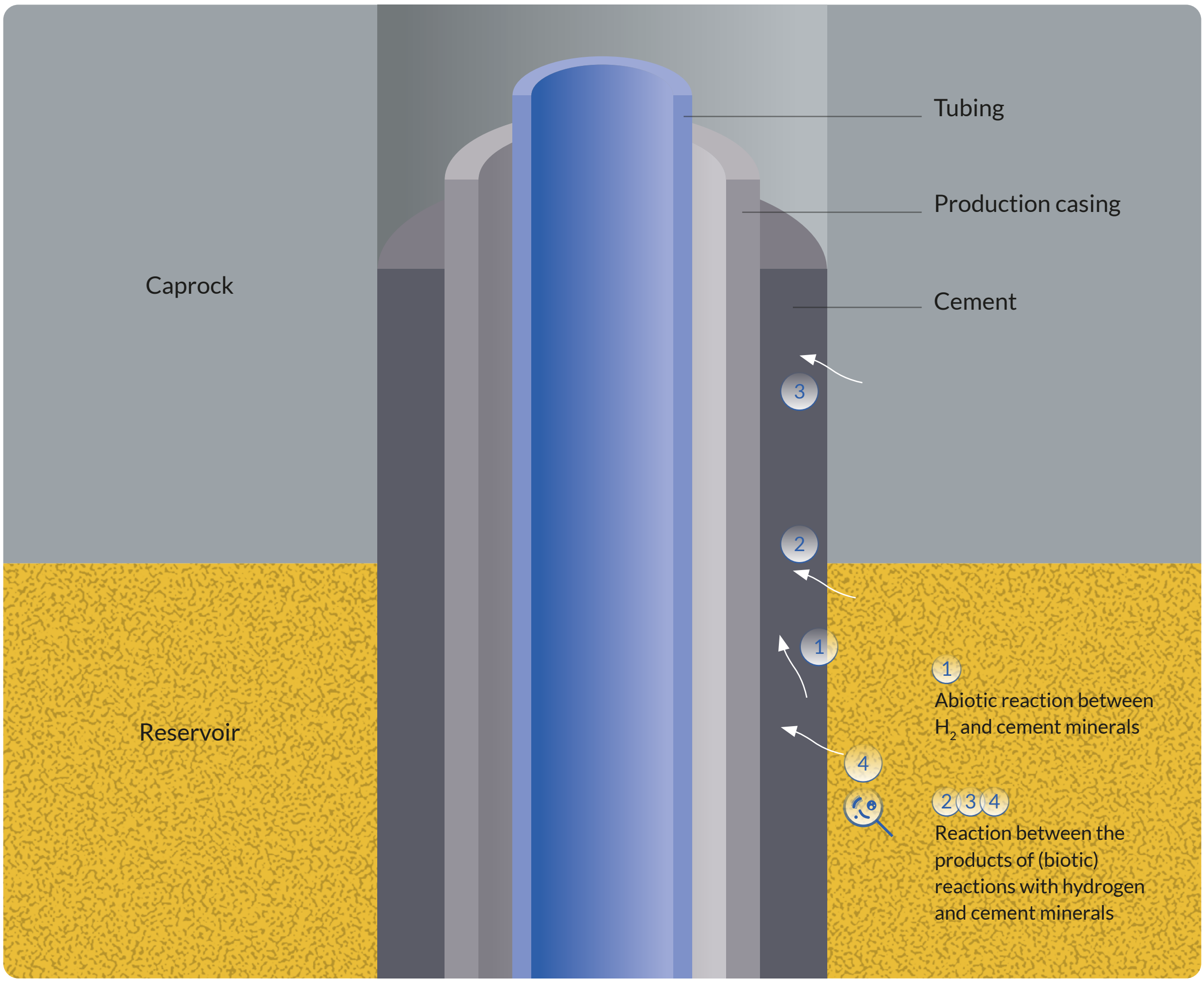
5.1.1 Develop UHS-specific compression, gas cleaning, wells and materials

Concerning the technological development of hydrogen storage, some existing technologies need adaptation or verification with respect to hydrogen and further upscaling. Compressors that can handle high flowrates of hydrogen efficiently need to scale up in order to realise UHS. In addition, advanced purification technologies must be developed and tested to obtain the required purity of hydrogen.

The extent of purification depends on the use case. For fuel cells, a high purity of hydrogen is required, typically 99.99%, while usually a lower purity of hydrogen is required for industrial use, typically 98%. For porous reservoirs, the expectation is that the injected hydrogen will mix with the initial gas in place, leading to the need for purification of the withdrawn gas mixture. Depending on the use case of the hydrogen, guidelines should be established to determine which gas qualities or hydrogen purity levels need to be provided by storage operators. This is especially crucial because higher quality means more purification effort and therefore higher costs for UHS. In addition, utilisation possibilities of the tail gas after purification should be investigated in more detail. Tail gas may contain relatively large amounts of natural gas and other constituents in minor amounts which were that was co-produced from the reservoir on withdrawal and may be considered a resource that can be utilized either in chemical processes or to generate process heat for the storage facility.

For wells and materials, several studies were published about experimental testing of materials (Vallourec, 2022; San Marchi and Somerday, 2012, Loder, 2022).[41,42,43] In addition, work in HyUSPRe[44] showed no significant effect of hydrogen on cements (Figure 8). Going forward, special emphasis on UHS specific conditions such as

Figure 8: *Possible interactions with cement in an UHS system.* *Figure modified from Corina et al., 2023.*[45]



cyclic pressure for developed equipment and required materials is essential, however, experience gained from UGS operations can be used.

Monitoring of long-term effects and accelerated stress tests on the equipment and materials should also be part of the further research.

Repurposing existing wells, if possible from an integrity and capacity perspective, reduces initial capital expenditures and shortens the timeline for project deployment. However, adapting these wells for UHS introduces challenges that must be addressed to ensure safe and efficient operations. These include ensuring the suitability of the well's architecture for the new operational conditions and the placement of the well within the reservoir to provide the required storage capacity and hydrogen retrievability. Overcoming these obstacles requires a combination of research and development efforts with practical applications, such as pilots and demonstrations on existing wells, to validate concepts and refine processes for commercial viability.

The development of abandonment well technologies is crucial for UHS deployment as it ensures the safe and environmentally friendly closure of wells, thereby mitigating potential risks associated with UHS. Abandonment technologies for legacy wells should be developed jointly by academia and industry to address technical challenges and ensure regulatory compliance while optimising costs and minimising environmental impact.

While developing technologies for the surface and subsurface, safety should always be the highest priority and a risk assessment concerning failure of any of the technologies should always be made. Processes for circularity and efficient use of raw materials for UHS equipment and infrastructure including re-use and recycling should be defined and applied in terms of cost optimisation.

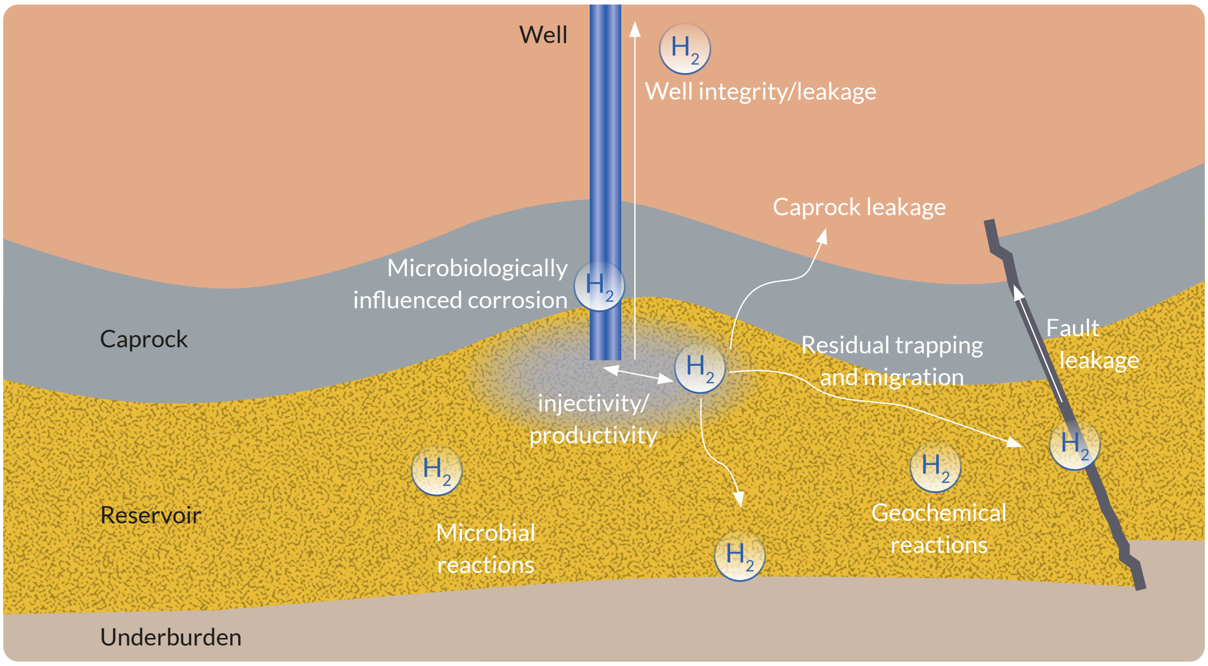
Call to Action

- **Facilitate the TRL progression from 5-6 now to 7-8 in 2030 and upscaling of compression and purification technologies, wells and materials for UHS to commercial scale through continued research activities, pilots and demonstrations.**
- **Support implementation of semi-commercial UHS projects that can develop market-ready storage solutions and optimise them for further scale-up.**
- **Develop processes for circularity of materials, equipment, and infrastructure.**

5.1.2 Continue R&D on quantifying UHS-relevant subsurface processes

Figure 9 illustrates the key subsurface processes related to UHS. Microbial reactivity may lead to hydrogen loss, H_2S (hydrogen sulphide) generation, and acetogenesis.[46,47,48] Generation of H_2S poses a particular risk, as this is a toxic gas which may lead to sulphur stress cracking and potential corrosion, impacting material selection and facilities design. Hydrogen loss and acetogenesis may have an unwanted impact on the economics and potential operability. Latest results from HyUSPRe[25] show that for porous reservoirs, microbial reactions are dominated by hydrogen loss via methane generation, at temperatures up to 65°C, while also acetogenesis was observed at 50°C maximum. Going forward, the scope for microbial research should include an increase in number of sites tested, extension of experiments to higher pressures and temperatures, and measuring kinetic rates of microbial activity under UHS

Figure 9: Key subsurface processes related to UHS. *Figure modified from Corina et al., 2022.*



storage conditions. In addition, the impact of hydrogen on microbially induced corrosion (MIC) needs to be better understood.

For geochemistry, initial experimental results from HyUSPRe indicate limited impact of hydrogen on the overall reservoir geochemistry.[49] A possible geochemical risk is the rate of hydrogen-induced pyrite reduction resulting in H_2S generation.[50] Experimental work on hydrogen-induced pyrite reduction extending to conditions relevant for hydrogen storage is currently ongoing and will provide key input for geochemical modelling to ultimately estimate H_2S levels. In addition, the rate of hydrogen consumption by other redox sensitive minerals, such as hematite, should also be further tested.[51,52]

Kinetic rates of both microbial and geochemical reactions will be important input for simulation models which will allow to upscale microbial activity and geochemical reactions to reservoir scale and gas composition changes within the storage reservoirs. These models can highlight risks and their outcomes can function as potential warning signals that need to be addressed during storage planning.

Knowledge gaps on storage are centred around optimisation of production and injection rates[53] and loss of hydrogen in the reservoir due to migration or trapping. Recent experiments on permeability and migration are currently being processed. Alternative cushion gases are also under consideration, which significantly impacts economics. Advances have been made on transport parameters such as relative permeabilities and diffusivity.[54] An option to investigate this is to upscale experiments to reservoir grid block scale, but it is potentially very challenging for some of these experiments.

The mechanical integrity of the hydrogen storage reservoir is closely linked to and dependent on the hydrogeology, geochemistry and microbial activity.[55] Several tests have been done in HyUSPRe[56] which did not show a consistent effect by exposure to hydrogen, but further studies are necessary through a) extending the testing of reservoir rocks from different sites that are exposed to hydrogen under static conditions to longer timescales, and b) performing the tests under dynamic conditions as experienced during cyclic storage. For the impact of UHS on the sealing capacity of cap rocks only a few datapoints are available, and in addition the effect of cyclic storage is not fully understood.

Research on thermodynamics and phase behaviour of hydrogen was not part of HyUSPRe however there is certainly a need for more experiments to describe the Pressure-Volume-Temperature (PVT) behaviour of hydrogen and hydrogen bearing gas mixtures under reservoir conditions, which will serve as input to improved Equation of State models.[57]

All obtained experimental data should be publicly shared with the hydrogen community and be added to existing or newly established global databases on microbiology, geochemistry, PVT, and transport properties. The models that finally use the output of the experimental results for reactive transport modelling can be based on open-source models[58,59,60] or models from commercial software vendors. Within HyUSPRe a validated open-source reservoir modelling software that can simulate coupled flow, geochemical and microbiological processes in a porous reservoir was developed. A further step up would be to couple reservoir models to geochemical software and databases and include microbial reactions for a valid prediction on gas compositions and mineral reactivity. Active collaboration by universities, research institutes and industry may help to further develop these models. Current geo-mechanical simulation capabilities are sufficient to address the questions at hand.

Ultimately, these models will have to be validated by field tests or full scale UHS sites. One of the first demonstration sites recently published their results, showing technical feasibility of underground hydrogen storage at the site of interest.[61] The next step is further validation through pilots and finally once commercial storages are in operation.

Call to Action

- **Extend experimental testing to provide the proper basis for upscaling and implementation in models.**
- **Improve and integrate geological, thermodynamical, geochemical, and microbiological models with reservoir flow models to improve capability to predict the produced fluid composition, including H_2 purity and H_2S, as well as flow performance.**
- **Intensify data sharing, databases and open-source model development between research, industry and software service providers.**
- **Calibrate models with data from operational UHS sites.**
- **Extend existing global databases with UHS relevant data on microbiology, geochemistry, thermodynamics and geomechanics.**

5.1.3 Develop UHS-specific operating standards and monitoring technologies

Clarification and definition of roles and responsibilities on UHS operating standards is needed. The level of purification for demand should be defined, if not done so already. Specifications for pipeline transport should be defined where still needed and harmonised. It should be decided whether hydrogen should be odorised. Current natural gas is odorised in some European countries with mercaptans, containing sulphur, which is not wanted for hydrogen. It needs to be discussed if system tracers will still be necessary in a future hydrogen system and in the case they are, whether different tracers can be used.

The development of Health, Safety, and Environment (HSE) standards and guidelines for operation of UHS sites in close cooperation with UHS operators from ongoing demo- and pilot-projects should take place. Operational experiences should be shared with other operators, for example in a HSE risk register, while developing a common set of guidelines. Cooperation with respective authorities in developing UHS related standards should be enhanced to ensure experience transfer.

The development of guidelines for site selection can help identifying the most suitable sites, using the results from HyUSPRe.[62] Development of guidelines and standards for well abandonment should start now and be finalised until 2030. Further learnings can be integrated as soon as new storages go online with an adjusted framework being available by 2040.

Monitoring technologies should be developed further along with guidelines for site-specific and risk-based monitoring, similar to the IOGP recommended practices[63] for CO_2 storage. Specific areas for monitoring development include the detectability of hydrogen, the impact of hydrogen on monitoring equipment, detection of hydrogen sulfide and other gases at the well head and at the site. Microbial monitoring is also under development. Active and passive time-lapse seismic monitoring can also be used where necessary, and existing technologies for oil and gas can be leveraged. Each field test, demonstration or field scale development should have a Measurement, Monitoring & Verification Plan (MMV) plan and a risk assessment exercise with a bowtie to identify risks and mitigation measures. Similar to Underground Gas Storage (UGS) an action plan should be put in place in case monitoring detects a positive signal and an emergency response plan should be available upon leakage detection.

Call to Action

- **Develop standards for material selection, well design, facilities design, and operational practices for UHS sites.**
- **Develop MMV technologies through continued R&D pilots and demonstrations, including low-cost solutions for safe UHS operation.**
- **Assess the suitability of existing monitoring techniques from UGS and supplement these with techniques needed specifically for UHS.**
- **Develop abandonment standards.**

5.2 Environmental impact and spatial planning

Deployment of UHS in porous reservoirs represents a critical nexus of challenges and opportunities in the search for sustainable energy systems. Concomitant with that careful consideration of various environmental and spatial factors is required to ensure safety, minimise environmental impact and optimise resource allocation. Environmental considerations are a key factor, and spatial planning also plays an important role, as hydrogen infrastructure needs to be carefully placed to ensure efficient distribution and integration into existing energy networks. Spatial planning needs to integrate subsurface and above ground interests and take into account competition with other land use forms, when assessing the suitability of storage sites, managing potential risks associated with UHS operations and mitigating impacts on surrounding ecosystems (Figure 10). Addressing these environmental and spatial planning challenges requires a holistic approach to effectively contribute to the transition to a sustainable and low carbon energy future.

5.2.1 Ensure integrity and mitigate leakage risk

Monitoring of environmental impacts is critical for sustainable development and a multidisciplinary approach involving scientists, policymakers, industry representatives and community stakeholders is needed to establish emission thresholds for UHS in porous reservoirs. It is essential to take into account the specific characteristics of UHS in porous reservoirs, the environment to be monitored and any regulatory frameworks that may apply.

Once limits have been established, continuous monitoring must ensure compliance with established limits. According to Murray et al.[64] monitoring programmes can use a variety of techniques including field measurements, remote sensing, and data analysis to track changes where quantitative thresholds specify clear decision points and where action to prevent negative outcomes must be taken.

Identifying risk conditions and developing best practices to mitigate them is fundamental to effective risk management across multiple dimensions, from environmental protection to economic factors and public health and safety. As a result, involved organisations can improve their ability to anticipate, prevent and respond to potential threats associated with UHS. By developing best practices that include a range of proactive measures to prevent, reduce or manage them to acceptable levels, they can be effectively mitigated. For further development of UHS in porous reservoirs, international collaboration is essential to learn from each other's successes and failures and thus advance related challenges rapidly.[65]

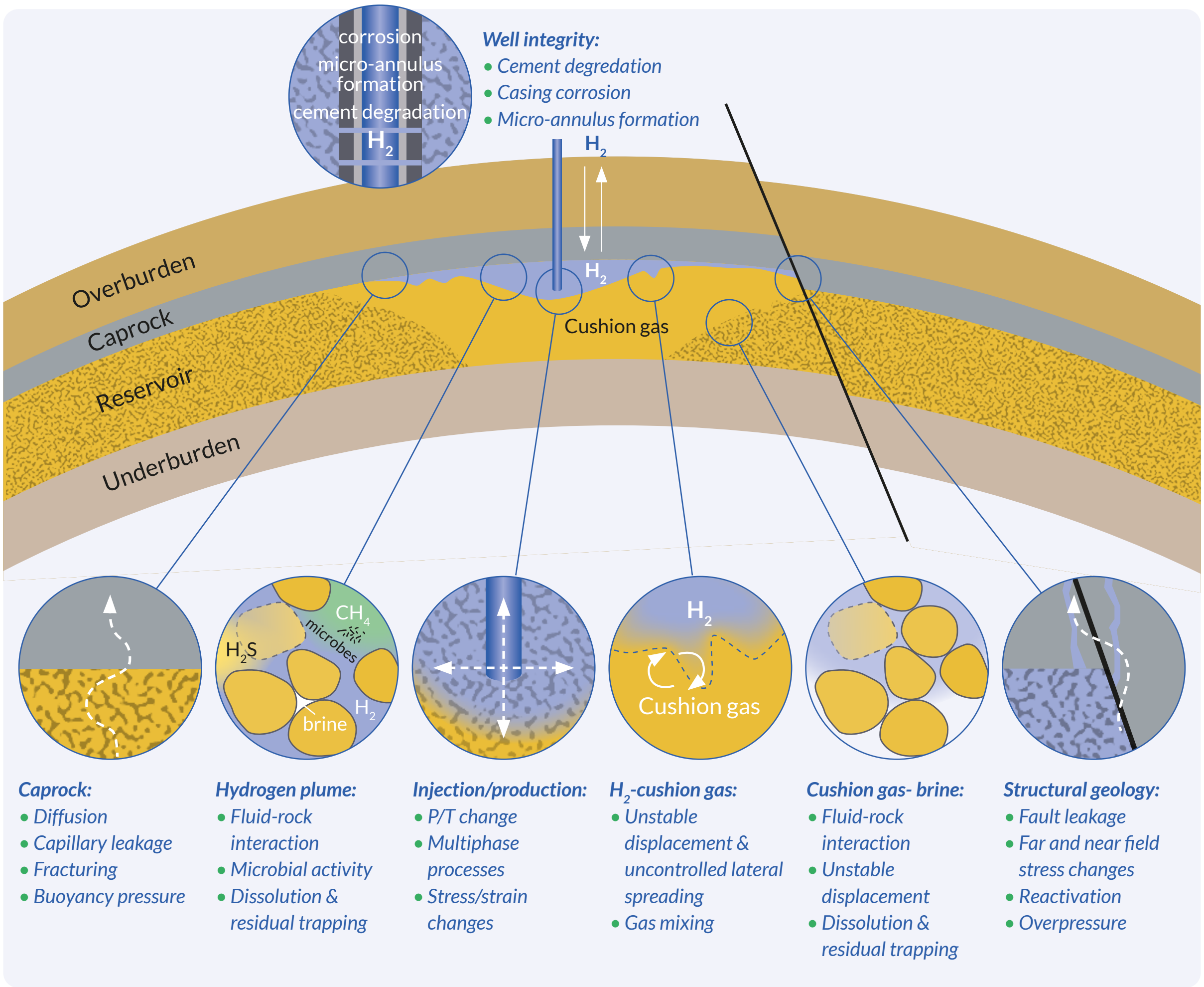
At UHS sites, monitoring for hydrogen leakage from the reservoir and within the facility is essential for ensuring safety and reliability, particularly as hydrogen becomes increasingly integral to various sectors, including energy, transportation, and industrial processes. By implementing robust monitoring systems and a catalogue of standards and best practices, operators can effectively mitigate hydrogen leakage risks and ensure the long-term integrity of hydrogen infrastructure.

Call to Action

- **Establish threshold values for monitoring environmental impact based on the experience from existing pilots and analogous applications.**
- **Identify conditions for risks and develop best practices to mitigate them.**
- **Develop a catalogue of best practices and standards to mitigate and monitor hydrogen leakage risk and safeguard long-term integrity.**

Figure 10. Uncertainties in geological processes relevant for underground hydrogen storage in porous reservoirs that may potentially pose risk.

Figure reused and modified from Heinemann et al., 2021.[66]



5.2.2 Implement monitoring plans

As UHS in porous reservoirs becomes increasingly important for energy storage and transition to renewable fuels, understanding and evaluating the long-term effects on the environment requires a holistic approach that considers multidimensional factors. Based on existing requirements for monitoring UGS sites, competent mining authorities in collaboration with operators should develop tailored guidelines specifically for UHS sites across Europe. According to Luo et al. (2024)[67], the experience can be extended to facilitate the development and operation of UHS projects to define common safety standards and reduce costs. The long-term effects of UHS in porous reservoirs on the environment encompass a broad range of considerations, from potential impacts on geological formations to implications for local ecosystems and greenhouse gas emissions.

Transparent operation of UHS facilities is essential to build public trust, ensure regulatory compliance and promote accountability in the process of energy transition and carbon neutrality. A key aspect of transparency is making monitored data available to the public so that stakeholders, including local communities, environmental organisations, and regulators, can access information on the performance and impacts of storage operations. According to Kovač et al. (2021)[68], end-users and investors are choosing transparent solutions that are already established in the market.

Call to Action

- **Develop monitoring guidelines for European UHS sites by responsible mining authorities based on existing underground gas monitoring requirements.**
- **Evaluate long-term effects of UHS in porous reservoirs sites on the environment.**

5.2.3 Demonstrate safety and minimise environmental impact

Technologies should be further developed to minimise the emissions and environmental impacts during construction and operation of UHS facilities. This requires improvements in construction and operation practices to minimise environmental impact (emissions, waste, noise, light) while maximising process efficiency. Measures to mitigate risks and monitor operations to verify conformance and compliance should be checked on their compatibility to hydrogen, made compatible when required, and then tested, first in a controlled environment, and afterwards in pilot and demonstration projects.

As the utilisation of UHS facilities continues to grow in the future, it becomes imperative to establish robust emergency response for hydrocarbon production to ensure the safety of operations and to effectively mitigate potential risks. A tailored emergency response plan is essential to address any unforeseen incidents promptly and to protect personnel, neighbours, infrastructure, and environment. By establishing risk assessments, clear procedures and protocols, robust communication systems and monitoring, stakeholders can mitigate risks and respond effectively to emergencies.

Call to Action

- **Improve technologies and practices for construction and operation to reduce emissions while maximising process efficiency, thus minimising environmental impact and footprint.**
- **Implement an emergency plan for safe UHS operation.**

5.2.4 Develop a land use plan in line with energy transition

Ensuring that spatial planning is consistent with energy system, planning is essential to promote sustainable development. According to De Pascali and Bagaini (2018)[69], the ongoing tendency to separate energy topics from spatial planning leads to less efficient results in the long term. Through encompassing strategic land use allocation into spatial planning processes, policymakers can optimise land use for renewable energy installations, prioritise energy-efficient infrastructure development, and mitigate environmental impacts as there are competing interests with many other sectors, such as CCS and geothermal use of the subsurface. Through dedicated regulations and land-use policies, the deployment of UHS in porous reservoirs in suitable locations is supported and therefore is the development of decentralised energy systems, enhancing energy security and reducing dependency on centralised power generation.

In this context, incorporating local stakeholders into spatial planning processes is essential to ensure transparency and engagement, regarding planned UHS facilities. Especially at the initial stages, authorities play a crucial role in facilitating communication between stakeholders and project operators keeping them informed about key milestones, construction activities, and any updates regarding operational procedures. Ongoing engagement ensures that stakeholder opinions are included, builds trust, fosters a sense of

accountability, and allows for timely resolution of any issues that may arise.

Also for Spyridonidou et al. (2021)[70], active participation of stakeholders into spatial planning processes can significantly boost the deployment of energy infrastructure projects. By initiating international calls, countries should collaborate to identify suitable land for UHS in porous reservoirs development by considering factors such as geographical suitability, environmental impact, and social considerations. The call for allocating land for energy transition ensures that cooperation across borders is required. In this context, transparency underscores the importance of openness and clarity in the process that decisions are made in a clear and accountable manner. Energy transition is a global challenge and a systematic land allocation approach for this transition is essential.

Call to Action

- **Ensure that spatial planning prioritises energy system transition planning.**
- **Involve local stakeholders in spatial planning processes to make them aware that certain strips of land offer opportunities for storage projects.**
- **Inform local and national stakeholders throughout all UHS development phases, with transparent channels for addressing concerns and questions readily available from both authorities and operators.**
- **Initiate transparent international calls for distribution of land for energy transition needs including cross-border energy system and spatial planning.**

5.2.5 Develop appropriate regulations for UHS in porous reservoirs

Effective monitoring of UHS sites in Europe requires a coherent legal framework, standardised monitoring protocols, and unified guidelines tailored to the specific characteristics of facilities. By establishing clear requirements and promoting consistency across member states, Europe can foster the sustainable deployment of hydrogen technologies while mitigating potential environmental and spatial impacts. Addressing environmental and spatial effects requires a multidisciplinary approach, involving expertise from different fields and monitoring efforts should encompass various parameters to comprehensively evaluate the potential impacts of UHS site operations.

The stimulation of worldwide sharing of experience regarding the monitoring of UHS is a crucial step towards fostering collaboration, improving safety, and advancing technological solutions in these critical areas of energy infrastructure. However, despite the high potential, experience in UHS in porous reservoirs so far remains limited[71] and therefore effective monitoring of sites is essential to mitigate risks associated with leakage, structural integrity, and environmental impact. To facilitate worldwide sharing of experiences, various platforms can be utilised, including international conferences, workshops, online forums, and collaborative research projects. Additionally, government agencies, industry associations, research institutions, and private companies can play pivotal roles in facilitating dialogue and knowledge exchange among stakeholders.

Call to Action

- **Establish legal requirements, standards, and unified guidelines regarding monitoring of environmental and spatial effects of UHS sites in Europe.**
- **Stimulate worldwide sharing of experience regarding monitoring of UHS and UGS.**

5.3 Economics and market

A key challenge for UHS options is to leverage the anticipated system value and bring this to sustainable business cases for UHS projects on the short-, medium- and long-term. Currently there is a mismatch between the anticipated system value for UHS (Figure 11) and an outlook for a sustainable business case due to very long lead times and high upfront costs without a secured revenue stream. This combination of an outlook for system value without a clear market incentive for project developers to invest in projects towards commercialisation can be regarded as a potential market failure that requires actions and market interventions on various levels in the energy system to enable the transition towards a well-functioning hydrogen market in the future energy system.

5.3.1 Facilitate development of a hydrogen market

Developing a hydrogen market involves several critical steps to shape the right conditions to spur aligned investments in demand, supply, transport, and storage elements of the value chain. Transport and storage infrastructure elements form an integral part and an enabling step of the value chain. They enable secured coupling of supply and demand centres and provide balancing options to absorb hick-ups and shocks in supply or demand provision. However, these infrastructure elements have long lead times, high upfront investments, and high exposure to market delay risks. This hydrogen infrastructure investment dilemma could be alleviated by reducing uncertainty in all key elements of the hydrogen value chain: demand, supply, transport, and storage by enabling technology, regulatory frameworks, and cooperation in the value chain. The stimulation of the hydrogen market development through target setting and financial support with risk sharing between all parts of the hydrogen economy (production, transport, storage, and demand) will play an essential role for the successful hydrogen market development.

Also, it is essential to develop and implement dedicated hydrogen valleys or clusters with hydrogen infrastructure development strategies for transport and storage at local and regional level to spur hydrogen market development. Connecting these major hydrogen valleys and forming a larger EU hydrogen backbone as early as possible to create a hydrogen market with a European playing field will be of great importance. With aligned import strategies and the establishment of bilateral partnerships with important exporting countries security of supply could be facilitated lowering supply risks for demand sectors.

The value of storage comes to its full potential in the case of a European highly connected hydrogen infrastructure. For the early phases of market development, it is necessary to design regulated hydrogen markets and set network tariff structures that ensure that the market, system, and security of supply contributions of storage are adequately rewarded.[72] In this process it is important to secure predictable revenue streams for hydrogen storage and transportation projects. Simultaneously it is critical to set market conditions to avoid market distortion, market failure and natural monopolies by early hydrogen storage projects. Clear rules on ownership and third-party access to storage capacity is a prerequisite. Finally, fostering public-private collaborations is needed to share risks and benefits across the value chain.

Call to Action

- **Prevent market failure and establish clear strategies to leverage the energy system value of storage of hydrogen in the subsurface, i.e. porous media and salt caverns.**
- **Develop pre-financing and derisking strategies for storage infrastructure build-up in the pre-commercial era of UHS.**
- **Shape market conditions for underground hydrogen storage before the onset of wide-scale hydrogen market development in Europe**
- **Provide a clear outlook for the envisioned market transition from pre-commercial to commercial and mature market phases of UHS.**
- **Identify and report critical supply chain risks and mitigating actions for scale-up and replication of UHS projects.**

5.3.2 Overcome cost-related challenges

The results of the HyUSPRe study show that underground storage of hydrogen in porous reservoirs and salt caverns are complementary technologies in the future hydrogen system. Both the HyUSPRe and Hystories projects foresee a cost range for future UHS projects ranging between typically 0.4 and 3.5 EUR/kgH_2 (LCOS).[73,74,75] The costs of storage for pioneering projects with likely several euros per kg need to come down to 1 EUR/kgH_2 or less in the future, when storage is conducted on a large scale.

In practice, costs of storage are very much project specific. This relates to unique subsurface conditions that vary as well as surface facilities that have different optimal cushion gas requirements and compression, injection, production, and cleaning facilities. This depends strongly on whether the storage is designed and operated for seasonal storage or for more frequent cycling and thus more storage cycles per year. It also depends on whether reusing existing subsurface and surface infrastructure is possible from gas storages and depleted gas-fields.

The sizing of hydrogen storage surface facilities (injection, production, and gas processing) in relation to demand and supply has emerged as a critical factor influencing LCOS. This affects project investments that together with long lead times and pre-financing needs have a large impact on the total LCOS. Results from HyUSPRe further indicate variation in LCOS estimates depending on variations and supply and demand progression of hydrogen that can vary in time and location. To achieve a sustainable market position for UHS several cost-related challenges need to be overcome.

Call to Action

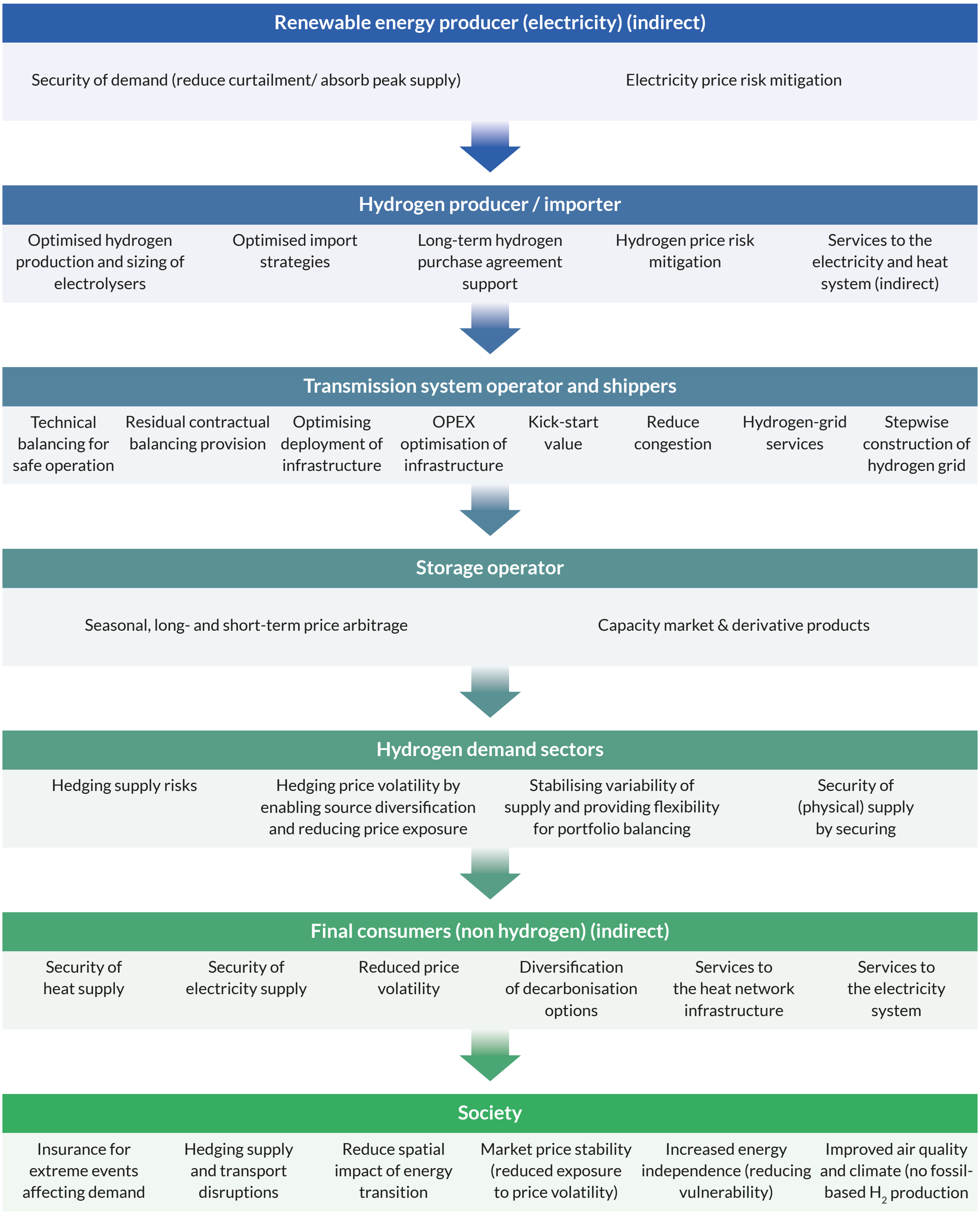
- **Develop public-private cost sharing and reliable financing incentives for pioneer UHS projects with long lead times and pre-commercial market conditions.**
- **Stimulate innovation to achieve cost reduction and cost efficiency for UHS scale-up in porous media.**
- **Work towards early standardisation to reduce capital, operating and financing cost.**
- **Facilitate the roll-out and replicable learnings of a portfolio of demonstration projects to build trust for this new asset class, improve market readiness and establish bankable UHS projects in porous media.**

5.3.3 Develop positive UHS business cases with innovative business models

Next to establishing a hydrogen market and driving costs down including both investment and operational costs, respectively, it is critical to establish robust business models for UHS projects. This means getting the revenue pillar of the business model right. This is achieved by matching a revenue model for the value that a storage project provides to the system and to individual actors in the value chain. UHS projects have generic and site-specific value propositions and thus require an approach to identify, stack and valorise multiple propositions based on the system services the projects offer. This could include one or preferably many of the system services described in Figure 11.

As it is very likely that a portfolio of different and geographically differentiated hydrogen storage projects will be developed, this also holds for the diversity in business models that will unfold. As seen for other storage technologies these business models are not static but very much dynamic, changing with needs of the hydrogen market growing to maturity.[76]

***Figure 11:** An overview of potential energy system services offered by UHS.* *Figure modified from Satish and Koornneef, IEA ES TCP on Economics of Energy Storage, 2023.*[77,78]



Renewable energy producer (electricity) (indirect)

- Security of demand (reduce curtailment/ absorb peak supply)
- Electricity price risk mitigation

Hydrogen producer / importer

- Optimised hydrogen production and sizing of electrolysers
- Optimised import strategies
- Long-term hydrogen purchase agreement support
- Hydrogen price risk mitigation
- Services to the electricity and heat system (indirect)

Transmission system operator and shippers

- Technical balancing for safe operation
- Residual contractual balancing provision
- Optimising deployment of infrastructure
- OPEX optimisation of infrastructure
- Kick-start value
- Reduce congestion
- Hydrogen-grid services
- Stepwise construction of hydrogen grid

Storage operator

- Seasonal, long- and short-term price arbitrage
- Capacity market & derivative products

Hydrogen demand sectors

- Hedging supply risks
- Hedging price volatility by enabling source diversification and reducing price exposure
- Stabilising variability of supply and providing flexibility for portfolio balancing
- Security of (physical) supply by securing

Final consumers (non hydrogen) (indirect)

- Security of heat supply
- Security of electricity supply
- Reduced price volatility
- Diversification of decarbonisation options
- Services to the heat network infrastructure
- Services to the electricity system

Society

- Insurance for extreme events affecting demand
- Hedging supply and transport disruptions
- Reduce spatial impact of energy transition
- Market price stability (reduced exposure to price volatility)
- Increased energy independence (reducing vulnerability)
- Improved air quality and climate (no fossil-based H_2 production

Value stacking, searching for new revenue streams, markets, and innovative business models is essential for UHS projects to not rely on one value stream. A critical challenge is here that the storage sector has highlighted that storage projects are not always remunerated properly for the energy system services they provide.[72] For UHS, there are currently insufficient incentives for long term and strategic storage of energy. As long term to seasonal and strategic storage is the key value that UHS provides to the system, this service should have proper remuneration to kick-start UHS projects.

Call to Action

- **Develop proper remuneration schemes and markets for energy system services potentially offered by UHS.**
- **Shape market conditions for creating secured revenues for UHS on the short term to support sustainable business cases to spur first mover project investments for UHS.**
- **Create market transparency and allow for stacking revenue streams for efficient hydrogen storage services.**
- **Identify existing business models in related and mature sectors that could be adopted.**
- **Develop innovative business models to share profits, risks and costs across the value chain and avoid high overhead and margins.**

5.4 Policy and regulation

Implementation of UHS in Europe is still in its early stages, especially in porous reservoirs, characterised by initial demos and pilot projects that are beginning to operate and gather valuable insights into both technical and legal challenges. The legal framework related to hydrogen is also in its formative phase at the European level, with varying degrees of progress at the national levels. As UHS emerges as pivotal element of the energy transition, regulatory frameworks must be adapted to ensure safety, environmental protection, and operational efficiency. Updating legal structures can streamline permitting processes, establish clear operational guidelines for storage facilities, and address liability concerns.

5.4.1 Develop strategic goals, policy and legal frameworks

A clear regulatory framework and policy objectives are essential for the establishment of UHS, including the upstream and downstream process steps, and the establishment of a hydrogen economy, as well as for the improvement of the energy economy as a whole. These are needed both at EU level and nationally to ensure that the hydrogen economy transitions from mere blending into the natural gas grid to a fully developed one for pure hydrogen. Similar to the European hydrogen strategy[79], which includes a graduated set of targets for hydrogen production in three phases[80], strategic orientations at the European level are also needed for the blending of hydrogen and low-carbon gases into the natural gas grid. These orientations can then be supported politically and from a regulatory perspective at the national level. This strategy should consider measures like lower taxation on renewable gases, to ensure that renewable energy becomes more attractive than the one from fossil sources.

However, not only strategic orientation is required, but also legal provisions to guarantee market participants legal clarity regarding the regulations in these highly innovative areas. Specifically in the context of gas quality, calculation methods and certification methods, such as those for renewable hydrogen in of the delegated acts[81], must additionally follow quickly after the adoption of the new internal gas market directive[82] and regulation[83] for low-carbon gases and low-carbon hydrogen. Harmonised gas quality standards and guarantees of origin for both low-carbon gases as well as renewable gases are of paramount importance for the establishment of an intact hydrogen economy including cross-border trade.

According to the EU framework to decarbonise gas markets, the European Commission will be assigned the competence to pass the calculation and certification methods for low-carbon gases and low-carbon hydrogen.[84]

As this field is a highly innovative one, there must be public financial support for early adopters across the whole hydrogen value chain. This support serves as incentive to mitigate financial risks and uncertainties associated with new technologies, fostering a conducive environment for innovation and investment. The support can vary from subsidising hydrogen infrastructure development to funding of research and development initiatives, as well as providing market incentives for the development of business projects encompassing both hydrogen production and consumption.

Call to Action

- **Define pathways at EU and country levels for the transition from blending to pure hydrogen that are aligned with strategic objectives and supported by policies and regulations.**
- **Harmonise international standards for hydrogen gas quality and guarantees of origin to support and implement cross-border trading and accreditation of green and low-carbon hydrogen within Europe and with third countries.**
- **Introduce European and national public financial support from the EU and national funds for early adopters across the hydrogen value chain to increase hydrogen uptake.**
- **Establish harmonised EU-wide regulatory framework on hydrogen infrastructure and usage.**

5.4.2 Remove legal insecurities

Legal security is of high importance in terms of ensuring a smooth operation of a certain technology. In cases where the legal framework is not developed enough it can have negative impacts on the establishment and improvement of the technology.

Developing clear permitting requirements and a clear regulatory framework, interconnected with hydrogen-specific technical standards, is indispensable for the advancement of hydrogen infrastructure, including UHS. Such a framework serves multiple critical functions: ensuring safety by imposing stringent standards, streamlining approval processes to facilitate efficient deployment and bolstering investor confidence through transparent compliance pathways. Moreover, an interconnected regulatory framework and technical standards promote interoperability across different storage sites and geographical regions. This harmonisation simplifies cross-border operations, enhances system resilience, and facilitates the seamless integration of UHS into existing energy infrastructures.

However, it is not only interoperability between storage sites that needs to be emphasised, but also the growing interconnectedness of the different sectors. An important challenge for sector coupling is that the legal framework is often not yet flexible enough to ensure a smooth cross-sectoral flow of energy from a legal point of view. The reorganisation of the legal framework should be based on the perspective that the various legal acts should be adopted in a coordinated manner, so that individual sectors are not regulated in isolation from each other, but rather enable an integrated view.

Article 15 (2a) RED III[85] requires Member States to promote the testing of innovative renewable energy technology for producing, sharing, and storing of renewable energy through pilot projects in a real-world environment.

Simultaneously, leveraging the experiences gained from the development of demonstration sites is important for ongoing regulatory framework enhancement. The Renewable Energy Directive even requires Member States to support the testing of such new technologies. These projects provide very valuable insights that enable proactive identification and addressing of emerging challenges. By utilising this knowledge, a culture of continuous improvements can be fostered, adapting framework to evolving technological landscapes, enhancing stakeholder engagement, and driving iterative refinement to optimise regulatory effectiveness. Thus, the synthesis of clear regulatory structures and insights from demonstration sites is pivotal in supporting the sustainable evolution of UHS.

Call to Action

- **Develop clear permitting requirements and regulatory frameworks, interconnected with hydrogen-specific technical standards.**
- **Use the experience from developing demonstration sites to identify regulatory framework challenges and bottlenecks and continuously update respective framework.**
- **Greater consideration of the increasing interplay of the power, gas, heat and transport sectors in European legislation and the relevance of large-scale storages for seasonal storage to enable and enhance the effects of sector coupling.**

5.4.3 Implement longer hydrogen storage periods and adjust certification framework

As the share of renewable energy sources increases, especially in the electricity sector, so does the need for flexibility services to compensate for inevitable fluctuations in production or use. Hydrogen can make a significant positive contribution to this. In order to clarify exactly how hydrogen should be used and in which sectors the use of other energy sources might be more effective, it would be useful to develop an EU-wide strategic vision that addresses these issues and at the same time clarifies open questions, such as what is meant by short-, medium- or long-term storage.

Article 19 of the Renewable Energy Directive[86] contains regulations for guarantees of origin for renewable energy. What is still missing, however, is a common, standardised approach specified by the EU regarding guarantees of origin or certification of the sector-coupling use of renewable hydrogen. The problems that arise from this are of different nature.

> **Article 19 (1) RED III: "For the purposes of demonstrating to final customers the share or quantity of energy from renewable sources in an energy supplier's energy mix and in the energy supplied to consumers under contracts marketed with reference to the consumption of energy from renewable sources, Member States shall ensure that the origin of energy from renewable sources can be guaranteed as such within the meaning of this Directive, in accordance with objective, transparent and non-discriminatory criteria."**

On the one hand, the European legislator does not specify a procedure that clearly sets out how the process of converting renewable electricity into hydrogen is to be recorded. This results in different implementation options for each member state such as transfer, cancellation, and reissue of the guarantees of origin. This means that the member states are free to regulate this differently, which leads to greater effort in the case of cross-border flows or cross-border trade. Another problem is the documentation of any storage of renewable electricity via hydrogen in the natural gas grid or in a separate underground storage facility if it is reconverted to electricity later. Here too, the EU provisions do not specify any standardised rules that would ensure that the records reflect the path that the renewable electricity has "travelled" in a standardised and clean manner. On the other hand, the standardised validity period of 12 months for guarantees of origin for all energy sources (electricity, gas including hydrogen, heat, cooling) is an obstacle as it applies to all energy sources in the same way and does not reflect the differences between the energy sources nor their physical ability to be stored. This is a particular barrier in the case of storage, as the period simply continues to run from the generation of the energy unit, even if the electricity was stored using hydrogen and the final utilisation was therefore postponed.

Furthermore, developing longer-term storage bookings, such as strategic hydrogen reserves, by public bodies is vital for advancing UHS in Europe. These reserves ensure stable hydrogen supply, enhance energy security, expand infrastructure, boost investor confidence, and foster collaboration among stakeholders of the European UHS sector.

Call to Action

- **Develop an EU strategic vision on the role of hydrogen storage in providing energy security.**
- **Develop a harmonised certification scheme for hydrogen: Differentiate according to carbon content and include sectoral coupling of electricity, hydrogen and heat and enable imports from European and third countries.**
- **Develop long-term storage bookings (e.g., strategic hydrogen reserves) by public bodies to overcome a market maturity and to ensure security of supply.**

5.4.4 Establish a vision for the transition from natural gas to hydrogen

A step-by-step plan is needed to ensure that the hydrogen economy gains momentum and that the development and expansion of hydrogen infrastructure progresses equally across the EU. This plan should provide a clear time frame to guide the hydrogen market development at pan-European and national levels and to ultimately enable effective market competition. The publication of such a plan is of great importance as transparency and planning certainty are essential elements for all stakeholders.

Given that the revised version of the Internal Gas Market Regulation[87] and Directive contains a variety of provisions which, although not specifying dates, provide a rough timetable for the emergence of a hydrogen energy economy or indicate that the drafting of the legislation was based on a certain timeframe, it would be worthwhile to consider specifying dates for the development steps. This could be published in the form of a step-by-step plan with a timetable for the main points of the legal acts. This would not only provide stakeholders with an approximate timetable but would also inform the public of the plans for the coming years, which is likely to have a very positive effect on acceptance.

Call to Action

- **Develop a step-wise plan with precise time frame on hydrogen infrastructure developments in alignment with European and regional hydrogen market uptake and make it public, that all stakeholders including population are aware on when which conversion steps to pure hydrogen will be undertaken.**
- **Set clear targets for UHS development in Europe (e.g. for 2030 and 2050).**
- **Include UHS in integrated infrastructure planning (e.g. in TYNDP – gas and electricity network development plans).**

5.5 Societal awareness and acceptance

The large-scale deployment of renewable energy technologies, and specifically UHS, as a key enabling technology for the emerging hydrogen value chain, requires perspectives beyond the often discussed technical or economic aspects and a special focus on societal acceptance and awareness. Societal awareness plays a crucial role in fostering acceptance of hydrogen projects among stakeholders and will be essential to engage the public in understanding the benefits, potential challenges, and safety considerations associated with hydrogen technologies. Raising public awareness is fundamental to gain support and ensuring the successful integration of UHS in porous reservoirs into the overall European energy landscape.

5.5.1 Increase general public awareness on hydrogen

Public awareness of hydrogen is highly dependent on different factors and therefore, effective communication strategies are required. To increase confidence in hydrogen technologies in general, and specifically storage of hydrogen in the subsurface, activities that address any potential knowledge gaps are essential.[88,89] As individuals' awareness depends on age group, education and knowledge level[90], acceptance should be increased through various information channels improving knowledge of hydrogen as an energy carrier, hydrogen technologies, the enabling role of storage, and potential impacts on society and local community by positive user-driven campaigns.

Public acceptance is important for production, distribution and use of hydrogen produced from renewable energy sources and therefore, governments need to address potential concerns with information strategies.[91] As further development will be critical to realising the full potential of hydrogen as a key element of a sustainable energy future[92], fact-based independent research on technical feasibility and safety should be part of communication strategies.

Raising public awareness for the hydrogen sector as a potential employment opportunity for future generations is crucial. In this context, measures should be based on real facts and cost data, as widespread awareness can be achieved by holding the dedicated sector and industry accountable. In particular, the knowledge of non-technical stakeholders on hydrogen should be improved[93] by communicating the benefits combined with cross-sectoral, practical, best practice applications.

Call to Action

- **Conduct positive, user-driven information campaigns on hydrogen technologies through various media and information channels.**
- **Use solid independent research on technical feasibility as well as safety for external communication strategies.**
- **Facilitate effective communication of practical cross-sectoral and best practice applications based on facts and cost data.**
- **Define key audience groups and deliver best practice examples by keeping in mind to engage stakeholders at their level of knowledge and understanding. As simple as possible, as sophisticated as necessary.**

5.5.2 Develop educational measures on UHS for schools

Awareness of hydrogen technologies is linked to knowledge and in this respect, the introduction of energy education from primary school onwards, initiated by the government, is a necessary measure where the need for hydrogen in combination with long-term or seasonal energy storage should be addressed. Research shows[94] that energy transition issues are understood by primary school children when presented in simple, interactive models such as didactic games, maps, and experiments. For secondary schools, renewable energy and hydrogen issues should include technological answers, as alternative energy sources alone cannot solve essential supply problems. The inclusion of expert presentations at all educational levels can further emphasise the need for renewable energy systems and give interested students firsthand experience. Overall, educational activities in schools should be intensified to raise social awareness of hydrogen technologies to prepare scientists, economists, and engineers for new challenges. This also includes the involvement of parents and relatives via school projects and site visits.

In the medium and long term, targeted visits to UHS pilot and demonstration sites combined with expert talks could be integrated into the curriculum. This will allow primary and secondary schools to inform about and build confidence in UHS technology in a simple and practical way, alongside the teaching of theoretical content. In addition, the necessary increase in acceptance should go hand in hand with targeted social media activities and general awareness campaigns.

Call to Action

- **Facilitate implementation of energy lessons from primary school onwards.**
- **Facilitate site visits of UHS projects for primary and higher education, their families, and citizens in general.**
- **Facilitate the relevance of the topic of seasonal storage and security of supply and the inclusion of expert talks into the curriculum.**

5.5.3 Develop information campaigns on UHS on local to European level

Objective information campaigns can have a significant impact on the adoption of sustainable energy transition policies.[95] Particularly, industry and research should launch campaigns for storage of hydrogen with representatives from responsible authorities and politicians at different levels and regions. These actions should draw attention to necessary infrastructure requirements that appear to be indispensable for UHS in porous reservoirs. In addition, the introduction of a European hydrogen label for the hydrogen readiness of products by the European Union could indicate the use of hydrogen and thus increase awareness of hydrogen.

An important measure could be the establishment of national ministries exclusively for energy transition in member states of the European Union to bundle political activities towards renewable energy including hydrogen. In this context, roundtables on energy transition should be a direct measure to link policy with the local population on the benefits and importance of UHS. Local policy campaigns and information exchange can provide operators with ideas to support further deployment and avoidance of problems. According to Horwacik (2023)[96], successful implementation of UHS in porous reservoirs requires effective community involvement and a comprehensive approach.

Call to Action

- **Conduct objective information campaigns on awareness regarding UHS in porous reservoirs for policy makers at various levels, initiated by industry and research.**
- **Introduce a European hydrogen readiness label for products and technologies to indicate the possibilities of use of hydrogen.**
- **Establish national ministries for energy transition and roundtables to bundle political activities towards renewable energies, including hydrogen.**
- **Facilitate cooperation between UHS initiatives and industry stakeholders (H2eart for Europe, Gas Storage Europe, Hydrogen Europe).**

5.5.4 Learn from stakeholders to improve design, planning and operation

Identifying and assessing the relevant stakeholder environment early in the development process of an UHS project is considered as important aspect for the long-term establishment of UHS in Europe.[97] In this context, public opinion surveys are a crucial and effective measure in evaluating stakeholder perspectives on concrete planned and implemented demonstration projects.

Learning from different perspectives, ranging from storage operators to industries and refineries to energy producers or grid operators, should be part of engagement strategies as renewable technologies may play a key role for them in the future. Their need for large-scale UHS in porous reservoirs facilities can support implementation, as dedicated use cases and sector-specific business models are key drivers for upscaling. They should therefore be considered, for example in the implementation of a dedicated transport and distribution infrastructure as a component for hydrogen imports or the necessary cross-border or cross-continental exchanges.

Operators of UHS facilities should promote the concrete development of specific standards involving various relevant stakeholders to improve design, planning and operation. In this context, site visits and exchange of results should take place under the responsibility of industry and local authorities to learn from different perspectives and to develop general awareness and acceptance.

The establishment of advisory boards for various UHS projects nominated by ministries or other public authorities is seen as an important measure for future development. This approach enables the targeted involvement of various cross-sectoral and interdisciplinary stakeholders from industry, universities, associations, civil initiatives, and funding organisations in the development process. The members should meet regularly to ensure public interest is taken into account during the planning and execution phase.

Call to Action

- **Use public opinion surveys to integrate stakeholder perspectives as an important aspect of developing UHS in porous reservoirs.**
- **Stimulate cooperation between storage operators, industry, refineries, energy producers and grid operators on their future hydrogen needs as this can support implementation of business models, which are the key drivers for upscaling.**
- **Organise frequent site visits and sharing of results under the responsibility of industry and local authorities.**
- **Form advisory boards in different UHS projects to involve various stakeholders during the planning and execution phase.**

5.5.5 Facilitate engagement of direct neighbours and energy communities

To facilitate engagement of direct neighbours, actions should aim to identify how a community can benefit from UHS facilities. Information evenings for residents and simple communication with visual illustrations, developed by the authorities together with operators, are crucial, and transparent risk assessments of pilot projects and containment measures may play a particular role in building confidence. Comparable projects in the energy sector[98] show that direct participation of local residents, for example through co-ownership, can counteract potential resistance. Discussions with locals are therefore considered important, as there is usually a need for dialogue in the forthcoming project development phases of UHS in porous reservoirs facilities.

When concrete pilot, demonstration, and commercial sites for UHS in porous reservoirs are available, one measure should be the construction of visitor centres where neighbours or interested citizens can physically participate. In addition, a dedicated website with an integrated webcam for online attendance and presentation of operation and progress could be used. According to the stakeholder analysis[99] done within HyUSPRe, stakeholders expected to be ambivalent towards UHS were mainly found in the categories politics, economic players, and civil society. Early involvement of the civil society and especially the regional and local population through transparent and easy-to-use communication tools (Chat, Mail, FAQs) can be a key measure as they tend to be ambivalent. As analysed by Friedl and Reichl (2016)[100], measures for public engagement have mainly an informative character and less active participation elements.

In the development of UHS facilities, the direct or indirect involvement of system operators in the local community can be important, for example through participation and sponsorship of local community projects. Social incentives such as job creation or a residents fund can be important and lead to relevant corresponding effects. Energy communities organise collective and citizen-led energy actions, paving the way for a clean energy transition.[101] In the long term energy communities near UHS facilities could act as participating operators and store their regionally generated renewable energy also to reduce the risk of import dependency or supply problems and related price risks.

Call to Action

- **Organise information evenings for residents including simple communication with visual illustrations about UHS.**
- **Construct visitor centres and a dedicated website with an integrated webcam where neighbours or interested citizens can participate.**
- **Foster local value creation by including local suppliers, cooperations, build-up of local workforce or through sponsorship of local community projects.**
- **Provide UHS facilities as surplus energy storage option and supply risk mitigation for energy communities.**
- **Establish an easy to use and transparent way stakeholders can communicate with operators to address their concerns directly.**

Bibliography

1 HyUSPRe website (www.hyuspre.eu)
2 Cavanagh, AJ, Yousefi, SH, Wilkinson, M & Groenenberg, RM. 2023: Classifying hydrogen storage potential in porous reservoirs as an aid to European site selection. H2020 HyUSPRe project report. 64 pp incl. appendices.
3 Groß, T., Dunkel, P., et al. 2024: Report on EU-scale hydrogen system scenarios, H2020 HyUSPRe project report.
4 Artelys and Frontier Economics for Gas Infrastructure Europe, 2024: Why European Underground Gas Storage needs should be fulfilled – final report.
5 www.uss-2030.at
6 https://www.uniper.energy/hystorage
7 Communication from Commission to European Parliament, European Council, Council, European Economic and Social Committee and Committee of the Regions, REPowerEU Plan, COM (2022) 230 final.
8 Lower Heating Value; 1kg hydrogen= 33.3 kWh
9 Communication from Commission to European Parliament, Council, European Economic and Social Committee and Committee of the Regions, 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality, COM/2021/550 final
10 Communication from Commission to European Parliament, European Council, Council, European Economic and Social Committee and Committee of the Regions, The European Green Deal, COM/2019/640 final
11 Groß, Theresa, Philipp Dunkel, David Franzmann, Heidi Heinrichs, Jochen Linßen, and Detlef Stolten, 2022. "Report on H_2 Supply from Renewable Energy Sources, H_2 Demand Centers and H_2 Transport Infrastructure." H2020 HyUSPRe Project Report, 67 pp incl. appendix.
12 ENTSO-E // ENTSOG TYNDP 2022 Scenario Report – Version. April 2022
13 METIS studies, Generation and system adequacy analysis, 2016, European Commission, Contract no. ENER/C2/2014-639. https://op.europa.eu/en/publication-detail/-/publication/59a1b96c-713f-11e9-9f05-01aa75ed71a1/language-en/format-PDF/source-96287997
14 UHS Technology Monitor Report, H2-TCP Task 42 (IEA), 2023
15 Artelys and Frontier Economics for Gas Infrastructure Europe, 2024: Why European Underground Gas Storage needs should be fulfilled – final report.
16 EASE whitepaper "Energy Storage Targets 2030 and 2050", 2022. https://ease-storage.eu/publication/energy-storage-targets-2030-and-2050/
17 Artelys and Frontier Economics for Gas Infrastructure Europe, 2024: Why European Underground Gas Storage needs should be fulfilled – final report.
18 Pure hydrogen storage in salt caverns is already commercially deployed in 4 locations worldwide to provide feedstock to the chemical industry.
19 https://www.underground-sun-storage.at/en/
20 https://www.uniper.energy/hystorage
21 Cavanagh, AJ, Yousefi, SH, Wilkinson, M & Groenenberg, RM. 2023: Classifying hydrogen storage potential in porous reservoirs as an aid to European site selection. H2020 HyUSPRe project report. 64 pp incl. appendices.
22 The Hystories project estimates a storage potential in underground gas storage reservoirs of 390 TWh (455 TWh including offshore) https://hystories.eu/hydrogen-storage-resource-for-depleted-fields-and-aquifers-in-europe/
23 Groß, T., Dunkel, P., et al. 2024: Report on the EU-scale hydrogen system scenarios, H2020 HyUSPRe project report.
24 The HyUSPRe modelling study aligns well with a study by Artelys and Frontier Economics commissioned by GIE concludes that the optimal dimensioning of underground hydrogen storage for Europe grows from 45 TWh by 2030 and 270 TWh by 2050. The study clearly observes that currently only 25 UHS projects are expected to be commissioned by 2030 with an equivalent of 9 TWh. https://www.gie.eu/wp-content/uploads/filr/9697/RPT-EU_Underground_Hydrogen_Storage_Targets-090424-CLEAN.pdf.
25 Cavanagh, AJ, Yousefi, SH, Wilkinson, M & Groenenberg, RM. 2023: Classifying hydrogen storage potential in porous reservoirs as an aid to European site selection. H2020 HyUSPRe project report. 64 pp incl. appendices.
26 Groß, T., Dunkel, P., et al. 2023: Report on the EU-scale hydrogen system scenarios, H2020 HyUSPRe project report.
27 Caglayan 2020 A Robust Design of a Renewable European Energy System Encompassing a Hydrogen Infrastructure
28 The main reason is that alternative options with higher costs then need to be installed and dispatched in the future energy system such as dispatchable generation and other flexibility (storage) technology to compensate for the intermittency of variable renewable energy supply.
29 Germán Morales-España, Ricardo Hernández-Serna, Diego A. Tejada-Arango, Marcel Weeda, Impact of large-scale hydrogen electrification and retrofitting of natural gas infrastructure on the European power system, International Journal of Electrical Power & Energy Systems, Volume 155, Part B, 2024, https://doi.org/10.1016/j.ijepes.2023.109686.
30 Artelys and Frontier Economics for Gas Infrastructure Europe, 2024: Why European Underground Gas Storage needs should be fulfilled – final report.
31 IEA. World Energy Outlook 2022; IEA: Paris, France, 2022.
32 Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions, REPowerEU Plan, COM (2022) 230 final.
33 European Hydrogen Backbone – EHB report, April 2022. Online: https://www.ehb.eu/files/downloads/ehb-report-220428-17h00-interactive-1.pdf, accessed: September 1, 2023
34 European Hydrogen Backbone Maps | EHB European Hydrogen Backbone
35 Cavanagh, AJ, Yousefi, SH, Wilkinson, M & Groenenberg, RM. 2023: Classifying hydrogen storage potential in porous reservoirs as an aid to European site selection. H2020 HyUSPRe project report. 64 pp incl. appendices.
36 Corina, A., Zikovic, V., Soustelle, V. & Ter Heege, J. 2022: Review of current practices and existing experimental data for well and rock materials under cyclic hydrogen injection and withdrawal, H2020 HyUSPRe project report. 60 pp.
37 https://hyunder.eu/
38 www.uss-2030.at
39 https://blogs.ed.ac.uk/hystorpor/
40 https://hystories.eu/
41 Vallourec "Vallourec Qualifies Materials for a wide Range of Hydrogen Applications" [Online]. Available: https://www.vallourec.com/en/all-news/group-2022-hydrogen-materials.
42 San Marchi C. and . P. Somerday "Technical Reference for Hydrogen Compatibility of Materials" Sandia National Laboratories, 2012.
43 Loder, B. "Summary report on steels K L80 including H_2S containing atmosphere and a benched reference material" Hystories project report 4.4-0, 2022.
44 Corina, A.N., Soustelle, V. & Ter Heege, J.H. 2023: Report with new experimental data on reactions between H_2 and well cement and effects on fluid flow and mechanical properties of well cement, H2020 HyUSPRe project report. 37 pp.
45 Corina, A.N., Soustelle, V. & Ter Heege, J.H. 2023: Report with new experimental data on reactions between H_2 and well cement and effects on fluid flow and mechanical properties of well cement, H2020 HyUSPRe project report. 37 pp.
46 Gregory, S.P., Barnett., M.J., Field, L.P., Milodowski, A.E. 2019; Subsurface Microbial Hydrogen Cycling: Natural Occurrence and Implications for Industry. Microorganisms 2019, 7(2), 53; https://doi.org/10.3390/microorganisms7020053.
47 Schwartz E, Fritsch J, Friedrich B (2013) H_2-metabolizing prokaryotes. In The Prokaryotes; Springer: Berlin/Heidelberg, Germany; pp. 119–199. ISBN 9783642301407.
48 Ahn, A.C., Hidalgo-Ulloa, A., Pererva, Y., Lomans, B., Sousa, D.Z., 2022: Review of the window of viability of the different microbial metabolisms relevant for subsurface H_2 storage application, H2020 HyUSPRe project report. 36 pp.
49 Kilpatrick A., Hassanpouryouzband, A., Edlmann, K. 2023: Assessment of the impact of CH4 and CO2 on the geochemical response of the hydrogen-brine-rock system. H2020 HyUSPRe project report. 32 pp.
50 Truche, L., Berger, G., Destrigneville, C., Guillaume, D. and Giffaut, E., 2010. Kinetics of pyrite to pyrrhotite reduction by hydrogen in calcite buffered solutions between 90 and 180 C: Implications for nuclear waste disposal. Geochimica et Cosmochimica Acta, 74(10): 2894-2914.
51 Thüns, N., et al., The effect of H_2 pressure on the reduction kinetics of hematite at low temperatures. Internal Journal of Hydrogen Energy, 2019. 44: p. 27615-27625
52 Alpermann and Ostertag-Henning, Kinetics of the abiotic oxidation of hydrogen (H_2) by hematite at subsurface storage conditions, in Goldschmidt2020. 2020: Virtual.
53 Kruck, O., Crotogino, F., Prelicz, R., Rudolph, T., 2013. HyUnder Deliverable No. 3.1 Overview on all Known Underground Storage Technologies for Hydrogen. 93.
54 Michelsen, J., Thaysen, E.M., Hogeweg, S., Hagemann, B., Hassanpouryouzband, A., Langanke, N., Edlmann, K., Ganzer, L.

2023: Hydrogen reservoir flow behaviour: Measurements of molecular diffusion, mechanical dispersion and relative permeability, H2020 HyUSPRe project report, 67 pp.

55 Heinemann, N.A., J.; Miocic, J. M.; Hangx, S. J. T.; et al., Enabling large-scale hydrogen storage in porous media - the scientific challenges. Energy & Environmental Science, 2021. 14, 853.

56 Soustelle, V., van Winden, J., Houben, M. 2023: Experimental data on reactions between hydrogen and rock samples from reservoir and geological seals and effects on fluid flow and mechanical properties of reservoir and caprock, H2020 HyUSPRe project report. 66 pp.

57 Heinemann, N.A., J.; Miocic, J. M.; Hangx, S. J. T.; et al., Enabling large-scale hydrogen storage in porous media - the scientific challenges. Energy & Environmental Science, 2021. 14, 853.

58 Hogeweg, S., Hagemann, B. (eds.) 2022: Integrated modelling approach for the overall performance, integrity, and durability assessment of hydrogen storage at the reservoir and near-wellbore scale, H2020 HyUSPRe project report, 49 pp.

59 Hogeweg, S., Hagemann, B. & Ganzer, L. (2023) Validated open-source reservoir modeling software that can simulate coupled flow, geochemical and microbiological processes in a porous reservoir under operational hydrogen storage conditions, H2020 HyUSPRe project report. 17 pp

60 Tremosa, J., Jakobsen, R., Le Gallo, Y. 2023. Assessing and modeling hydrogen reactivity in underground hydrogen storage: A review and models simulating the Lobodice town gas storage. Front. Energy Res., 11. doi.org/10.3389/fenrg.2023.1145978

61 Hellerschmied, C., Schritter, J., Waldmann, N., Zaduryan, A.B., Rachbauer, L., Scherr, K.E., Andiappan, A., Bauer, S., Pichler, M., Loibner, A.P., 2024. Hydrogen storage and geo-methanation in a depleted underground hydrocarbon reservoir, Nature Energy 9, 333-344. doi.org/10.1038/s41560-024-01458-1

62 Cavanagh, AJ, Yousefi, SH, Wilkinson, M & Groenenberg, RM. 2023: Classifying hydrogen storage potential in porous reservoirs as an aid to European site selection. H2020 HyUSPRe project report. 64 pp incl. appendices.

63 IOGP Carbon Capture, Transportation, and Storage Committee. (2022) Recommended practices for measurement, monitoring, and verification plans associated with geologic storage of carbon dioxide. Report 652.

64 Murray, C.C., Wong, J., Singh, G.G., Mach, M., Lerner, J., Ranieri, B., Peterson St-Laurent, G., Guimaraes, A., Chan, K.M.A., 2018. The Insignificance of Thresholds in Environmental Impact Assessment: An Illustrative Case Study in Canada. Environmental Management 61, 1062–1071. https://doi.org/10.1007/s00267-018-1025-6

65 Hassan, Q., Sameen, A.Z., Salman, H.M., Jaszczur, M., Al-Jiboory, A.K., 2023. Hydrogen energy future: Advancements in storage technologies and implications for sustainability. Journal of Energy Storage 72, 108404. https://doi.org/10.1016/j.est.2023.108404

66 N. Heinemann, J.,Alcalde, J. M. Miocic, S. J. T. Hangx, J. Kallmeyer, C. Ostertag-Henning, A. Hassanpouryouzband, E. M.,Thaysen, G. J. Strobel, M. Wilkinson, C. Schmidt-Hattenberger, K. Edlmann, M. Bentham, R. S. Haszeldine, R. Carbonell and A. Rudloff, Energy Environ. Sci., 2021, DOI: 10.1039/D0EE03536J

67 Luo, X., Tveit, S., Gholami, R., Andersen, P.Ø., 2024. Underground hydrogen storage (UHS) in natural storage sites: A perspective of subsurface characterization and monitoring. Fuel 364, 131038. https://doi.org/10.1016/j.fuel.2024.131038

68 Kovač, A., Paranos, M., Marciuš, D., 2021. Hydrogen in energy transition: A review. International Journal of Hydrogen Energy 46, 10016–10035. https://doi.org/10.1016/j.ijhydene.2020.11.256

69 De Pascali, P., Bagaini, A., 2018. Energy Transition and Urban Planning for Local Development. A Critical Review of the Evolution of Integrated Spatial and Energy Planning. Energies 12, 35. https://doi.org/10.3390/en12010035

70 Spyridonidou, S., Sismani, G., Loukogeorgaki, E., Vagiona, D.G., Ulanovsky, H., Madar, D., 2021. Sustainable Spatial Energy Planning of Large-Scale Wind and PV Farms in Israel: A Collaborative and Participatory Planning Approach. Energies 14, 551. https://doi.org/10.3390/en14030551

71 Miocic, J., Heinemann, N., Edlmann, K., Scafidi, J., Molaei, F., Alcalde, J., 2023. Underground hydrogen storage: a review. SP 528, 73–86. https://doi.org/10.1144/SP528-2022-88

72 European Commission, Directorate-General for Energy, Breitschopf, B., Zheng, L., Plaisir, M. et al., The role of renewable H_2 import & storage to scale up the EU deployment of renewable H_2 – Report, Publications Office of the European Union, 2022, https://data.europa.eu/doi/10.2833/727785

73 LCOS= Levelised Cost of Storage

74 De Maigret, J., Viesi, D., 2023: Report on equipment requirements and capital as well as operating costs for the hydrogen scenarios, H2020 HyUSPRe project report. 104 pp incl. appendices.

75 De Maigret, J., Viesi D., Testi M., Luca G., Urbani M., 2024: Report on levelized cost of hydrogen, H2020 HyUSPRe project report. 53 pp

76 European Commission, Directorate-General for Energy, Hoogland, O., Fluri, V., Kost, C. et al., Study on energy storage, Publications Office of the European Union, 2023, https://data.europa.eu/doi/10.2833/333409

77 Translation of energy storage configurations into business cases, A. Satish, J. Koornneef, IEA EcoEneSto, IEA ES TCP- Economics of Energy Storage - EcoEneSto Subtask 4: Energy storage valuation framework

78 Artelys for Gas Infrastructure Europe, 2022 - Showcasing the pathways and values of underground hydrogen storages.

79 Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, A hydrogen strategy for a climate-neutral Europe, COM(2020) 301 final.

80 Cf European Hydrogen Strategy, pp 6.

81 Commission Delegated Regulation (EU) 2023/1184 of 10 February 2023 supplementing Directive (EU) 2018/2001 of the European Parliament and of the Council by establishing a Union methodology setting out detailed rules for the production of renewable liquid and gaseous transport fuels of non-biological origin, OJ 2023 L 157/11.

82 Proposal for a Directive of the European Parliament and of the Council on common rules for the internal markets in renewable and natural gases and in hydrogen (recast), COM(2021) 803 final.

83 Proposal for a Regulation of the European Parliament and of the Council on the internal markets for renewable and natural gases and for hydrogen (recast), COM(2021) 804 final.

84 Cf Article 9 (5) Revised Gas-Directive.

85 Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources, OJ 2018 L 328/82 as amended by OJ 2023 L 77/1.

86 Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources, OJ 2018 L 328/82 as amended by OJ 2023 L 77/1.

87 Please note that the new gas and hydrogen market package has been finalised by the European Parliament and the Council of the European Union shortly before finalising this roadmap, but has not yet been published in the Official Journal of the EU

88 Clean Hydrogen Partnership, 2023. Awareness of hydrogen technologies (Survey report).

89 Horwacik, A., 2023. Hystories, D6.4: Social impact of the underground H2 storage.

90 Bayrakdar Ates, E., Calik, E., 2023. Public awareness of hydrogen energy: A comprehensive evaluation based on statistical approach. International Journal of Hydrogen Energy 48, 8756–8767. https://doi.org/10.1016/j.ijhydene.2022.12.070

91 Bentsen, H.L., Skiple, J.K., Gregersen, T., Derempouka, E., Skjold, T., 2023. In the green? Perceptions of hydrogen production methods among the Norwegian public. Energy Research & Social Science 97, 102985. https://doi.org/10.1016/j.erss.2023.102985

92 Tang, D., Tan, G.-L., Li, G.-W., Liang, J.-G., Ahmad, S.M., Bahadur, A., Humayun, M., Ullah, H., Khan, A., Bououdina, M., 2023. State-of-the-art hydrogen generation techniques and storage methods: A critical review. Journal of Energy Storage 64, 107196. https://doi.org/10.1016/j.est.2023.107196

93 Müller, C., Markova, D., 2023: Report on stakeholder analysis of underground hydrogen storage, H2020 HyUSPRe project report. 24 pp.

94 Karwasz, G., 2021. FCHgo, Deliverable No. 3.4: Report with general recommendations for educational activities in school at EU level.

95 Botrel, C.A., Rekker, S., Wade, B., Wilson, S., 2024. Understanding the lobbying actions taken by the Australian renewable energy industry. Journal of Cleaner Production 434, 139674. https://doi.org/10.1016/j.jclepro.2023.139674

96 Horwacik, A., 2023. Hystories, D6.4: Social impact of the underground H2 storage.

97 Hydrogen TCP-Task 42, 2023. Underground Hydrogen Storage: Technology Monitor Report.

98 Rodhouse, T.S.G.H., Cuppen, E.H.W.J., Pesch, U., Correljé, A.F., 2023. From expectational conflicts to energy synergies: The evolution of societal value co-creation in energy hub development. Project Leadership and Society 4, 100098. https://doi.org/10.1016/j.plas.2023.100098

99 Müller, C., Markova, D., 2023: Report on stakeholder analysis of underground hydrogen storage, H2020 HyUSPRe project report. 20 pp.

100 Friedl, C., Reichl, J., 2016. Realizing energy infrastructure projects – A qualitative empirical analysis of local practices to address social acceptance. Energy Policy 89, 184–193. https://doi.org/10.1016/j.enpol.2015.11.027

101 European Commission, 2024. Energy communities, https://energy.ec.europa.eu/topics/markets-and-consumers/energy-communities_en

HyUSPRe 2024: Roadmap for successful deployment of underground hydrogen storage in porous reservoirs in Europe. H2020 HyUSPRe project report. 44 pp.

This report represents HyUSPRe project deliverable number D7.5

Contact: Holger Cremer (holger.cremer@tno.nl),
Remco Groenenberg (remco.groenenberg@tno.nl)
https://www.hyuspre.eu/

Design: KNOEFF Communication Design

Hydrogen
Underground
Storage in
Porous **Re**servoirs

HyUSPRe