WHY EUROPEAN UNDERGROUND HYDROGEN STORAGE NEEDS SHOULD BE FULFILLED

Final report

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Executive summary

The European Union has set itself the ambition to achieve climate neutrality across all sectors by 2050, and energy storage is widely seen as a key enabler for this transition to “net zero”.

Gas Infrastructure Europe (GIE) has commissioned Artelys and Frontier Economics to assess how underground hydrogen storage (UHS) could contribute to the ambitious energy and climate policy targets in the European Union.

- We find that underground hydrogen storage has the potential to deliver significant benefits to the system;
- We quantify that optimising the energy system to minimise costs to society requires important underground hydrogen storage capacities;
- However we show that currently-announced projects do not meet the optimal storage needs of the energy system and a significant gap results;
- We demonstrate that under current conditions the market alone will fail to close the gap between planned UHS capacities and the optimal level for the system;
- Hence, we recommend targeted policy intervention to promote UHS and support a more cost-efficient, integrated European energy system.

Underground hydrogen storage has the potential to deliver significant benefits to the system

Renewable and low carbon hydrogen will create a link between the electricity and gas sectors, with electrolysis using electricity as a key input for hydrogen production. Electrolytic hydrogen will not only be a new energy vector contributing to the decarbonisation of otherwise hard-to-abate industrial processes; it can also provide flexibility to the energy system as a whole – in particular through the ability to store hydrogen much more easily and at larger scale than can be done with electricity.

Indeed, as the penetration of volatile renewable energy sources (RES) in the power generation mix increases, and as use cases of electricity and associated consumption profiles diversify, electricity networks will come under additional strain, ultimately driving increased flexibility needs on power networks. **UHS, together with electrolysis and hydrogen-to-power applications (such as hydrogen turbines) can be an effective way to address these flexibility needs**.

Renewable and low carbon hydrogen will also play a central role in the energy transition as the primary decarbonisation pathway for hard-to-abate industrial and mobility sectors[1]. **UHS**

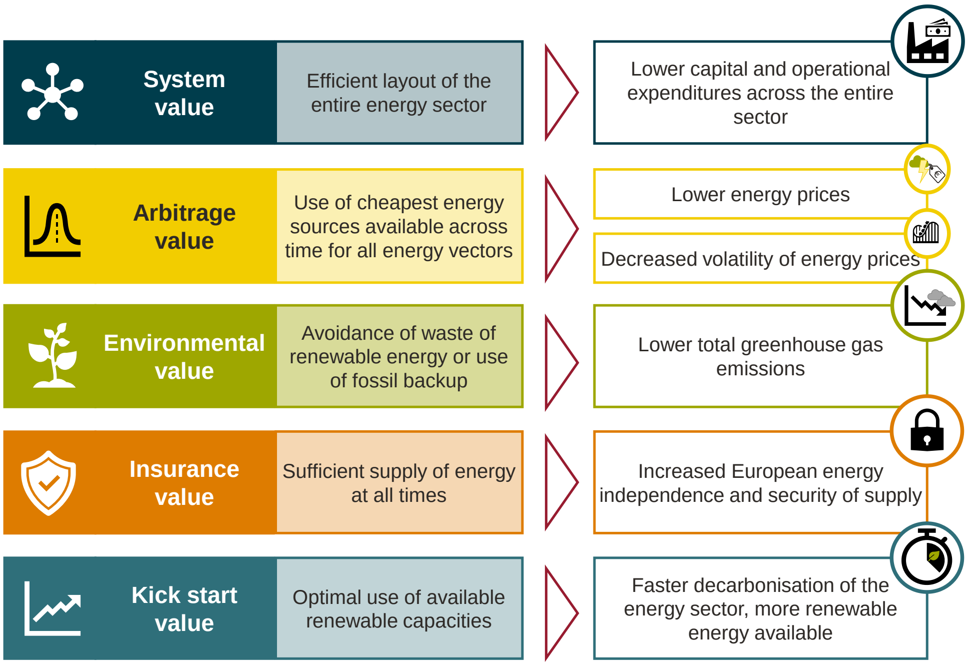
[1] Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions (2022): REPowerEU Plan.

will be a key enabler in accelerating this transition because it enables a smoothed and constant supply of hydrogen to users that require visibility and certainty of su pply over time.

Cutting across the power and hydrogen sectors, UHS will **significantly contribute to European security of energy supply**. Alongside an optimised use of domestic hydrogen production, ensuring sufficient storage capacity to accommodate imported hydrogen volumes and strategic reserves will be a key mitigation factor against energy scarcity risks.

These **benefits can be summarised across five distinct value dimensions** that were first developed in an Artelys study for GIE in 2022[2].

Figure 1 The five value dimensions through which UHS provides benefits to the energy system as a whole



Source: Frontier Economics based on Artelys study on behalf of GIE

- **System value**. By providing flexibility, UHS optimises the setup of the energy system as a whole, which leads to lower capital and operational expenditures across energy sectors (i.e. both electricity and gas/hydrogen) hence a cheaper supply for European consumers.
- **Arbitrage value**. By storing energy over time, UHS allows to use the cheapest energy sources available across time for all energy vectors. This smooths price volatility and also reduces average price levels, to the benefit of consumers.
- **Environmental value**. By enabling the optimal use of renewable energy sources, UHS also enhances the environmental sustainability of the European energy system and

2 "*Showcasing the pathways and values of underground hydrogen storages – Final report*", September 2022

accelerates the decarbonisation of the sector. UHS limits the curtailment of RES generation and increases the total volume of renewable hydrogen available to the market at all times.

- **Insurance value**. By providing storage capacity, UHS enhances the security of European energy supply and ensures that there is sufficient supply to match demand at all times.
- **Kick start value**. UHS enables the production of hydrogen whenever cheap renewable electricity is available, and this improves the viability of electrolyser business cases. In addition, UHS also supports the roll-out of other renewable energy sources by being able to absorb otherwise curtailed electricity generation transformed into hydrogen, which improves the economic viability of RES generation assets overall.

In summary, **UHS will be vital across the energy system as a whole** and across time It will of course eventually provide flexibility to an established and integrated European hydrogen system, in the long-term steady state. But most importantly to the current policy debate, to unlock the different value dimensions for UHS, particular attention needs to be paid to the role of hydrogen storage to support the energy transition in the short- and medium-term, allowing the hydrogen sector, but also the system as a whole to meet the ambitions of the REPowerEU plan and wider decarbonisation objectives[3].

An optimised energy system should feature important UHS capacities

Reaching the ambitious climate and energy objectives set out by the European Commission for the 2030 and 2050 horizons will require substantial investments into energy infrastructure. Only an appropriate dimensioning of the various categories of energy infrastructure will be able to support a cost-effective transition to a net zero economy. Energy infrastructure provide a variety of services by exploiting the complementarities between different sectors of the energy system (sector coupling) and exploiting the local specificities of energy systems.

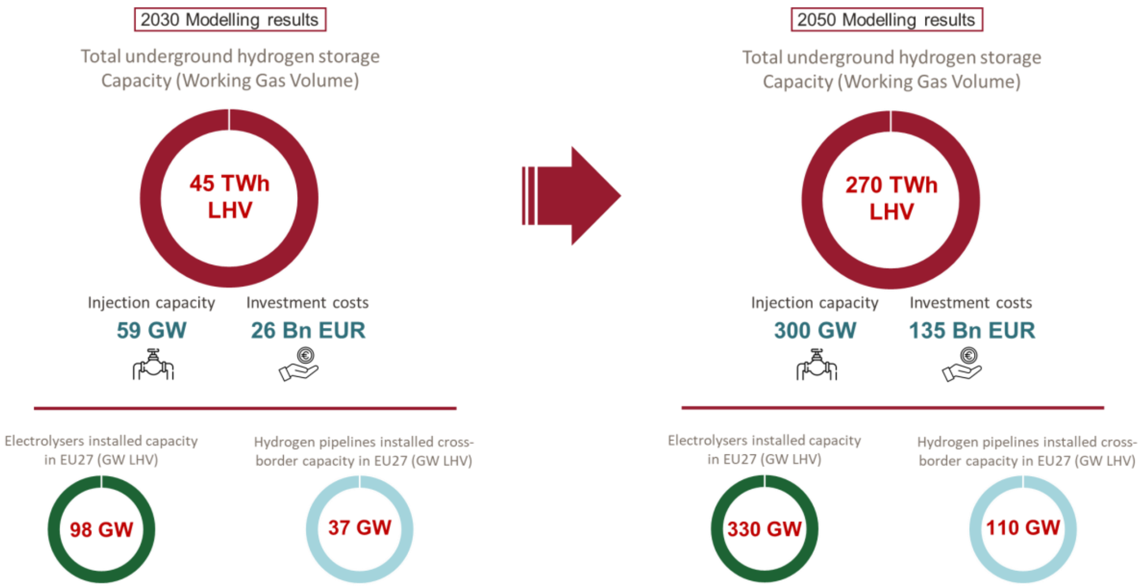
In this context, a model-based evaluation of the need for underground hydrogen storage (UHS) has been conducted at two time horizons, 2030 and 2050. The objective of the modelling was to identify these needs by minimising the total costs (capital expenditures and operational expenditures) to meet the ambitions set out in the REPowerEU plan by 2030 and for Europe to become carbon neutral by 2050.

By leveraging the multi-energy capabilities of Artelys Crystal Super Grid, a modelling solution that captures the interactions between the electricity and hydrogen systems with an hourly time resolution, the analysis concludes that the optimal dimensioning of the UHS fleet is of 45 TWh by 2030 and 270 TWh by 2050. The identified dimensioning of UHS enables an efficient development of the European hydrogen infrastructure. In particular, this allows electrolysers to provide flexibility services on all timescales, by adapting their production profile to the availability of low-cost and low-carbon electricity sources, thereby also minimising the GHG

[3] Notably also facilitating satisfying the criteria of the Delegated Regulation 2023/1184 on the rules for the production of renewable fuels of non-biological origin.

content of the produced hydrogen. Figure 1. In particular, this allows electrolysers to provide flexibility services on all timescales, by adapting their production profile to the availability of low-cost and low-carbon electricity sources, thereby also minimising the GHG content of the produced hydrogen.

Figure 2 Detailed modelling work identifies a need for UHS of 45 TWh by 2030 and of close to 300 TWh by 2050



Source: Artelys

Currently-announced projects do not meet the storage needs of the energy system and a significant gap results

A number of underground hydrogen storage projects are already in development at the time of writing, raising the question as to whether this pipeline of projects will meet optimal system needs.

We find that **expected capacity**[4] **will fall significantly short of the optimal UHS storage needs quantified above**. This will would result in significantly higher system costs and other negative effects compared to the optimal scenario.

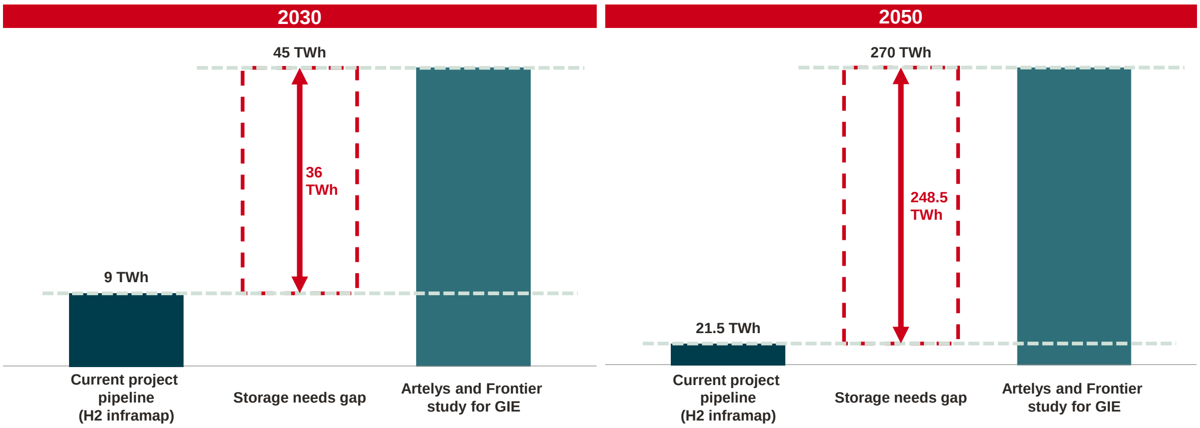
- According to the H2 Inframap, 25 UHS projects are expected to be commissioned by 2030. These projects would deliver a total storage capacity of 9 TWh (c. 270 kt) across the EU. Hence, **by 2030, the sector is at risk of falling significantly short of the**

4 We use data from the European Hydrogen Infrastructure map (H2 Inframap) to assess the expected capacities that will be available to the energy system by 2030 and 2050. We then compare these capacities to the optimal UHS storage needs estimated by our modelling. It is worth noting that the hydrogen sector is evolving quickly and new projects are announced regularly, with others updating their scope or even others being abandoned. As a result, the data presented in this section can only represent a snapshot at a given point in time.

identified UHS capacity needs – by 36 TWh. This gap is four times the size of the total capacity that is expected to be developed if all currently planned projects indeed become operational by 2030.

- Ignoring the gap between 9 and 45 TWh of underground hydrogen storage in 2030 comes at a high economic and environmental cost to the European energy system.
  - Investing in underground hydrogen storage delivers system-level savings from the very first year of operations, in contrast to typical infrastructure projects that only recoup their costs after multiple years of operations. Indeed, the sum of the impact on overnight costs, fixed operational costs per annum and operational savings per annum (including environmental costs) amounts to circa 2.5 Bn€.
  - Beyond this first year, investing in underground hydrogen storage significantly decreases the costs of operating the EU energy system every subsequent year of operations, in particular by avoiding curtailment costs and reducing CO2 emissions. Under the assumptions adopted in this report, the cost differential, factoring in operational savings and impacts on fixed operational costs and carbon costs, over a 20-year period with a 4% discount rate, reaches 32 Bn€.
- Based on the H2 Inframap data, 34 storage projects are planned to be operational by 2050, delivering a total UHS capacity of 21.5 TWh (c. 646 kt) to the system. This is in contrast to the optimal UHS capacity of 270 TWh, pointing to a gap of **248.5 TWh**. This suggests that, similarly to what is expected for 2030, available capacity of currently planned projects **would fall significantly short of the storage needs of an optimised, integrated and decarbonised European energy system by 2050** – indeed, it would fall short by more than ten times the amount of currently-planned capacity.

Figure 3 Under current circumstances, a significant gap of UHS capacity may prevail in both 2030 and 2050



Source: Frontier Economics based on H2 Inframap data

The market alone will fail to close the gap under current conditions

To close the significant infrastructure needs gap identified above, investment decisions for additional UHS capacity would need to be taken urgently. Storage projects face significant and long lead times for commissioning – even longer than other parts of the hydrogen value chain, up to between 6 and 11 years depending on the site.

As a result, when making investment decisions, project promoters and storage operators risk being "locked-in": during the project development phase, they are not able to react to changes in market signals and environments as flexibly as would be the case for hydrogen producers and/or offtakers facing shorter lead times[5].

The lack of **maturity in today's renewable and low carbon hydrogen market** is a key barrier preventing the five values of hydrogen from being fully and appropriately reflected in decision-making by project promoters and storage operators. Indeed, only where these values can be quantified or, ideally, monetised[6], will economic signals be most efficient. Where this is the case, the viability of business cases improves and uncertainty is reduced.

Over and above the absence of strong economic signals, a **limited awareness amongst policy makers of the values** that UHS can deliver to the energy system further hinders the incentives of storage operators to take optimal investment decisions. Inefficient processes and risk exposures remain, which contribute to the lack of strong economic signals for operators.

These two shortcomings result in a range of barriers to UHS investment, which can be grouped into three broad categories:

- **A lack of visibility and hence long-term uncertainty of UHS business cases.** Given the current stage of the hydrogen market – notably lacking integration and clear and liquid price signals (for both hydrogen and the provision of flexibility services more generally), individual stakeholders find it challenging to estimate the appropriate valuation of their specific activity and may struggle to construct viable business cases, leading to suboptimal underinvestment into UHS.
- **The persistence of complex and lengthy approval processes for both new projects and repurposed storage facilities.** Approval processes for the preparation of hydrogen storage facilities (in particular caverns, porous storage and aquifers) do not yet follow standardised procedures. They are therefore at risk of becoming very drawn-out and possibly further delayed through gaps in national regulatory and legal frameworks.

5 For instance, the International Energy Agency estimates that lead times for electrolyser projects lie between one and three years : https://www.iea.org/energy-system/low-emission-fuels/electrolysers

6 With "monetised" we define the possibility to attach a monetary value to a specific quantity, which in turn allows to reflect this quantity in a business plan. For instance, a hydrogen quantity can be monetised with a hydrogen price, which therefore allows to "monetise", e.g. a certain level of hydrogen production.

The complexity for hydrogen projects is further amplified by a certain level of duality with natural gas. Even if natural gas demand decreases, several studies[7] have shown that the need to ensure sufficient levels of natural gas supply and, in fact, high levels of security of said supply will likely remain in the EU over the medium term. This duality between natural gas and hydrogen may persist for several years, and this has direct implications for the availability of infrastructure, including storage, to repurpose.

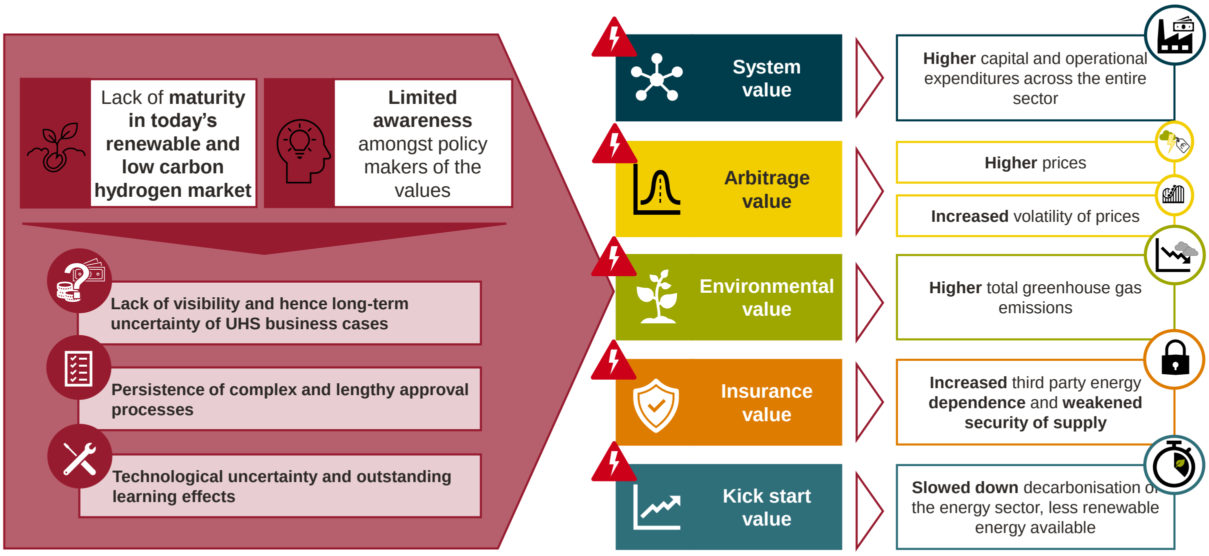
- **Technological uncertainty and outstanding learning effects on both Capex and Opex.** Projects are first of their kinds. Hence, UHS promoters currently commissioning projects face technological and therefore cost uncertainty due to the novelty and innovative character of the technologies used for UHS. The sector expects significant learning effects in the future, in particular for large-scale industrial projects – however, the trajectory and magnitude of these remain subject to additional testing on large-scale projects. This further adds to the uncertainty regarding potential future earnings.

It is worth recalling that several project promoters and storage operators do continue to develop their businesses and have already committed to investing in additional UHS capacity. However, as long as the barriers above continue to exist, this level of investment will likely remain inferior to the optimal level.

The illustration below shows how these barriers not only negatively impact the investment into and deployment of additional UHS capacity, but also lead to additional ramifications for the energy system as a whole.

[7] For instance, a December 2023 study from Frontier Economics for GIE title "*Maintaining security of supply while decarbonising our infrastructure with renewable and low-carbon gases*" pointed to a number of challenges associated with managing a cost-efficient energy transition to low carbon renewable gases while equally continue to ensure security of supply for CH4. Amongst others, challenges involve cross-vector coordination, cross-border coordination, an appropriate definition of SoS, governance arrangements for renewable and low carbon gases as well as the need to align incentives for the repurposing of infrastructure.

Figure 4 Barriers preventing the implementation of optimal UHS capacity and their negative implications for the energy system as a whole



Source: Frontier Economics

Targeted policy intervention to promote UHS would support a more cost-efficient, integrated European energy system

Swift and decisive intervention can help overcome the barriers to investment in UHS, and thereby foster optimal decisions in service of a more cost-efficient, integrated and decarbonised European energy system.

We propose the following measures to support UHS going forward:

- Set an **explicit EU-wide target** and ambition for UHS capacity at (temporal) checkpoints, including a target of 45 TWh in 2030 to enshrine and **recognise the values of storage** and associated capacity needs in official EU policy (similar to REPowerEU).
- **Address administrative and complex approval processes** to facilitate project implementation.
- Introduce **targeted and tailored support mechanisms** for UHS projects with multiple objectives.
  - **Signalling mechanisms** – such as a UHS "project of common interest" label to, e.g. formalise support from Member states and facilitate the attraction of third-party investments.
  - **Financial support mechanisms** – to support financing explicitly and reduce potential funding gaps for storage projects (e.g. financed by ETS revenues, via existing mechanisms like CEF, but could also be via low/zero interest loans from public financing bodies).

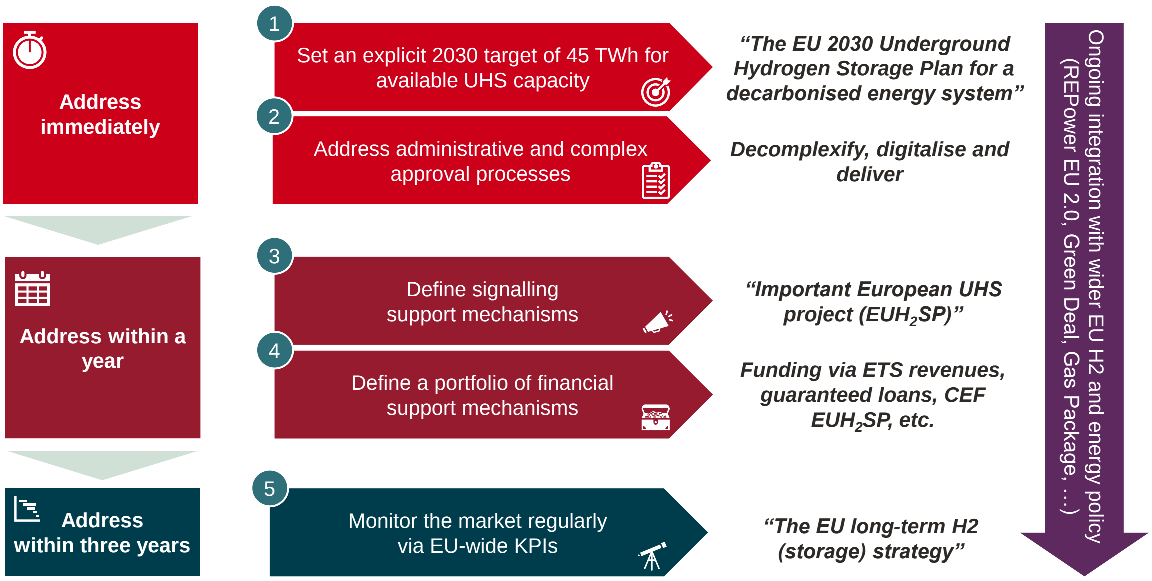
- **Monitor the market** via the regular (e.g. annual) assessment of a range of EU-wide KPIs on both project pipeline and planned/commissioned capacity and UHS needs, fostering the agility to react to possible changes in market needs and the wider system environment.

The optimal intervention will likely reflect a portfolio of several measures rather than a binary choice between one or another. In addition, one size does not necessarily fit all: the appropriate way to implement each measure (or a combination thereof) across the EU will depend on the progress of the hydrogen ramp-up and specific market circumstances. Given the provision of regulated third-party access (rTPA) by 2033 in the hydrogen and decarbonised gas market package, some of the proposed measures may only be transitory, and the design of measures will have to be driven by the way in which each Member state will choose to implement rTPA[8].

In addition to the measures presented here, other, market-based or "hybrid" instruments may emerge that could also drive a more explicit recognition of the values of UHS. For instance, these could involve the development of more complete flexibility markets for electricity grids, which may in turn also drive the development of "new" hydrogen business cases such as electrolyser + storage bundles.

The following graph visualises our proposed measures, highlighting the recommended phasing to policy-makers.

Figure 5 Roadmap of recommended measures to support and promote investment into additional UHS capacity by 2030 and beyond



Source: Frontier Economics

[8] 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), https://data.consilium.europa.eu/doc/document/ST-16522-2023-INIT/en/pdf

1 Underground hydrogen storage must be an integral part of the future integrated and low-carbon European energy system

The European Union has set itself the ambitious target of achieving climate neutrality across all sectors by 2050. Energy storage is widely seen as a key enabler for this transition to "net zero", in particular for the energy system[9]. It delivers required energy to the system when it is most needed and absorbs surplus production without energy being lost.

Renewable and low carbon hydrogen will create a novel link between the electricity and gas sectors, with electrolysis using electricity as a key input for hydrogen production. This electrolytic hydrogen will not only be a new energy vector contributing to the decarbonisation of otherwise hard-to-abate industrial processes, it can also provide flexibility to the energy system as a whole – in particular through the ability to store hydrogen much easier and at larger scale than can be done for electricity. **UHS, together with electrolysis and hydrogen-to-power applications (such as hydrogen turbines) can therefore be an effective way to address these flexibility needs.**

- Indeed, the ongoing electrification of use cases (electric vehicles, heating, hydrogen production and others) leads to an increase in electricity demand that may put further strain on electricity grids. And as the volatility of energy production increases following the roll-out of additional renewable electricity sources (RES) and consumption profiles evolve due to the implementation of decarbonisation efforts across the different sectors of the economy, the need for flexibility in the energy system also grows. While grid management measures (such as redispatch of RES and increased cross-border flows) address some of the resulting bottlenecks on the electricity side in the short-term, the need for large-scale energy storage will continue to grow.
  - High penetration of RES calls for flexibility over different timescales, from seconds to long-term seasonal or even multi-year storage. The power system needs (i) to respond to very short and fast fluctuations, but also needs to (ii) adapt itself to the lasting long-term trend of high RES deployment and the evolution of electricity use cases[10]. **Compared to short-term flexibility provided by batteries, UHS can provide a wider suite of services**[11], from short-term operating reserves to filling an

[9] Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions (2020): A hydrogen strategy for a climate neutral Europe.

[10] By way of example, electricity demand from electric vehicles is expected to remain constant throughout the year, while the related energy supply will vary following meteorological conditions.

[11] Electric storage installations are designed for the short-term storage and quick withdrawal of small energy volumes. However, the cost and resource demand for those facilities relative to their storage capacity are high. As storage needs continue to grow, there are only very limited economies of scale for large scale batteries. Using electric storage to address the large-scale storage needs would therefore impose significant additional cost to the energy system.

energy storage facility over a longer time period – and it is also scalable to adapt to the respective needs of the system at a specific location. This is underpinned by the significant geological potential for UHS across Europe with important capacity potential across salt caverns, porous rock, aquifers or depleted gas fields.

  - Notably, the implementation of Power-to-Hydrogen-to-Power (P2H2P) alongside UHS will support the decarbonisation of the electricity merit order during peak demand times by providing H2 previously produced from RES on top of direct RES generation at that specific moment in time. This will reduce the need for fossil-based plants[12], allowing RES to become a round-the clock resource and avoiding socially suboptimal investments focused on short-term solutions or inefficiently oversized RES production capacity.

- Alongside electrification, **renewable hydrogen will play a central role in the energy transition** as the primary decarbonisation pathway for hard-to-abate industrial and mobility sectors[13]. Beyond its direct use in end-applications, hydrogen produced via electrolysis will allow to constitute a direct link between electricity generation and energy consumption. Flexibility needs, storage requirements and contributions that each energy vector can provide will and should therefore be assessed at the energy system level as a whole[14].

- Finally, the Russian war of aggression in Ukraine and ongoing wider geopolitical tensions have amplified **an additional dimension of the need for large-scale energy storage: improving security of energy supply in Europe**. Indeed, large-scale energy storage has proven to be essential to ensure the efficient functioning of the energy system[15]. As energy imports will continue to play a significant role in the European energy mix, ensuring that sufficient storage capacity is available to guarantee security-of-supply will and should be a key objective.

Underground hydrogen storage (UHS) can address all of these challenges and can constitute an economically and financially efficient, large-scale, long-term storage solution to support the advent of a low-carbon, and ultimately net-zero, European energy system.

The benefits of UHS can be grouped across five dimensions through which UHS adds value to the European energy system. Figure 6 provides an overview of these five dimensions, which

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12 Indeed, an improved ability to provide RES supply to the energy system will further degrade the viability of fossil-based generation, crowding this out of the merit order.

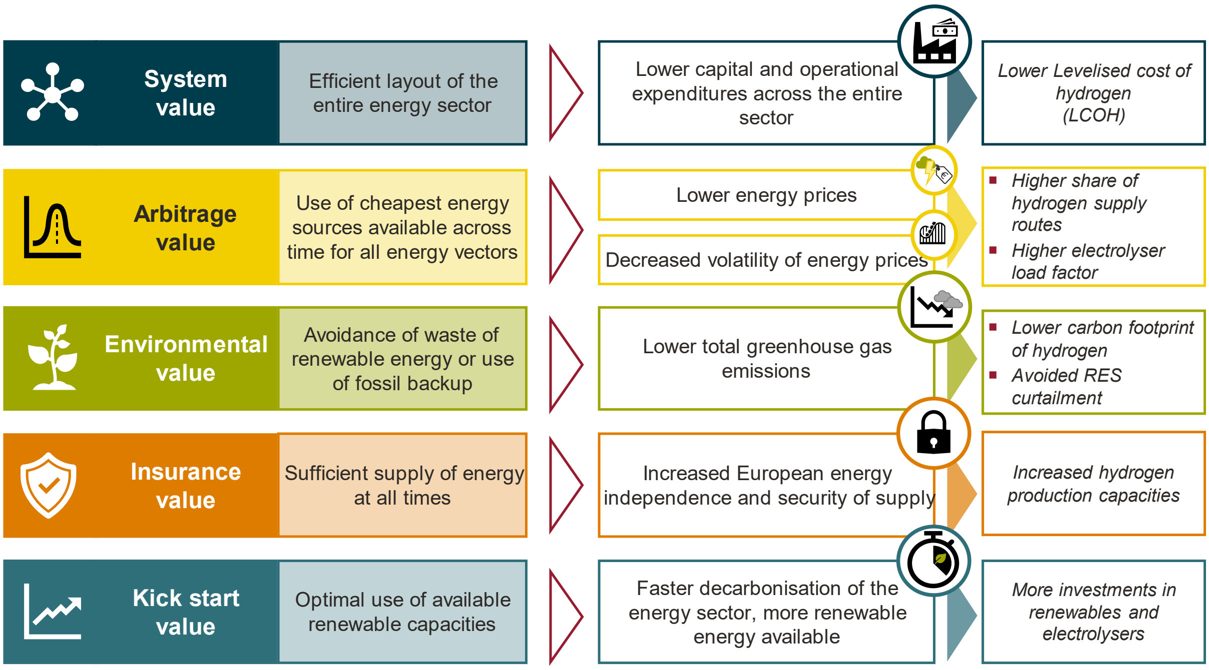
13 Communication from the Commission to the European Parliament, the European Council, the Council, the European Economic and Social Committee and the Committee of the Regions (2022): REPowerEU Plan.

14 For instance, other flexibility sources, as a complement to UHS may in some cases also become relevant. These could include, amongst others, increased and diversified hydrogen imports or increased (cross-border) hydrogen pipeline capacity.

15 Historically, this is most visible in the use of seasonal gas storages in several EU countries to support and improvement of security-of-supply throughout the year.

are then further explained in detail below as well as some key performance indicators (KPIs) that could be used to measure their impact over time and that were first developed in an Artelys study for GIE in 2022[16].

Figure 6 The five value dimensions through which UHS can provide benefits to the European energy system and KPIs that could be used to measure these



Source: Frontier Economics based on Artelys study on behalf of GIE

The five dimensions are:

- **System value**. UHS can break the immediate link between energy supply and demand. By doing so, it ensures that energy demand can be met as efficiently as possible, and thereby as cheaply as possible, on both the gas and electricity sides. Combined with electrolysis and hydrogen-to-electricity conversion technologies[17], UHS has the ability to withdraw and inject not only hydrogen but also electricity from and into the system. As a result, UHS ensures that
  - sufficient energy volumes are available whenever demand occurs; and that
  - surplus energy generation does not need to be curtailed because it is not immediately met with corresponding demand.

16 "*Showcasing the pathways and values of underground hydrogen storages – Final report*", September 2022

17 Hydrogen turbines, CHP, CCGT, GT, fuel cells, etc.

This allows for more efficient use of generation and transmission assets (both for electricity and hydrogen), such that they can be optimally dimensioned[18], in particular based on average rather than peak demand. By reducing the need for economically inefficient overinvestment in generation capacity and/or a specific type of network infrastructure to address bottlenecks[19], UHS supports and promotes the increased production of renewable energy and ultimately a more efficient operation of the integrated energy system as a whole.

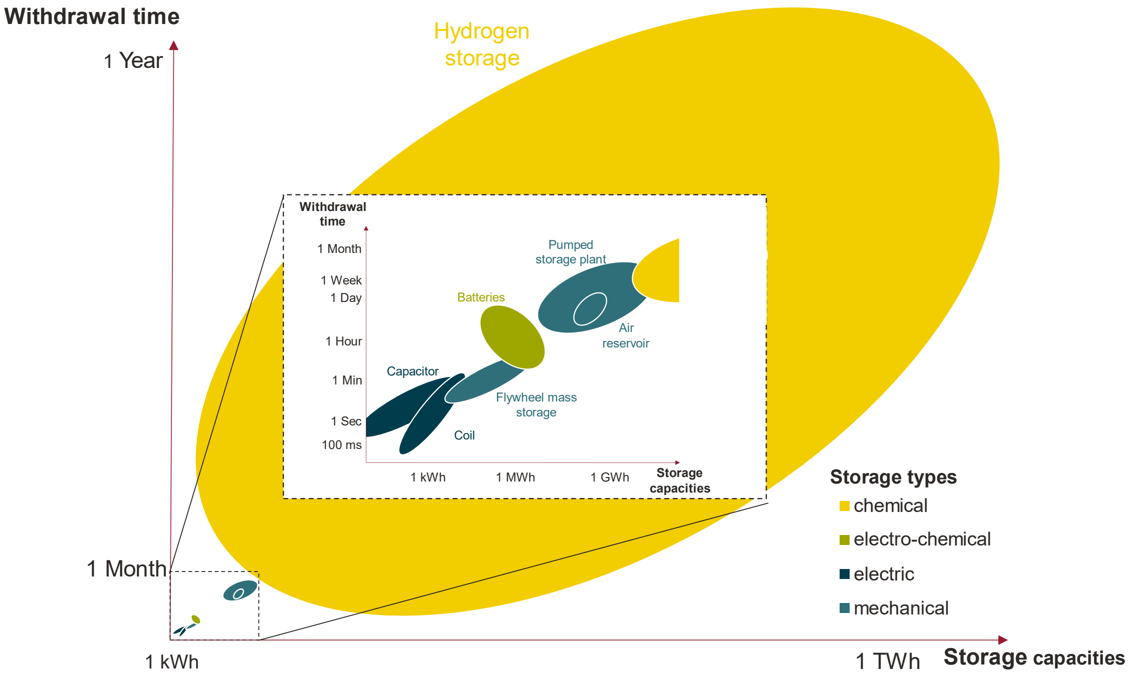
- **Arbitrage value**. UHS also reduces the cost of hydrogen supply. It stores hydrogen at times of high supply and low prices and delivers it back to the system when demand (and thus prices) is high. As the share of RES generation increases, produced volumes and consequently prices will likely become more volatile. If electricity and hydrogen supply had to follow demand patterns directly, consumers would be immediately exposed to this volatility. At times of low production and high demand (for example during dark winter months), they would regularly face higher price levels. Energy storage is a key lever to avoid this. Amongst energy storage technologies, both caverns and depleted gas fields to store gases are particularly well-suited as they uniquely enable both short- and long-term storage of high energy volumes[20]. Figure 7 illustrates the uniquely wide range of storage needs that can be addressed by UHS.

18 For instance, with storage, less RES capacity is needed to meet a given level of demand (as well as its potential variations over time). Similarly, electrolysers dimensioning can also be optimised as storage allows a constant and secure supply of hydrogen without the need to over-dimension electrolysers to guarantee a certain level of hydrogen production at a given point in time.

19 Without storage, RES generation and electrolysers in particular would need to be scaled up substantially (at high cost and land use) to supply sufficient energy at times of low production and high demand.

20 Indeed, some pilot UHS projects have already demonstrate an ability to realise up to 100 cycles over a period of three months only, in addition to an ability for seasonal or even multi-year storage.

Figure 7 Properties of different storage types



Source: Frontier Economics (2018) for FNB Gas

Note: For illustrative purposes, both axes are presented at logarithmic scale. Note that colours indicate the respective storage capacities.

As a result, UHS accelerates price convergence between renewable hydrogen and fossil alternatives, which improves market integration and competition between suppliers and ultimately lowers overall hydrogen prices.

- **Environmental value**. By enabling the optimal use of renewable energy sources, generation and transmission assets, UHS also enhances the environmental sustainability of the European energy system and accelerates the decarbonisation of the sector. UHS limits the curtailment of RES generation and increases the total volume of renewable hydrogen available to the market at all times. As a result, even at times of low renewable generation, the use of fossil alternatives, in particular grey hydrogen, can be increasingly crowded and priced out of the energy mix.

  UHS, combined with electrolysis and hydrogen-to-electricity technologies (renewable storage instead of fossil-fuel-based power plants) can immediately contribute to the avoidance of greenhouse gas (GHG) emissions both in the energy sector, and in sectors where hydrogen (and electricity) are employed as material-use production inputs (e.g. HVC, pharmaceutics, etc.).

- **Insurance value**. Hydrogen volumes stored in UHS facilities can be essential to ensure that there is sufficient supply to match demand at all times. UHS can balance (unexpected) increases in demand or shortfalls in supply and smooth any associated price volatility. This will be particularly relevant in the future decarbonised energy system:

electricity and hydrogen supply and demand may follow opposing seasonal patterns based on weather conditions, and may further be subject to short-notice fluctuations.

- In the short term, UHS can immediately provide stability and security-of-supply to hydrogen consumers – in particular for those applications that depend on a continuous and constant supply of hydrogen (i.e. delivering H2 to flat industrial demand) and/or that cannot adapt to the intermittent pattern inherent to RES generation while responding to RED III (i.e. demand for H2 quota or thermosensitive clients)
- In the medium- to long-term, renewable hydrogen imports will complement EU domestic production[21]. With UHS, hydrogen volumes can be produced at any point in time anywhere in the world and then stored locally. Storage can guarantee that sufficient energy volumes will be available, even if (unexpected) supply disruptions occur – and this applies to both the hydrogen and the electricity sector (via P2H2P).

As a result, UHS can significantly contribute to mitigating security-of-supply risks and creates additional flexibility regarding the procurement of hydrogen (and ultimately electricity).

- **Kick start value**. UHS enables the production of hydrogen whenever cheap renewable electricity is available, and this improves the viability of electrolyser business cases. UHS can facilitate the ramp-up of the renewable hydrogen economy, which will then unlock additional benefits for the energy system as a whole further down the line. Through a domino effect of lower production costs, and thus increased competition and reduced prices, hydrogen becomes a viable decarbonisation option for additional use cases, which in turn speeds up the development of the hydrogen ecosystem.

It is worth noting that the combination of electrolysis with UHS also allows hydrogen producers to more easily comply with the additionality criteria set out in the Delegated Act 2023/1184[22]. Concretely, the storage of hydrogen produced from RES would allow to ensure that this hydrogen always qualifies as a renewable fuel of non-biological origin (RFNBO) and in particular complies with the hourly correlation requirements as set out by the Delegated Act.

The roll-out of other renewable energy sources will also benefit from UHS. Electricity generation that would otherwise have been curtailed (and not have generated any revenues) can be sold to electrolysis for subsequent storage. As described for electrolysers above, UHS improves the viability of additional RES generation, ultimately unlocking an accelerated roll-out of RES production capacity.

21 European Commission, Key actions of the EU Hydrogen Strategy (2022), available on https://energy.ec.europa.eu/topics/energy-systems-integration/hydrogen/key-actions-eu-hydrogen-strategy_en

22 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.

Hence, UHS has the potential to kick-start the development of the EU hydrogen ecosystem and to bring substantial benefits to a decarbonised European energy system, both short- and long term.

In a mature and efficient market, each of these value dimensions should be perfectly quantifiable and monetisable and accrue to the part of the value chain that provide them to the system – in this case, UHS operators. However, as explained in further detail below, the nascent nature of the hydrogen market currently limits the extent to which these values can be captured by UHS operators or their users, which in turn reduces the price signals and strength of incentives for investment into additional UHS capacity. Similarly, a more complete electricity market with explicit products valuing flexibility to the system (across timescales and geographies) would be required to ensure that UHS operators can be rewarded for the flexibility and efficiency they provide to the electricity system.

The integrated system-level model used in this study allows to fully and appropriately reflect these values via a range of key performance indicators (KPIs)[23], which allows to demonstrate the importance that UHS can bring to the energy system.

It is worth noting that the magnitude of these values will at least partly depend on the maturity of the underlying hydrogen as well as the wider market for flexibility services:

- The kick-start value will naturally be more prevalent in the short- to medium-term as the renewable and low carbon hydrogen ecosystem first emerges on the regional and national levels, and then across Europe. In fact, the improved visibility that UHS can provide to sector stakeholders will be vital to support and drive forward the market's development in the absence of sufficient integration and international interconnections. In a nutshell, being able to access and use storage facilities during the early stages of the market development will allow to reduce scarcity and security-of-supply concerns on renewable hydrogen.

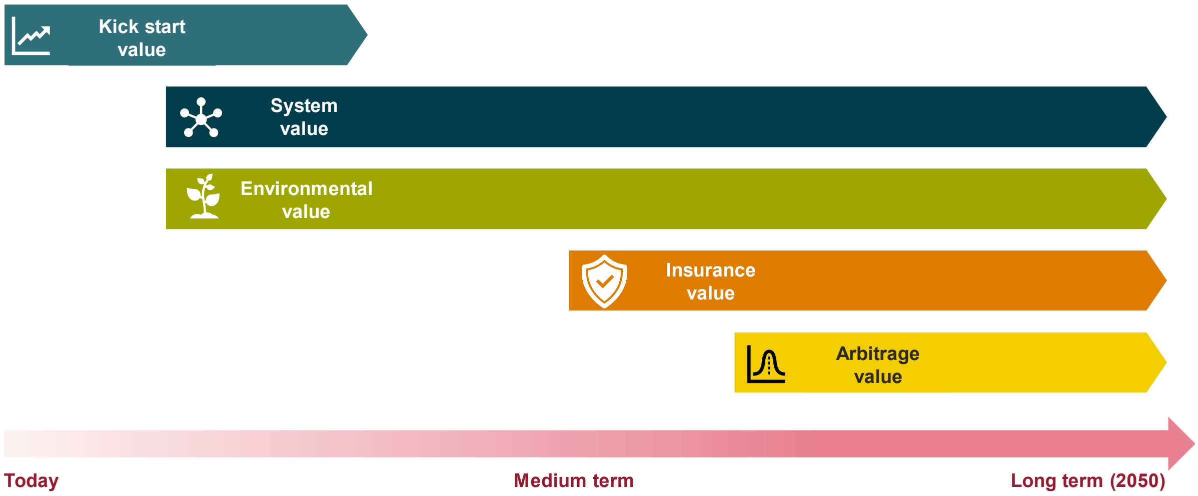
- In contrast, over the medium to long-term this scarcity will be reflected in hydrogen prices (i.e. prices increase with demand or with reduced supply). In such a context, storage will provide an arbitrage value as storage users will be in a position to take advantage from price differentials, which allows e.g. to smooth out the costs of H2 supply over time.

In summary, **UHS will be vital across all stages of the market development and across the energy system as a whole**. It will of course provide flexibility to an established and integrated European hydrogen network, in the long-term steady state. But most importantly to the current policy debate, the different value dimensions above demonstrate that particular attention also needs to be paid to the role of hydrogen storage to support the energy transition

23 As per Artelys' 2023 report for GIE, these include amongst others the levelised cost of hydrogen, hydrogen production capacities, the share of hydrogen supply routes and electrolyser load factors or the carbon footprint of hydrogen or avoided RES curtailment.

in the short- and medium-term and beyond the hydrogen sector alone, across all energy systems.

Figure 8 Values of UHS over the course of time



Source: Frontier Economics

In other words, UHS can support a trajectory of further optimisation of the energy system in favour of renewable energy sources, leading in turn to better use of RES generation capacity in the electricity grid and increased share of renewable hydrogen in the hydrogen mix. Promoting this trajectory ensures a smooth transition for the energy system as a whole in line with European energy policy objectives, such as REPowerEU or the Green Deal.

This is why Gas Infrastructure Europe (GIE) has commissioned this study, with the following objectives:

- To assess the capacity needs of underground hydrogen storage for a cost-efficient, sustainable and integrated European energy system that complies with the REPowerEU ambitions.
- To take stock of how the UHS sector is progressing towards investment into needed storage capacity.
- To understand the potential risks that may lead to investment falling short of identified system needs previously assessed.
- To propose a portfolio of policy interventions to support the delivery of needed investments and project implementation – including an explicit ambition on UHS capacity to develop by 2030 and beyond.

2 Assessing underground hydrogen storage needs for an optimised energy system

The quantification of the underground hydrogen storage (UHS) capacities that allow to comply at the lowest overall cost with the ambitious REPowerEU targets by 2030 as well as with the net-zero objective by 2050 in a cost-effective and sustainable way is a key contribution of this study.

The identification of UHS needs have been obtained leveraging the multi-energy capabilities of the Artelys Crystal Super Grid modelling solution[24], its integrated models of the European energy system, and datasets for the years 2030 and 2050 that are aligned with the latest EU policy objectives.

This analysis provides unique insights into the UHS capacities needed to ensure a cost-efficient development of the energy market, supporting the EU's ambitious decarbonisation trajectory in the medium- and long-term. When contrasted with the current pipeline of UHS projects, the result of this analysis highlights the need to set a hydrogen storage target.

2.1 A modelling approach that captures total societal benefits

This section presents the methodology that was implemented to evaluate the needs for UHS in the future energy system from a techno-economic perspective. Artelys Crystal Super Grid jointly models the European electricity and hydrogen systems, minimising both investment and system operation costs. Following an approach that jointly optimises the installed capacities for key flexibility solutions (incl. UHS) as well as the hourly dispatch of the European energy system enables the model to determine the optimal balance of investments into a range of flexibility solutions supporting the future energy system. Crucially, the modelling explicitly represents the interlinkages between the hydrogen and electricity system with an hourly time-resolution, and hence the services that UHS can provide to the electricity system by enabling (a) a flexible operational management of electrolysers and (b) the delivery of hydrogen to hydrogen-fuelled electricity generation technologies.

2.1.1 Role of UHS to meet evolving flexibility needs

Today, the gas infrastructure is at the forefront of the provision of flexibility to the EU energy system, via, for instance, storage in salt caverns, depleted oil/gas fields, aquifers, lined rock caverns, etc. The development of underground gas storage has been driven by several objectives, and notably the need to reconcile imports and production patterns with highly seasonal demand patterns.

24 See https://www.artelys.com/crystal/super-grid/

In an effort to decarbonise the European energy system, and to reduce import dependency on Russian gas as soon as possible, policy makers envision that electrolytic hydrogen will play a key role in the European energy system as early as 2030. In such a system, underground storage will again play allow supply and demand to meet in a cost-effective way.

Structurally, the flexibility needs that induce a need for underground hydrogen storage will be different in a system relying on hydrogen compared to the current system, notably due to the dynamics of domestic hydrogen production, that is assumed to be based on electrolytic hydrogen exclusively in the REPowerEU plan set out by the European Commission.

As highlighted in Table 1, the inherent variability of renewable energy sources feeding electrolysers and other end-uses is a key driver for seasonal, weekly, hourly and sub-hourly flexibility needs.

Table 1 Characterisation of key flexibility drivers for methane and hydrogen

	Methane infrastructure		Hydrogen infrastructure	
	Consumption	**Production**	**Consumption**	**Production (for electrolytic H2)**
Drivers of hourly flexibility needs (and below)	Daytime vs nighttime activities (residential, tertiary)	Methane production and imports are largely constant over these timescales (except in cases of maintenance)	Daytime vs nighttime activities (residential, tertiary), H2-fuelled power generation	RES production variability (solar PV in particular), network congestions
Drivers of weekly flexibility needs	Weekday vs weekend activities (residential, tertiary)		Weekday vs weekend activities (residential, tertiary), H2-fuelled power generation	RES production variability (wind power in particular), network congestions
Drivers of seasonal flexibility needs (and higher)	Thermo-sensitivity (mostly residential)		Thermo-sensitivity (mostly residential), H2-fuelled power generation	RES production variability (hydro, wind and photovoltaics), network congestions

Source: GIE study on the pathways and values of UHS, by Artelys[25]

[25] Gas Infrastructure Europe, Showcasing the pathways and values of underground hydrogen storages. Final Report. September 2022.

In this context, the economic needs for underground hydrogen storage derive from a structural mismatch between the sub-hourly to monthly dynamics of electricity markets (accentuated by the large-scale development of variable renewables that is foreseen), the development of electrolysis and transmission capacities for hydrogen, and the dynamics of hydrogen demand and other sources of supply (including extra-EU imports).

To capture the impact of these novel sources of flexibility needs, a methodology involving the joint modelling of the electricity and hydrogen sectors was developed and implemented, with an hourly time resolution to capture the effects of the variability of renewables such as photovoltaic solar, onshore wind and offshore wind.

2.1.2 Jointly optimising the hydrogen and power systems reveals the UHS needs

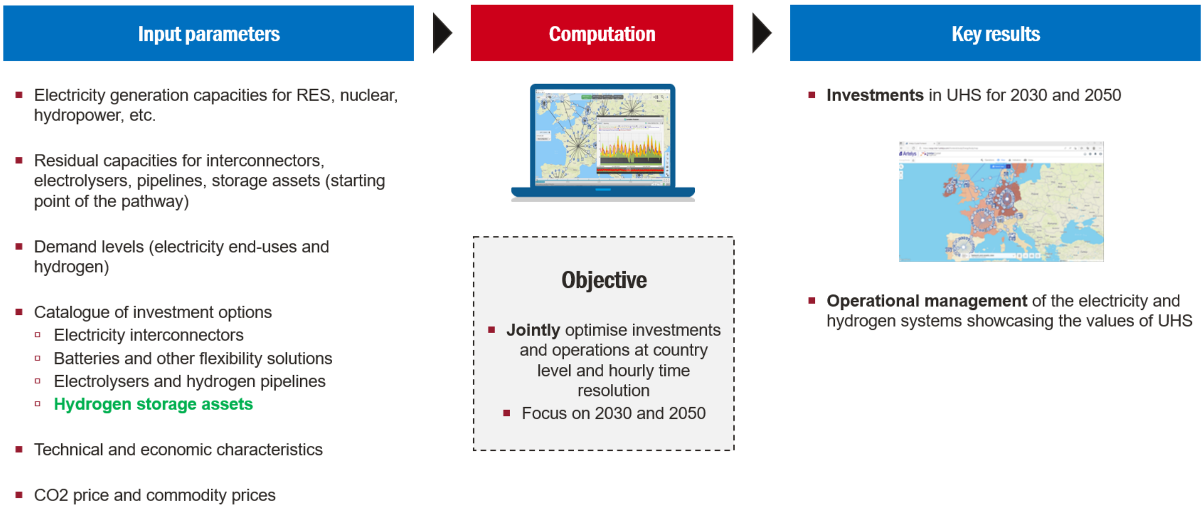
In this work, Artelys Crystal Super Grid has been used to identify the needs for UHS capacities for the 2030 and 2050 time horizons, based on the minimisation of capital and operational expenditures over a full year, simulated with an hourly time granularity. The modelling has been carried out at European level, with a country-level granularity.

Artelys Crystal Super Grid is a web-based software solution dedicated to modelling multi-energy systems, from the regional scope to intercontinental contexts. The platform notably allows the modelling of a vast array of technologies for multiple energy vectors, as well as the optimisation of associated dispatch and investment decisions based on a set of techno-economic parameters and environmental constraints.

As detailed in Figure 9, the modelling runs conducted for 2030 and 2050 integrate a catalogue of investment options that include underground hydrogen storage and other flexible technologies, including above-ground hydrogen storage, hydrogen pipelines, electricity interconnectors and short-term flexibility solutions in the electricity sector. The assumptions related to the different investment options are presented in Section 2.1.3.

The main outputs of the model include the levels of investment in technologies such as underground hydrogen storage, hydrogen pipelines and electrolysis, but also operational outcomes – e.g. the way UHS assets are operated to meet the needs for flexibility on various timescales.

Figure 9 Modelling approach based on Artelys Crystal Super Grid



Source: Artelys

Context of the evaluation of 2030 UHS needs

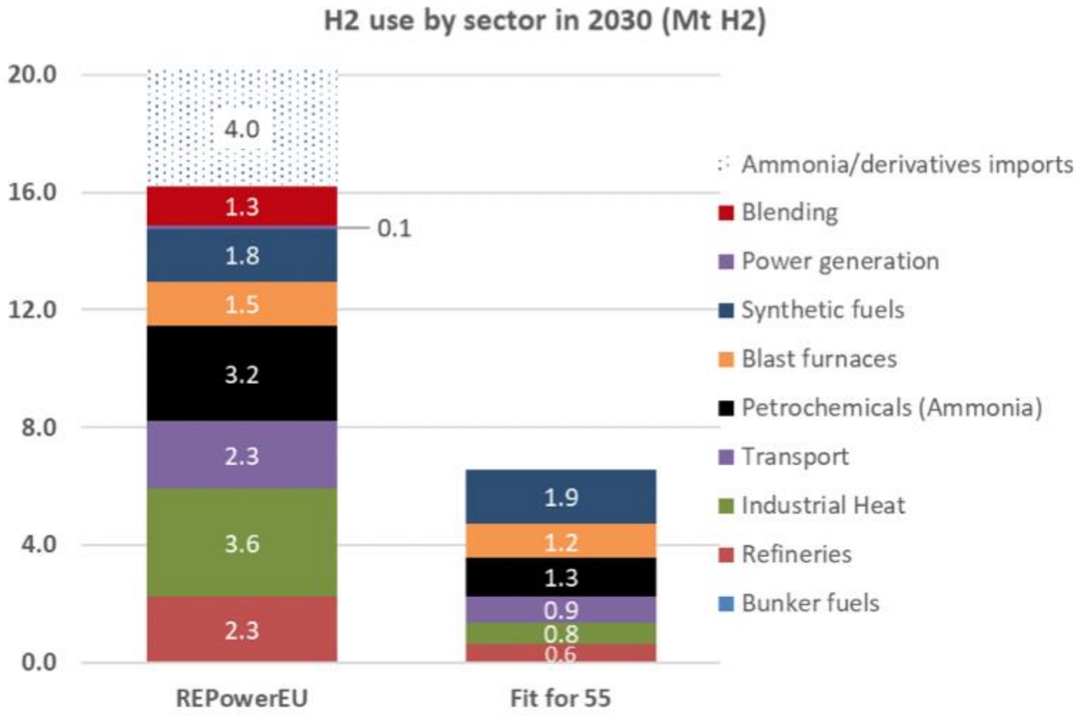
The needs for UHS depend on several aspects of the underlying energy system. The optimisation of UHS capacities by the model can therefore be impacted by the main determinants of hydrogen demand (volumes, sectors), the ability to import hydrogen and/or derivatives, electricity generation dynamics (deployment of renewable sources, structure of the electricity mix, commodity and EU ETS prices, etc.).

The context of the evaluation of the 2030 UHS needs corresponds to the one of the REPowerEU plan. In particular, the total demand for hydrogen is set at 20 million tonnes per year. REPowerEU assumes that these 20 million tonnes (circa 670 TWh LHV[26]) will be supplied as follows: 4 million tonnes will be imported in the form ammonia and other derivatives, 6 million tonnes will be imported from extra-EU sources, and 10 million tonnes will be produced domestically, exclusively via the electrolysis route. As highlighted in Figure 10 the corresponding demand is mostly directed to industrial and transportation end-uses. Structural techno-economic parameters of the model are also aligned with REPowerEU assumptions[27], including commodity prices.

26 All hydrogen volumes are expressed with low heating value assumptions (LHV).

27 European Commission, Commission Staff Working Document for the REPowerEU Plan, May 2022

Figure 10 REPowerEU assumptions for 2030 hydrogen demand



Source: European Commission

As REPowerEU figures are provided at the EU level, disaggregation keys have been required to allocate demand and supply at national level. The disaggregation keys have mostly been chosen to align on the “Distributed Energy” scenario from the 2022 edition of ENTSO-E and ENTSOG’s Ten-Year Network Development Plan scenarios[28], notably regarding the national breakdown of electricity and hydrogen demands as well as renewable capacity targets and generation profiles.

Assumptions related to the thermal electricity generation technologies and the associated parameters (e.g. national capacities, efficiencies, availabilities) have also been derived from the “Distributed Energy” scenario from TYNDP 2022. Electricity demand amounts to 3400 TWh in this 2030 scenario in EU27 (this figure includes transport and distribution losses but not the electricity demand for electrolysis). The additional electricity demand for electrolysis is reoptimized to meet hydrogen demand and reaches 500 TWh. National installed photovoltaics and onshore and offshore wind capacities have been scaled up to allow for the additional hydrogen production in REPowerEU compared to the TYNDP 2022[29], reaching a total of 650 GW for photovoltaics, 115 GW for offshore wind and 465 GW for onshore wind at EU27 level.

28 ENTSO-E & ENTSOG, TYNDP 2022 Scenario Report, April 2022

29 In proportion to national production and taking into account differences in load factors by country and technology.

The breakdown of imported hydrogen volumes from extra-EU regions (notably including North Africa, Ukraine, and Norway) is based on potentials identified in ENTSOG's System Assessment Report from TYNDP 2022[30]. For the year 2030, conservative assumptions have been used with regards to the dynamics of both the domestic hydrogen demand and extra-European imports, as no seasonal effects are assumed: demand is assumed to mostly be driven by non-thermo-sensitive end-uses in industry and transport; imports are assumed to maximise the use of infrastructure and are therefore modelled via flat import profiles.

The level of investments in the flexibility portfolio, notably including underground hydrogen storage, above-ground hydrogen tanks, hydrogen pipelines and electrolysers, is optimised by the model based on these assumptions.

Context of the evaluation of 2050 UHS needs

The energy system underpinning the identification of the UHS needs at the 2050 horizon is generally aligned with the Fit for 55 targets[31]. The main power system model is based on the "Distributed Energy" scenario from ENTSO-E and ENTSOG TYNDP 2022, notably including power generation capacities, power demand and hydrogen demand at national level. Nuclear generation capacities have been increased compared with TYNDP scenarios, consistently with the Fit for 55 datasets. The commodity prices used for the 2050 modelling have been extracted from the same sources as the ones used for the 2030 simulations[32].

As for 2030, the entire flexibility portfolio, including hydrogen storage, pipelines, and electrolysers, is fully optimised by the model (see Figure 9).

In the context described above, the EU-27 electricity demand amounts to 4300 TWh in 2050 (including transport and distribution losses but excluding demand for electrolysis). On the other hand, hydrogen demand amounts to about 1800 TWh LHV or 54 million tonnes at the EU27 level, including 200 TWh for residential and tertiary, 550 TWh for transport, 760 TWh for industry and 290 for TWh for power-to-methane and power-to-liquids. In addition, the model is allowed to increase hydrogen production to power hydrogen-fuelled power generation technologies. The hydrogen demand for transport, industry, power-to-methane, and power-to-liquids is modelled as flat profiles, while demand in residential and tertiary is modelled via dedicated thermo-sensitive profiles.

Extra-EU hydrogen imports represent close to 360 TWh LHV (11 million tonnes) in this scenario, mostly originating from North Africa, Ukraine and Norway, and are represented via flat import profiles, similarly as in the 2030 model. As for the 2030 scenario, the domestic production of hydrogen is entirely relying on electrolysis.

30 ENTSOG, TYNDP 2022 System Assessment Report, April 2023, import potentials include both pipelines and LH2 shipping.

31 See notably, JRC Digital Media Hub, Energy scenarios - Explore the future of European energy [Link]

32 Sources are REPowerEU for gas (36 €/MWh) and oil (63 €/MWh), TYNDP2022 for CO2 (168 €/ton) and Gas for climate 2021 study for biomethane [Link], based on a review of recent studies (60 €/MWh).

2.1.3 Optimisation of the cross-sectoral flexibility portfolio

To ensure a level playing field amongst flexibility solutions, investments in both the hydrogen infrastructure and key flexibility solutions in the electricity sector have been jointly optimised by the model, as can be read from Figure 9.

In particular, whilst the hydrogen demand levels and the level of extra-European imports are exogenously defined, the level of investments in hydrogen storage assets are a result of the model, that are identified via simulations minimising the total investments and operational costs of the 2030 and 2050 scenarios. The resulting UHS capacities correspond to an evaluation of economic UHS needs, taking into account the system value of UHS for the European energy system.

The investment catalogue for hydrogen storage technologies integrates national potentials for salt caverns, depleted gas fields, aquifers, hard-rock caverns, and above-ground storage. Investment options at national level have been attributed according to the existence of repurposable storage sites of each technology in the EU-27 countries, based on the potentials identified in a previous GIE study[33]. Investment assumptions presented in Table 2 are derived from the same sources[34].

Table 2 Assumptions on investment costs for underground hydrogen storage

Technology	CAPEX (€/MWh)	OPEX (%CAPEX)	Lifetime (yr)	WACC	Maximum annual number of cycles
Salt caverns	900	4 %	50	5 %	10
Hard rock caverns	1 200	4 %	50	5 %	10
Depleted gas fields	450	4 %	50	5 %	4
Aquifers	450	4 %	50	5 %	4
Above-ground storage	33 000	2 %	30	5 %	100

Source: *Artelys on the basis of input from GSE members and GIE, Gas for Climate and EHB studies (see notes 33, 34 and 35)*

Investment assumptions in hydrogen pipelines are based on the 2023 European Hydrogen Backbone study[35]. No exogenous pipeline capacities have been implemented in the model, to

33 Gas Infrastructure Europe, Picturing the value of underground gas storage to the European hydrogen system, June 2021. Attribution refers to whether or not it is possible in a given country to develop a given type of underground hydrogen storage. For example, the salt caverns investment options in the model are only possible in countries with salt cavern potential identified in this GIE study.

34 Gas for Climate, Assessing the benefits of a of a pan-European hydrogen transmission network, March 2023

35 European Hydrogen Backbone, 2023 [Link]. The assumptions of the previous update of this study [Link] were also used in the 2023 Guidehouse study for Gas for Climate [Link] and by the International Energy Agency.

preserve the optimal trade-off between the development of cross-border pipelines and underground hydrogen storage.

The costs of cross-border pipelines are calculated based on the characteristic distance between countries, following the same approach as in the previously mentioned 2023 study for Gas for Climate. For 2030, it is assumed that 60% of all pipeline capacities correspond to a repurposed gas infrastructure, a value that is consistent with European Hydrogen Backbone projections, and have adjusted the capital cost of pipelines accordingly. For 2050, the assumption is that 50% of all pipeline capacities correspond to repurposed gas infrastructure.

Table 3 Assumptions on investment costs for pipelines

<table>
<tr><th>Asset</th><th>Type</th><th>CAPEX (M€/1000 km)</th><th>OPEX (%CAPEX)</th><th>Lifetime (yr)</th><th>WACC</th></tr>
<tr><td rowspan="2">Pipeline</td><td>New (4,7 GW)</td><td>3200</td><td rowspan="2">0,9 %</td><td rowspan="2">40</td><td rowspan="2">5 %</td></tr>
<tr><td>Repurposed (3,6 GW)</td><td>640</td></tr>
<tr><td rowspan="2">Compression</td><td>New (4,7 GW)</td><td>376</td><td rowspan="2">1,7 %</td><td rowspan="2">25</td><td rowspan="2">5 %</td></tr>
<tr><td>Repurposed (3,6 GW)</td><td>165</td></tr>
</table>

Source: Artelys on the basis of input from GSE members and EHB study (see note 35)

Furthermore, investments in electrolysers, batteries, and OCGT units (gas-fired in 2030, H2 fired in 2050) are also optimised by the model according to investment parameters from the "Distributed Energy" scenario from TYNDP 2022[36] – see Table 4. Other dispatchable generation capacities, including H2-fired CCGT units in 2050, are also represented in the model in line with TYNDP's "Distributed Energy" scenario.

The model was also able to invest in cross-border electricity interconnection capacity under border-specific cost-curves corresponding to the investment options presented in ENTSO-E's System Needs study from TYNDP 2022[37].

Data from medium-sized pipelines (4.7 GW for new pipelines, i.e. 36'', and 3.6 GW for repurposed pipelines) are used to calculate costs in €/MW/km. Costs associated to compression are also taken into account.

36 ENTSOs, TYNDP 2022 Scenario Building Guidelines, April 2022

37 ENTSO-E, System needs study. Implementation guidelines, May 2023

Table 4 Assumptions on investment costs for other flexibility assets

<table>
<tr><th>Technology</th><th>CAPEX 2030 (€/kW)</th><th>OPEX 2030 (€/kW/yr)</th><th>CAPEX 2050 (€/kW)</th><th>OPEX 2050 (€/kW/yr)</th><th>Lifetime (yr)</th><th>WACC</th></tr>
<tr><td>Electrolysers[38]</td><td>366</td><td>11</td><td>200</td><td>10</td><td>25</td><td>5 %</td></tr>
<tr><td>Li-ion battery (3h)</td><td>456</td><td>15</td><td>404</td><td>13,1</td><td rowspan="3">25</td><td rowspan="3">6 %</td></tr>
<tr><td>CH4-fired OCGT</td><td>435</td><td>7,7</td><td></td><td></td></tr>
<tr><td>H2-fired OCGT</td><td></td><td></td><td>412</td><td>7,4</td></tr>
<tr><td>Electricity interconnectors</td><td colspan="4">Border-specific investment candidates based on TYNDP 2022 System Needs study</td><td>25</td><td>4%</td></tr>
</table>

Source: Artelys on the basis of input from GSE members and TYNDP 2022 studies (see notes 36 and 37)

2.2 Significant underground hydrogen storage capacities are required in the short term to support market development

The modelling for 2030 shows that significant underground hydrogen storage capacities are needed at EU-27 level to reach REPowerEU ambitions in a cost-effective and sustainable way. Underground hydrogen storage is found to be a key enabler of a large-scale hydrogen infrastructure, enabling flexibility services to be delivered by electrolysers and making the most out of the complementarities between transmission corridors.

The modelling results reveal a need for a total working gas volume of **45 TWh LHV,** with **a total injection and withdrawal capacity of 59 GW H2** and a **total investment cost of 26 billion euros[39].**

Crucially, the resulting system is found to rely on the **complementarity of multiple UHS technologies** like salt cavern, depleted gas fields, aquifers, and hard rock caverns to provide flexibility services on multiple timescales. This leads to an observed cycling rate of approximately 6 cycles per year on average for salt caverns and hard rock caverns, and an average 2 to 3 cycles per year for depleted gas fields and aquifers. These cycling rates correspond to EU-27 averages, and the solicitation of storage assets may vary significantly from one site to the next.

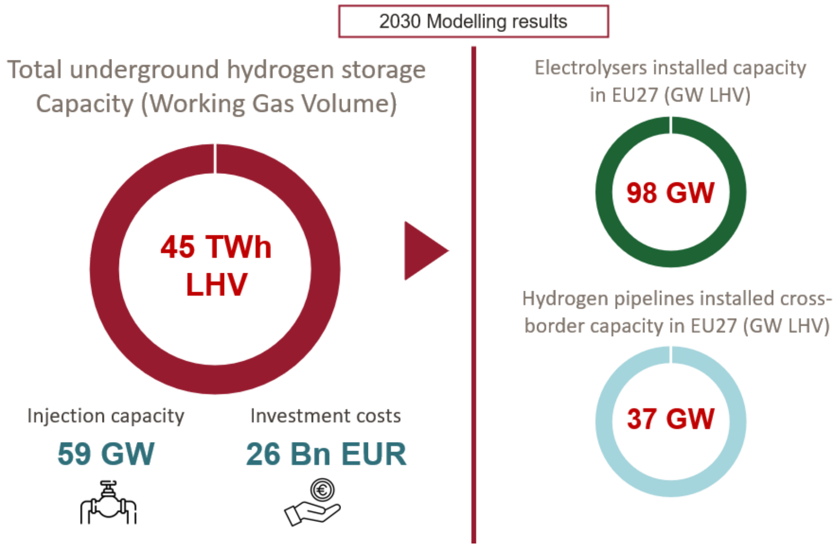
This new UHS fleet allows for an efficient co-optimisation of the rest of the hydrogen infrastructure, with a **total electrolysis capacity reaching 98 GW H2** (circa 860 TWh LHV/year) and **37 GW H2 for cross-border capacities** (325 TWh LHV/year) in total.

[38] Expressed in term of kW of electricity input. Assumptions on electrolysers efficiency are 69% in 2030, and 74% in 2050

[39] These investment costs concern underground hydrogen storage, based on assumptions presented in Table 2. Costs associated to electrolysers and hydrogen pipelines are not included in this figure.

This configuration allows for **highly flexible operating conditions** for the integrated power and hydrogen layers of the 2030 European power system, with a 41% average capacity factor for electrolysers over the EU-27 perimeter. In particular, underground hydrogen storage will be a decisive asset to manage the hourly, weekly and seasonal variations of renewable generation in the European Union. Figure 11 presents an overview of main results obtained with this 2030 scenario aligned with REPowerEU objectives.

Figure 11 Summary of key 2030 results



Source: Artelys

2.3 Substantial investments in UHS capacities are indispensable to meet our 2050 energy and climate objectives

The modelling for 2050 shows the growing role of underground hydrogen storage capacities at EU27-level to achieve a cost-effective hydrogen system, enabling large-scale infrastructures and bringing flexibility services to electrolysers and pipelines corridors.

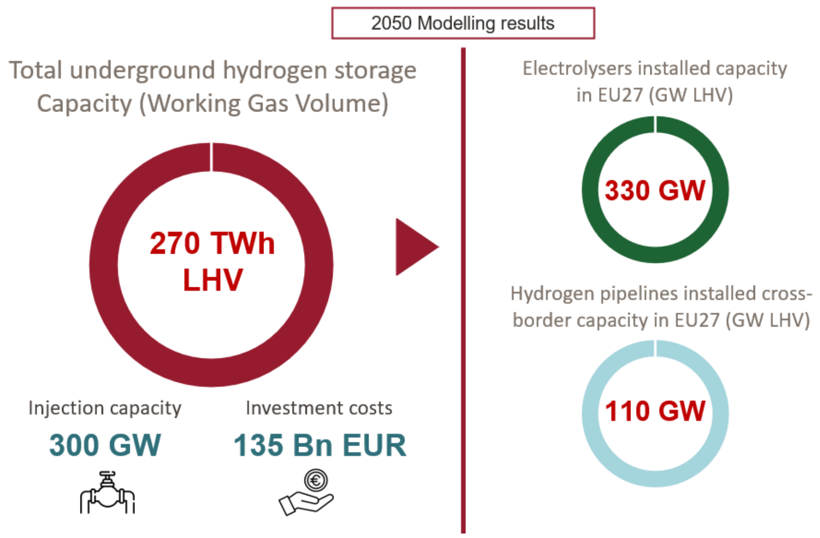
The modelling results reveal that the optimal system under this scenario needs a total working gas volume hydrogen storage of **270 TWh LHV**, with **a total injection and withdrawal capacity of 300 GW** and a **total investment cost of 135 billion euros.**

Similarly to the results obtained for 2030, the resulting energy system relies on the **complementarity of multiple UHS technologies** like salt cavern, depleted gas fields, aquifers and hard rock caverns to provide flexibility services on multiple timescales. The observed cycling rates in the 2050 modelling amount to an average 6 to 7 cycles per year at EU27 level for salt caverns and hard rock caverns, with an EU27 average of 1 to 2 cycles per year for depleted gas fields and aquifers. As for 2030, while these EU27 averages illustrate the complementarity of storage technologies, cycling rates may significantly vary from one site to another.

The UHS fleet allows for an efficient deployment of the rest of the hydrogen infrastructure, with a **total electrolysis capacity reaching 330 GW H2** (circa 2900 TWh LHV/year) and **110 GW H2 for cross-border capacities** (965 TWh LHV/year) in total. The 2050 infrastructure deployment levels therefore amount to **six times the UHS capacity** and **three times the electrolysis and cross-border pipeline capacity obtained for the 2030 time horizon.**

Underground hydrogen storage allows for **highly flexible operating conditions** for the integrated power and hydrogen systems, with a 51% average capacity factor for electrolysers at EU-27 level. The storage assets allow to cost-efficiently provide hourly, weekly and seasonal flexibility services required to integrate the foreseen level of deployment of variable renewable technologies.

Figure 12 Summary of key 2050 results



Source: Artelys

3 Currently-announced projects do not meet the optimal storage needs of the energy system

A number of underground hydrogen storage projects are already in development at the time of writing, raising the question as to whether this pipeline of projects will meet the optimal system needs that we have estimated above.

We use data from the European Hydrogen Infrastructure map[40] (H2 Inframap) to assess the expected capacities that will be available to the energy system by 2030 and 2050. We then compare these capacities to the optimal and urgently needed UHS storage needs estimated by our modelling.

We find that, **without intervention, available capacity will significantly fall short of the optimal UHS storage needs**, which would result in significantly higher system costs and other negative effects[41] compared to the optimal scenario.

3.1 Projects expected to be commissioned by 2030

3.1.1 Most projects will be commissioned only in 2030

According to the H2 Inframap[42], 25 UHS projects are expected to be commissioned by 2030. These projects **would deliver a total storage capacity of 9 TWh (c. 270 kt) by 2030** across the EU. Almost all of these projects are expected to be commissioned from 2025 onwards, and the majority of projects are expected to go into operation only in 2030. Figure 13 shows the ramp-up of capacity between today and 2030.

It is worth noting that the hydrogen sector is evolving quickly and new projects are announced regularly, with others updating their scope or even others being abandoned. As a result, the data presented in this section can only represent a snapshot at a given point in time.

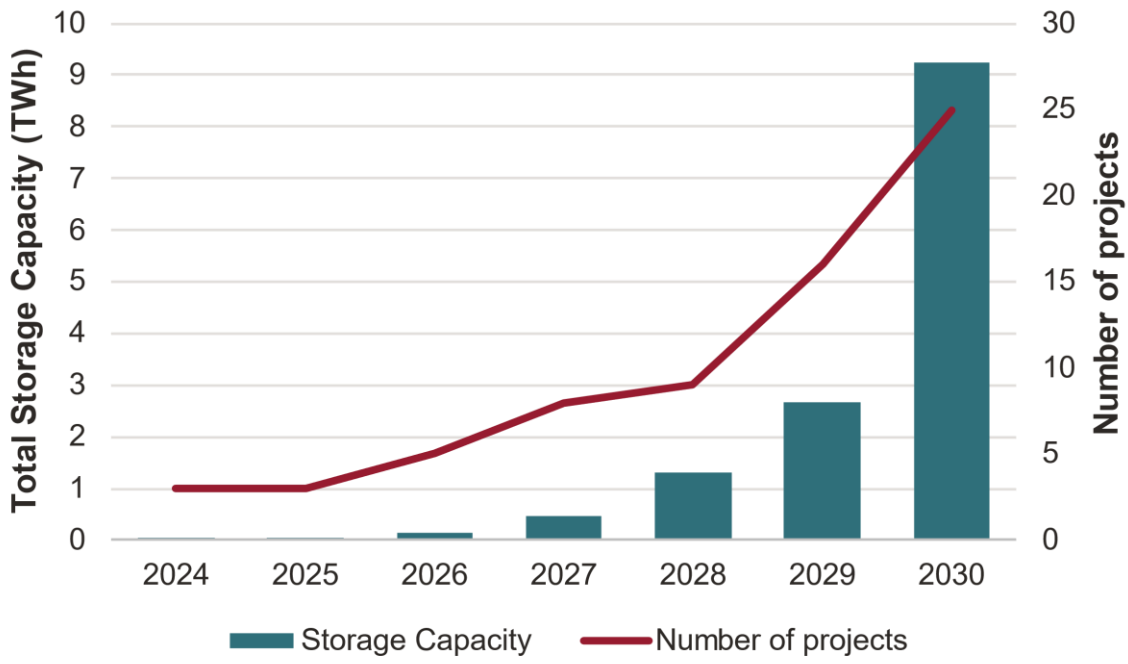
However, as described in further detail in the following sections, we consider our overall findings to remain valid, even as the pipeline of publicly-announced UHS projects shall evolve going forward.

40 Hydrogen Infrastructure Map: Showcasing concrete European hydrogen infrastructure projects and possibilities for transport routes and corridors, available on https://www.h2inframap.eu/, reported as of November 2023.

41 E.g. an increase in greenhouse gas emissions associated with the energy system (see above for the description on the environmental value of UHS).

42 The assessment was made based on Inframap data as of November 2023. Only projects which have indicated a share of 100% hydrogen with respect to “operation mode” and “share of transported hydrogen” have been included in the dataset. Projects which have not provided information on one of these two parameters have been excluded from the assessment.

Figure 13 Development of total available UHS capacity until 2030 based on currently announced projects



Source: Frontier Economics on the basis of H2 Inframap data as of November 2023

The size of individual storage facilities varies strongly and over time:

- Projects expected to be commissioned by 2030 will have an average size of about 400 GWh (c. 12 kt). By way of comparison, currently operational natural gas storage facilities usually range between 3 TWh[43] (for cavern storage) and 10 TWh (for depleted gas fields) per project, depending on the technology employed[44].
- In the first instance, planned projects are typically pilots of 1-2 GWh (c. 30-60 t), aiming to assess technology-readiness and commercial viability. At a later stage and where appropriate, these projects will increase available capacity, and could reach up to 200-300 GWh (c. 6-9 kt) per project. Towards 2030, project size generally tends to increase with some large scale projects expected to offer capacities of up to 3 TWh (c. 90 kt). These large scale projects account for almost a third of the total planned capacity in 2030.

The majority of the projects in the H2 Inframap dataset (20 out of 25 projects – representing 64% of total capacity by 2030) plan to store hydrogen in salt caverns[45]. By 2030, only five

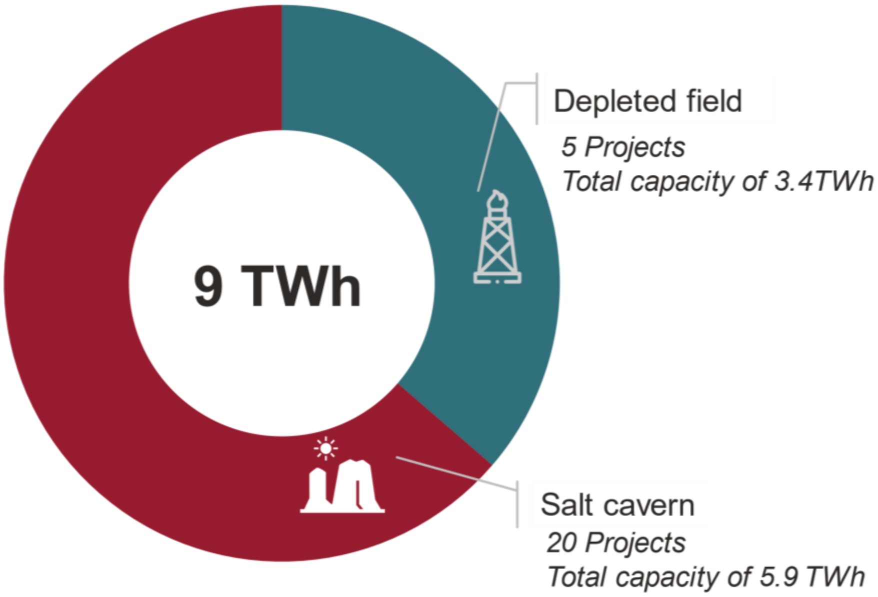
43 One storage site thereby commonly encompasses several caverns.

44 GIE Storage Database (2021), available on https://www.gie.eu/transparency/databases/storage-database/

45 Hydrogen Infrastructure Map: Showcasing concrete European hydrogen infrastructure projects and possibilities for transport routes and corridors, available on https://www.h2inframap.eu/https://www.h2inframap.eu/

projects – equivalent to 36% of total available capacity – plan to use depleted gas fields for underground hydrogen storage.

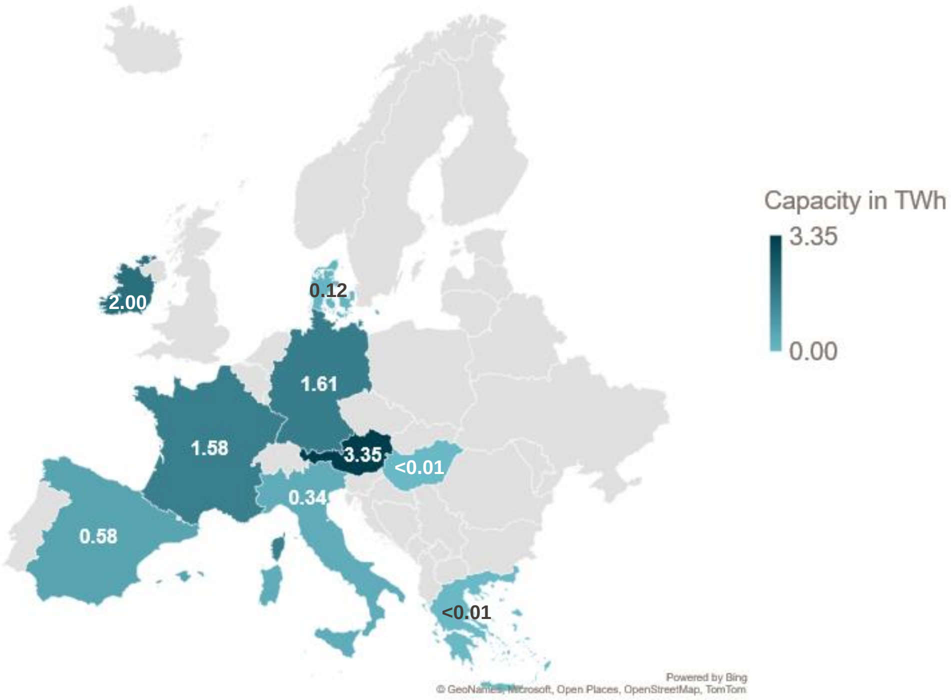
Figure 14 Currently announced UHS projects in 2030



Source: Frontier Economics on the basis of H2 Inframap data as of November 2023.

According to the H2 Inframap data, the UHS projects commissioned by 2030 will be distributed across eight European countries with the largest overall capacities available in Austria, Ireland, Germany and France respectively.

Figure 15 Country-by-country distribution of UHS capacity expected to be commissioned by 2030 based on currently announced projects



Source: Frontier Economics on the basis of H2 Inframap data as of November 2023. Projects looking to store pure hydrogen only. Additional projects storing various hydrogen blends could further increase the available capacity. We also note that additional capacities, e.g. in the Netherlands (0.8 TWh) have been announced and will be included in the H2 Inframap

3.1.2 Without intervention, a storage needs gap of 36 TWh will prevail in Europe

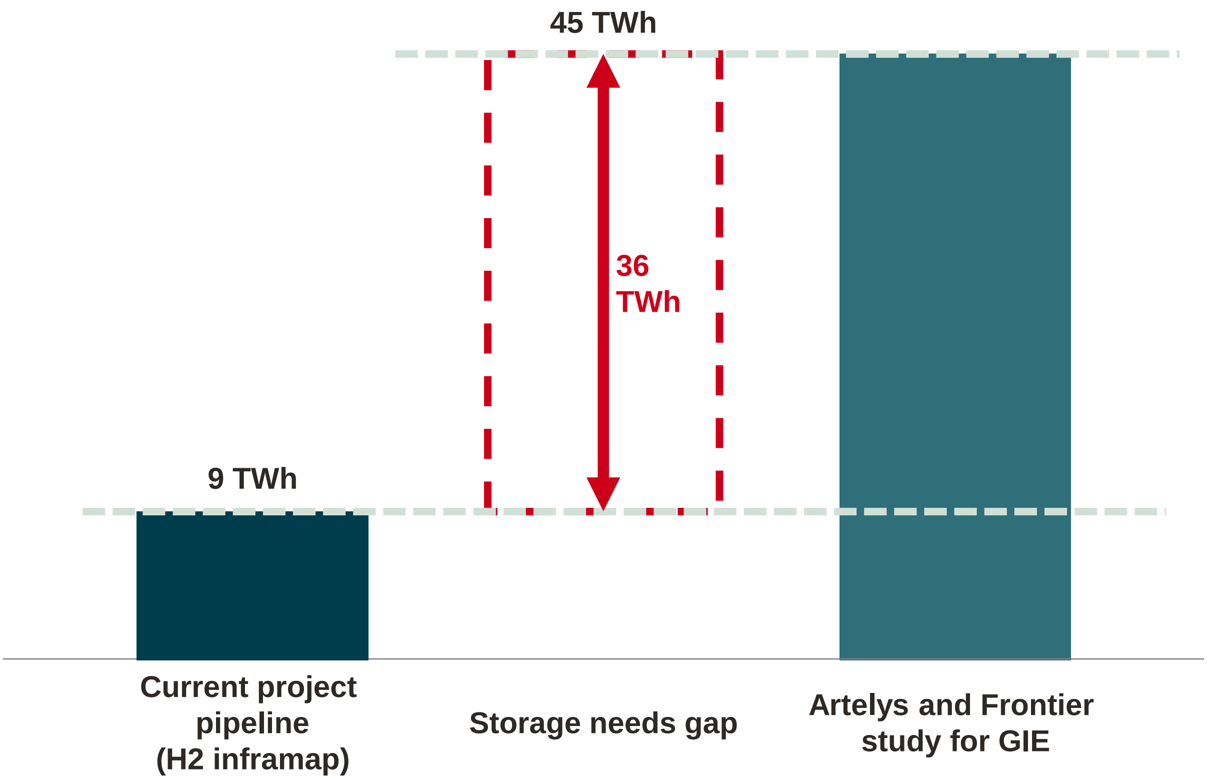
9 TWh (c. 270 kt) of UHS capacity are currently expected to be operational by 2030, whilst UHS capacity needs for an optimised energy system have been estimated at 45 TWh (c. 1,350 kt). Hence **the sector is at risk of falling significantly short of the identified UHS capacity needs – by 36 TWh**. This gap **is four times the size** of the total capacity that is expected to be developed if all currently planned projects indeed become operational by 2030.

As discussed above, the optimal UHS capacity of 45 TWh would be essential to secure the efficient functioning of a decarbonised energy system by the 2030 time horizon, and minimise the cost of getting there. It would, in particular

- Ensure security-of-supply, both for electricity and hydrogen end users;
- Enable system flexibility to manage variations in supply and demand ranging from daily to seasonal levels;
- Contribute to economically viable and reliable energy prices.

The figure below illustrates this substantial gap between the total capacity of all currently planned projects and the optimal UHS needs.

Figure 16 System-cost optimised versus planned UHS capacity in 2030



Source: Frontier Economics on the basis of H2 Inframap data as of November 2023.

It is worth noting that the actual gap between the ideal storage capacities and the realised capacities could in fact be even larger than 36 TWh. While 25 projects are currently planned to be operational by 2030, only two (pilot) projects have reached financial close (FID-stage) to date according to the H2 Inframap data:

- The Underground Sun Storage 2030 project by RAG Austria AG in Gampern, Austria, which features 5 GWh (c. 150t) of hydrogen storage in a depleted gas field.
- The first and second phase of Storengy's Hypster project in Etrez, France, which will provide a total of 2 GWh (c. 60t) of storage capacity in a salt cavern.

The combined capacity of these projects is close to 10 GWh, that is to say less than 1% of the optimal capacity for the 2030 energy system.

This suggests that whilst project promoters and storage operators are already committed to delivering capacity to the market, the prevailing uncertainty on hydrogen offtake or indeed production (which we further discuss in the next chapter) could not only impact potential future investment, but also projects that are already announced at the time of writing.

3.1.3 The gap between 9 and 45 TWh of underground hydrogen storage comes at a high economic and environmental cost to the European energy system

The gap between the current pipeline of projects (9 TWh) and the optimal level of underground hydrogen storage capacity (45 TWh) represents a significant excess cost for the European energy system. A quantification of the impact of the roll-out of UHS on economic and environmental costs is presented below.

The cost impact arises from the fact the presence of 45 TWh of underground hydrogen storage in the energy system enables electrolysers to operate more flexibly, allowing them to maximise withdrawals during episodes with high RES production volumes, whereas renewable production would have been curtailed in a system with only 9 TWh of underground hydrogen storage. Furthermore, such a system would require resorting more frequently to carbon-intensive electricity generation technologies. Finally, the integration of 45 TWh of underground hydrogen in the European energy system would allow for capital cost savings, since investments in alternative, more costly, flexibility solutions would be avoided.

The cost impacts have been evaluated by comparing two configurations of the energy system:

- **Optimal system configuration** – This first configuration of the EU energy system corresponds to the one where an optimal level of investment in underground hydrogen storage is developed, reaching a total capacity of 45 TWh. The investments and operational management characterising the optimal system configuration are the results of the optimisation process shown in Figure 9 and presented in detail in section 2.

- **Constrained UHS configuration** – This alternative configuration is based on a simulation of the energy system that follows exactly the same set of assumptions as the simulation underpinning the optimal system configuration, except for the fact that investments in underground hydrogen system cannot exceed 9 TWh. To compensate for this lack of flexibility from UHS, the model invests in alternative, more costly flexibility solutions, and adapts the operational management of the overall energy system to ensure the electricity and hydrogen demands can continue to be met.

The environmental and economic impacts of going from the optimal system configuration to the constrained UHS configuration are described in the following paragraphs.

Environmental impact

Between the constrained UHS configuration and the optimal system configuration, annual emissions of the electricity sector decrease by a total of 15 MtCO2eq in 2030 at the EU 27 level. This corresponds to a **10% reduction of GHG emissions** emitted by the power sector. The entirety of the emissions savings can be attributed to the avoidance of RES curtailment that is enabled by a higher underground hydrogen storage capacity in the optimal configuration.

In fact, the level of curtailment is significantly reduced in the optimal configuration. The amount of avoided curtailment reaches 14 TWh in 2030 at the EU 27 level. This corresponds to a **50% reduction of RES curtailment**, compared to the level observed in the constrained UHS configuration.

The economic value of this environmental impact is comprised in the overall economic impact further developed below.

Economic impact

Investing in 45 TWh instead of only 9 TWh of underground hydrogen storage has two types of impacts on costs: avoiding investments in alternative, more costly infrastructure elements, and saving on operational costs of the energy system, including environmental costs.

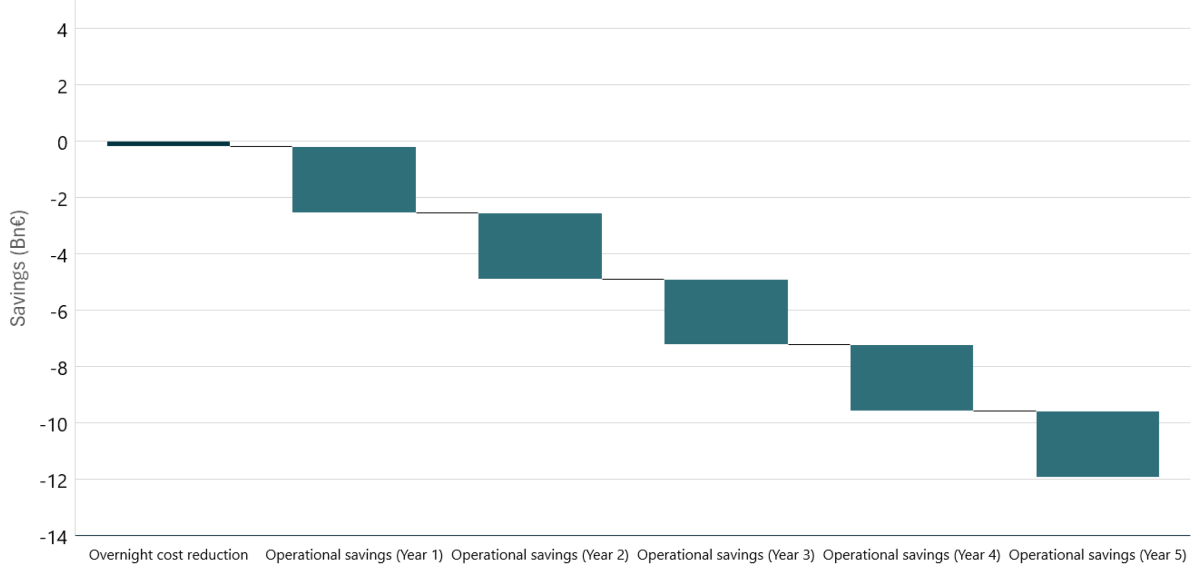
These two types of impacts can be summarised as follows:

- **Reduction of investments required in alternative, more costly technologies.** Integrating 45 TWh of underground hydrogen storage into the EU energy system instead of only 9 TWh allows to reduce investments in other infrastructure, notably above-ground tanks that are very costly. Investments in batteries and other flexibility solutions in the power sector also decrease. Investments in electrolysers increase to fully take advantage of the dynamics of renewable electricity production patterns. The following figure illustrates the main impacts on hydrogen storage capacities and on electrolysers:

  In terms of **overnight costs**, both systems are characterised by similar investment levels, as the increase of costs related to underground hydrogen storage and electrolysers is cancelled out by the decrease in the overnight costs of the other components (above-ground tanks, pipelines, flexibility solutions in the power sector). On balance, the constrained UHS configuration is found to cost circa 200 M€ more than the optimal system configuration. Hence, as described further below, most of the savings enabled by underground hydrogen storage is related to the optimisation of the operational management of the entire energy system that these assets enable.

- **Reduction of the reliance on carbon-intensive electricity generation.** Avoiding the curtailment of renewables decreases the frequency at which the system must rely on costly power generation technologies. In the 2030 configurations, the simulations results show of **annual operational savings of 3.1 B€ at the EU 27 level** thanks to the integration into the EU system of 45 TWh of underground hydrogen storage instead of 9 TWh. This figure integrates the savings in terms of commodity costs, carbon tax and other variable operational costs.

Figure 17 Energy system cost savings from reaching 45 TWh of UHS rather than 9 TWh



Source: Artelys

When analysed jointly, the combined effect of the impact on the overnight costs and of the savings on operational and environmental costs can be summarised into the following two key insights:

1. **Investing in underground hydrogen storage delivers system-level savings from the very first year of operations.** In contrast to typical infrastructure projects that only recoup their costs after multiple years of operations, investing in underground hydrogen storage is found to bring system-level benefits **from the very first year of operations**. Indeed, the sum of the impact on overnight costs, fixed operational costs per annum and operational savings per annum (including environmental costs) amounts to circa 2.5 B€.

2. **Investing in underground hydrogen storage significantly decreases the costs of operating the EU energy system.** On top of the fact that underground hydrogen storage brings system-level savings from year one, its integration into the EU energy system will deliver **savings for every subsequent year of operations**. Under the assumptions adopted in this report, the impact, factoring in operational savings and impacts on fixed operational costs, for a 20-year period with a 4% discount rate, reaches 32 B€.

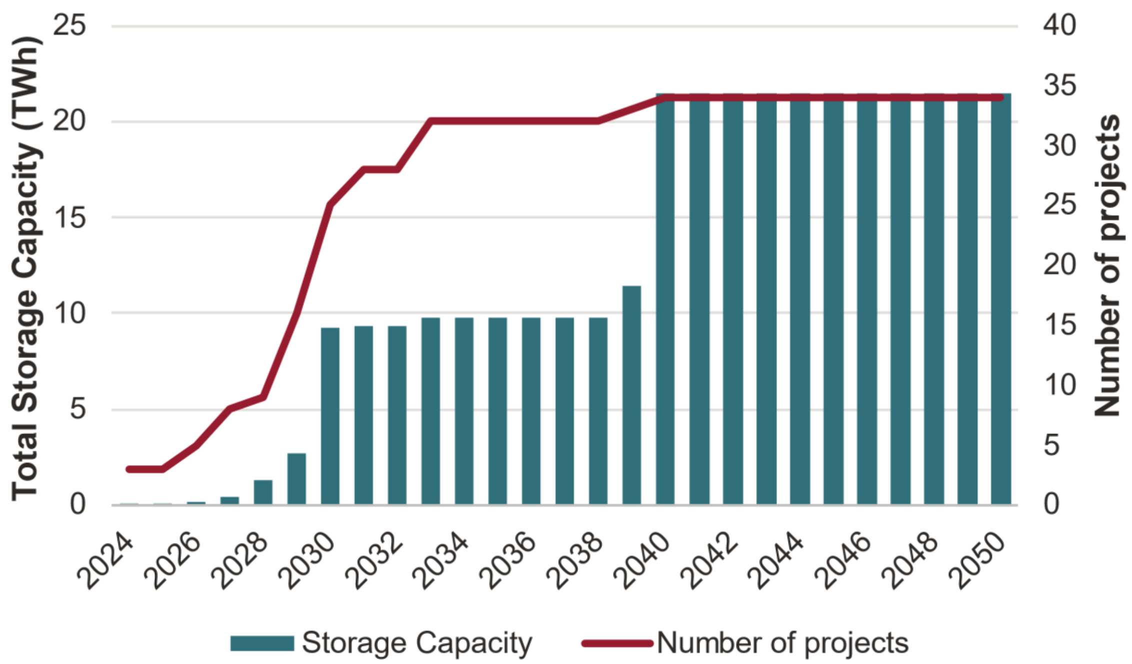
Finally, we note that the cost differential estimated above primarily reflects the system, arbitrage and environmental values discussed in this report. It is a conservative estimate of total cost savings to the extent it does not provide a monetary value to the kickstart and insurance values of underground hydrogen storage[46].

3.2 Projects expected to be commissioned by 2050

3.2.1 A limited number of projects commissioned after 2035 are currently known today

Based on the H2 Inframap data, 34 UHS storage projects are planned to be operational by 2050. As illustrated by Figure 18, a substantial increase in capacity is expected by 2040, but few projects have been announced to be commissioned beyond this point at the time of the analysis.

Figure 18 Development of total available UHS capacity until 2050 based currently announced projects



Source: Frontier Economics on the basis of H2 Inframap data as of November 2023.

By 2050, the average size of UHS facilities is expected to increase to about 750 GWh (c. 23 kt), with the largest planned project encompassing a total capacity of 10 TWh (c. 300 kt). For

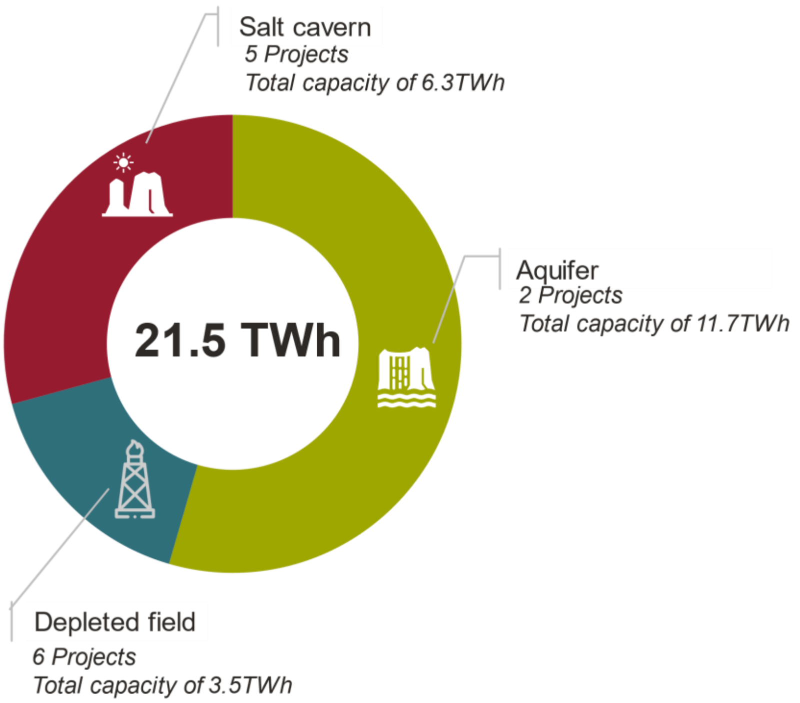
46 By focusing on the snapshot year 2030, it somewhat omits the kickstart which is more dynamic in nature, ie pertains to the acceleration of the energy system transition enabled by UHS. It also eludes the full insurance value of UHS. Indeed, the optimal system configuration entails a higher level of security of supply than the constrained UHS configuration; however the euro-value of this level of security of supply to system users has not been quantified.

ease of reference, this is in comparison to the 1-2 GWh capacity of pilots and maximum capacity of 3 TWh per project pre-2030.

This suggests that despite the longer time horizon until 2050, storage operators and project promoters have already included large-scale UHS projects in their long-term planning processes reflecting expected further development of the hydrogen market as well as technological evolution over this period.

Between 2030 and 2050 planned projects will also further diversify into large-scale hydrogen storage in aquifers, alongside salt caverns and depleted gas fields. The breakdown by technology is presented in the chart below.

Figure 19 Currently announced UHS projects in 2050

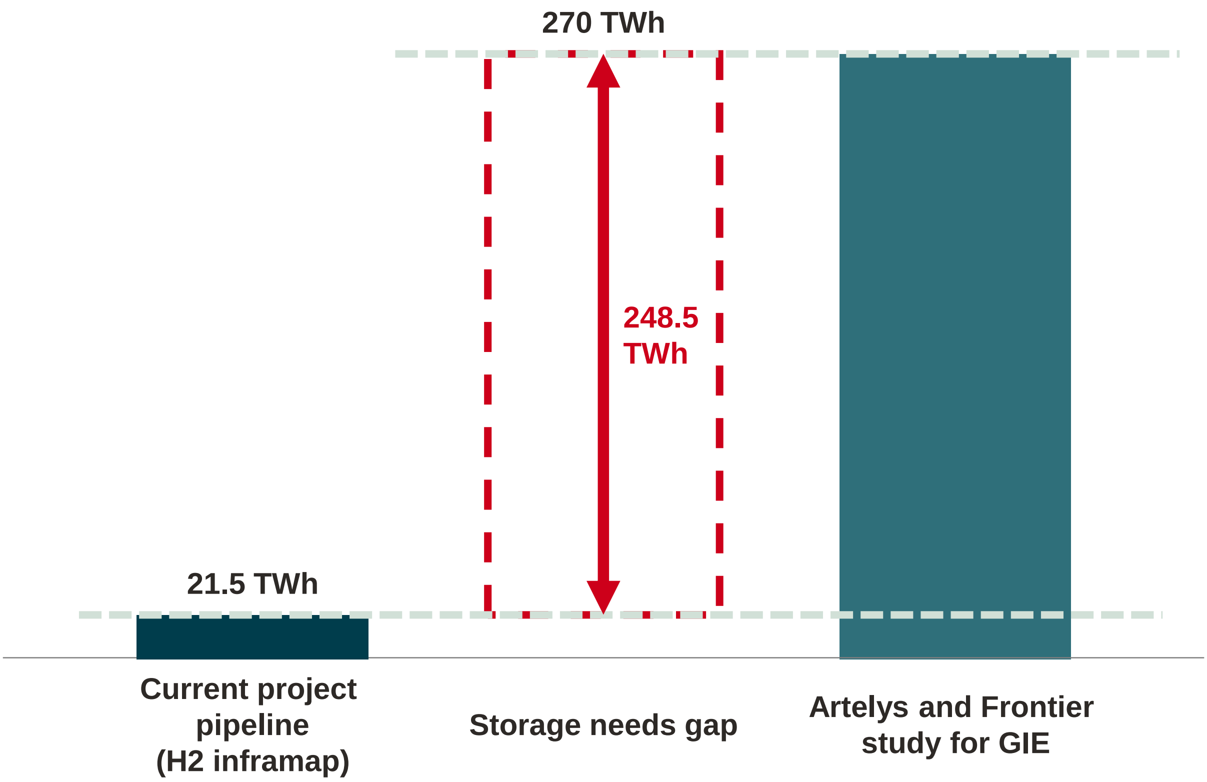


Source: Frontier Economics on the basis of H2 Inframap data as of November 2023.

3.2.2 In 2050 the storage needs gap will exceed planned capacity by more than ten times

According to the H2 Inframap data, a total UHS capacity of 21.5 TWh (c. 646 kt) is expected to be commissioned by 2050. This is in contrast to the optimal capacity to meet the needs of the energy system of 270 TWh, pointing to a gap of **248.5 TWh**. This suggests that, similarly to the expectation for 2030, available capacity of currently planned projects **would fall significantly short of the storage needs** of an optimised, integrated and decarbonised European energy system by 2050 – **indeed, it would fall short by more than ten times the amount of currently-planned capacity**.

Figure 20 System-cost optimised versus planned UHS capacity in 2050



Source: Frontier Economics on the basis of H2 Inframap data

Projects expected to be operational by 2050 are inherently more uncertain than those planned to be commissioned by 2030, merely in light of the time horizon. There is thus a significant risk that the actual gap between realised capacities and the optimum may be even greater than estimated above (e.g. if not all projects make FID)[47].

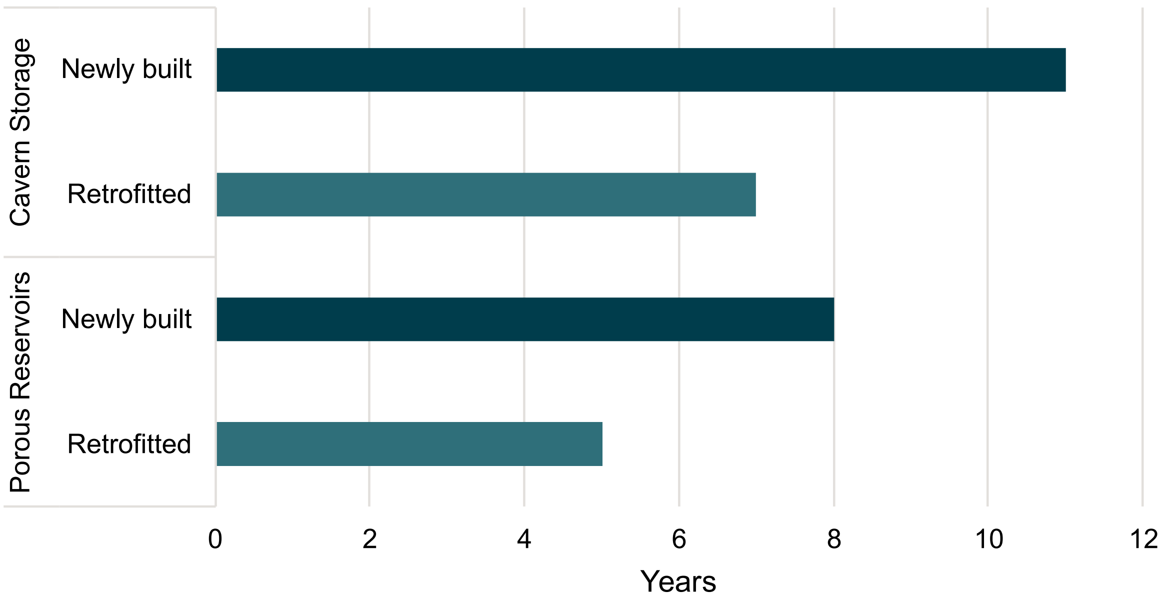
If UHS capacities were to remain below the optimal level in the long term, benefits from the values of UHS presented in section 1 would not materialise. This will not only impact the hydrogen economy but the entire energy system across numerous dimensions. Electricity and hydrogen prices will likely be higher and more volatile; and security-of-supply will be more difficult to ensure. Higher prices and lower available renewable energy sources may further extend the need to rely on fossil fuels, which would slow down the energy transition and ultimately puts the EU's net zero target for 2050 at risk.

47 Equally, promoters may plan additional projects and/or increases in capacity of earlier commissioned projects that may not be public knowledge today.

4 The market alone will fail to close the gap

To close the significant infrastructure needs gap identified above, investment decisions for additional UHS capacity would need to be taken urgently. Storage projects face significant and long lead times for commissioning (even longer than other parts of the hydrogen value chain), mainly due to their technical complexity and lengthy administrative approval processes. For both retrofitted as well as newly-built facilities, lead times reflecting these constraints currently lie somewhere between 5 and 11 years on average.

Figure 21 Development times of hydrogen storage



Source: Frontier Economics based on INES (2023) and operators' experience.

As a result, when making investment decisions, project promoters and storage operators risk being "locked-in" – during the project development phase, they are not able to react to changes in market signals and environments as flexibly as would be the case for hydrogen producers and/or offtakers facing shorter lead times[48].

In this section, we discuss how this risk is amplified by a number of barriers that are key drivers for the viability (or absence thereof) of UHS business cases and which, today, prevent operators and project promoters from taking optimal investment decisions (from the energy system's point of view). In particular, we demonstrate that the five value dimensions presented

48 For instance, the International Energy Agency estimates that lead times for electrolyser projects lie between one and three years : https://www.iea.org/energy-system/low-emission-fuels/electrolysers

above cannot, currently, appropriately be reflected and captured by storage operators, which has a direct implication on the investment levels into UHS.

As a result, without intervention, these barriers make it unlikely that sufficient additional UHS capacity will be established to allow to close or significantly bridge the gap.

In the following, we describe in more detail how current circumstances hinder additional optimal investments in UHS infrastructure (section 4.1) and why additional investments undertaken despite the present obstacles are unlikely to lead to an optimal outcome for the energy system (section 4.2).

4.1 Current circumstances will prevent storage operators from taking investment decisions that would allow to close the infrastructure gap

The lack of **maturity in today's renewable and low carbon hydrogen market** is a key barrier preventing the five values of hydrogen from being fully and appropriately reflected in decision-making by project promoters and storage operators. Indeed, only where these values can be quantified or, ideally, monetised[49], will economic signals be most efficient. Where this is the case, the viability of business cases improves and uncertainty is reduced.

Over and above the absence of strong economic signals, a **limited awareness amongst policy makers of the values** that UHS can deliver to the energy system further hinders the incentives of storage operators to take optimal investment decisions. Inefficient processes and risk exposures remain, which contribute to the lack of strong economic signals for operators.

These two shortcomings result in a range of barriers to UHS investment, which can be grouped into three broad categories:

- A lack of visibility and hence long-term uncertainty of UHS business cases;
- The persistence of complex and lengthy approval processes for both new projects as well as repurposed storage facilities; as well as
- Technological uncertainty and outstanding learning effects on both Capex and Opex.

In a nutshell, these barriers reflect the inability for project promoters to fully capture the five value dimensions of storage limiting the extent to which the benefits associated with these values can be unlocked for the energy system as a whole.

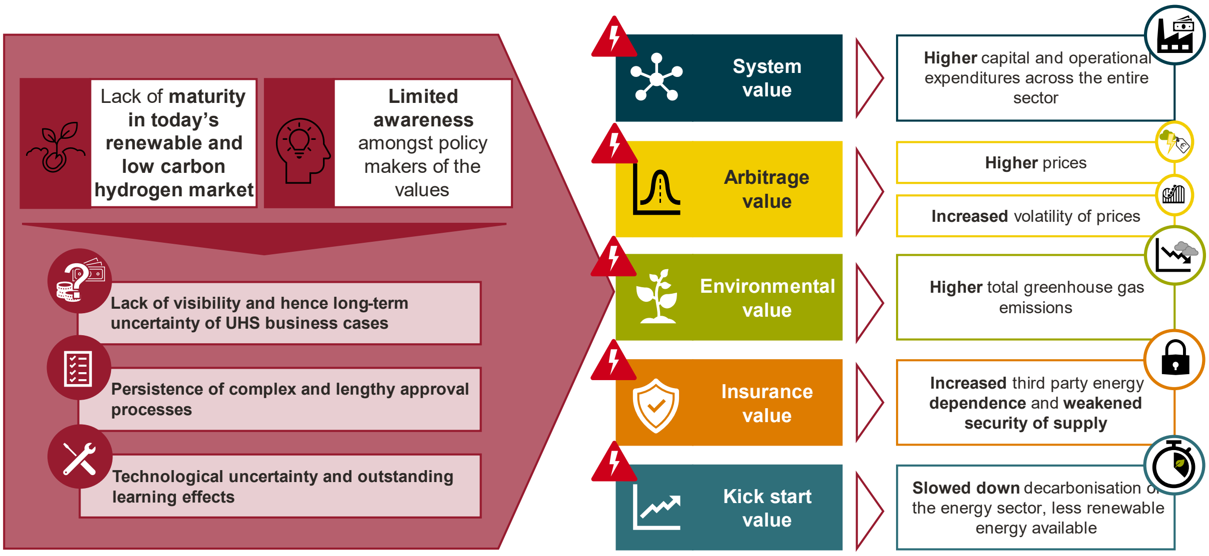
It is worth recalling that several project promoters and storage operators do continue to develop their businesses and have already committed to investing in additional UHS capacity.

[49] With "monetised" we define the possibility to attach a monetary value to a specific quantity, which in turn allows to reflect this quantity in a business plan. For instance, a hydrogen quantity can be monetised with a hydrogen price, which therefore allows to "monetise", e.g. a certain level of hydrogen production.

However, as long as the barriers above continue to exist, this level of investment will likely remain inferior to the optimal level.

Figure 22 summarises these impediments for UHS operators and project promoters, and highlights the long-term implications from not addressing these for the system as a whole.

Figure 22 Barriers limiting investment into additional UHS capacities and their implications for the energy system



Source: Frontier Economics

4.1.1 Uncertainty around the viability of storage business cases in the short- and medium-term

The energy sector is facing the unique challenge of having to transition from fossil to renewable energy sources in **all segments of the value chain – all at the same time**. The important links and interdependencies along the chain make it **hard for individual participants to correctly anticipate the demand for their services** (e.g. UHS).

In addition, stakeholders face legislative and regulatory uncertainty, for example regarding certification, (cross border) trading and crediting of renewable and low carbon hydrogen. Promoters may be hesitant to invest in segments of the value chain as long as key legislation, e.g. Delegated Acts around the qualification of renewable and low carbon hydrogen, explicit government support for storage, or the role of economic regulation have not been finalised.

Ambiguity regarding the translation of European Directives into national legislation further amplifies the uncertainty. These developments will impact the entire value chain and have exponential impacts on storage due to the interlinkages with the other parts of the value chain discussed further above.

The resulting overall uncertainty in the market impedes the effective planning of hydrogen infrastructure and storage in particular. As it is **challenging for individual stakeholders to estimate the appropriate valuation** for their specific activity, operators may struggle to construct viable business cases and refrain from investments.

Absent a hydrogen price UHS operators can only rely on imperfect information which leads to suboptimal underinvestment

The renewable and low carbon hydrogen market of today is missing a key economic indicator: **a market-based, liquid price signal**.

While the emerging legislative framework is starting to create incentives for the use and production of renewable and clean hydrogen, the market is still in a nascent stage[50]. Without a price, market participants need to rely on imperfect information and (often) bilateral agreements to value their projects. These will be primarily driven by individual needs and circumstances that do not (necessarily) reflect optimal outcomes for the system as a whole. In such an environment, stakeholders will place investments carefully to minimise the downside risk on expected returns. By way of example,

- Potential hydrogen end-users may delay investments in renewable technologies until they have confirmation that they will indeed be connected to the emerging hydrogen network and can obtain the volumes they need to reliably use renewable hydrogen in their processes.
- Hydrogen producers may in turn require (long-term) off-take agreements before investing in electrolyser capacity.
- The hydrogen network operator may in turn wait for potential future end-users and producers to confirm their demand to avoid unnecessary network expansion.
- Finally, storage operators are exposed to the triple uncertainty of the other three parts of the value chain, and with their long lead times to commissioning, face further uncertainty around the future market environment they will face.

The situation is representative of the nascent nature of the hydrogen market and is often being referred to as the **chicken-and-egg problem**.

Obtaining a cohesive market projection would currently still require a sophisticated scenario-based modelling approach (as the one carried out by Artelys in the context of this study) – and would *still* further need to rely on a number of key-assumptions (e.g. on hydrogen prices). As these modelling tools and, more generally, the adoption of a system-wide view in decision-making remain limited to date, most market participants will struggle to robustly assess the effective social, and indeed private value of individual components to the entire value chain,

50 By way of example, the ReFuel EU Aviation and Maritime plans introduced quotas for the use of RFNBOs. Similarly, penalties under the ETS for carbon emissions create incentives for the use of low-emission fuels.

in particular UHS on their own, and may choose to invest less – or in the worst case, not at all.

As noted before, this challenge is especially pronounced for hydrogen storage due to its inherent technical characteristics and its position in the value chain. Complex technical and engineering specifications make long planning horizons necessary. Specialised skills and equipment required to make caverns and porous reservoirs suitable for gas storage and long delivery times in the value chain for components further contribute to long lead times until commissioning. To ensure that sufficient UHS storage volumes are available to the market when they are needed, investment decisions would consequently need to be made well in advance of other parts of the value chain.

Beyond this temporal aspect, the exact characteristics of the demand for storage at specific storage locations are particularly uncertain – again largely made difficult by the absence of a hydrogen price. While there is a growing general consensus that UHS will be essential for the European energy system and that substantial capacities will be required, it is challenging for promoters to derive concrete implication for individual projects. Due to the strong and diverse links between UHS and the future energy sector – including the availability of other infrastructure elements such as hydrogen or electricity grids – the right moment to invest into additional UHS capacity is particularly challenging to foresee for individual operators.

- **Energy supply and demand**, both in the form of hydrogen directly and electricity indirectly, will naturally impact the need for UHS, but they are themselves currently highly uncertain. The net effect resulting from differences between supply and demand, which will determine the storage capacities required, cannot currently be foreseen.
  - For example, given that seasonality can only be estimated and established over the long term, the current lack of visibility regarding the development of the hydrogen market prevents investors from independently assuming the risks associated with the infrastructure. The lack of visibility is influenced by several drivers, such as the mix of industries that will use hydrogen on the demand side or the importance of imports on the supply side. Existing market mechanisms and signals for natural gas storage can only provide very limited insights for the emerging UHS market.
  - Demand and supply profiles for UHS are expected to differ from those currently observed for natural gas. Integration with the electricity sector introduces additional dimensions to the UHS needs and adds further complexity. The net need for storage is itself therefore subject to a range of (possibly countervailing) effects and cannot be precisely anticipated today.
- Beyond supply and demand for energy, the **market's need for storage will also depend on the roll-out of other types of energy infrastructure** – hydrogen networks and electricity grids in particular. To quantify these interdependencies, a complex integrated system optimisation considering local constraints and far exceeding the insights of individual market participants would be required.
  - The increased future share of renewable energy sources will intensify stress on electricity grids, expanding the need for ad-hoc network control.

- UHS can, in principle, provide an important contribution by alleviating network congestion. But the layouts of the future hydrogen network and the electricity grid remain uncertain and, as a result, so does their impact on the demand for UHS.

Uncertainty regarding monetisation opportunities and achievable returns amplifies the risk of failing to recover unforeseen cost

Storage developers also face a lack of visibility on the level of returns they can generate from their projects – even where it is unambiguous that these projects will provide significant social value to the system.

Indeed, these benefits can, at least today not necessarily be fully captured by storage operators and/or their immediate business partners. Instead, they may either accrue to other, unrelated, parts of the value chain, or, more prominently, not be able to be quantified appropriately in the absence of a hydrogen market price or indeed a price for wider system flexibility. To provide a concrete example,

- Storing hydrogen produced from otherwise curtailed / re-dispatched RES production for subsequent storage provides value to society by capturing energy that would otherwise have been lost.
- However, the flexibility this provides can today neither (i) be valued on the electricity side in the absence of priced flexibility services[51], nor (ii) on the hydrogen side in the absence of a price signal whose volatility storage could in theory contribute to smooth for the benefit of end-users (and decarbonisation)[52].

Concretely, this prevents various value dimensions of UHS – e.g. the system value, insurance value or kick-start value – to be appropriately quantified (and monetised) and has a direct impact on investment decisions and negative implications for the wider energy system. As a result, the willingness-to-pay and demand for storage services will be lower than it should be, which in turn reduces incentives to invest below their optimal values.

More generally,

- Taking advantage of the **arbitrage value of UHS requires a mature hydrogen market**. The hydrogen market is currently in its infancy. Prices for renewable and low carbon hydrogen are therefore highly uncertain – both in absolute terms and in terms of potential price-patterns. A diverse set of factors affects the future supply and demand of hydrogen and consequently the market prices. As mentioned above, neither hydrogen suppliers nor end users can currently predict the extent to which available and required volumes of hydrogen will follow seasonal patterns. Similarly, it is still uncertain if, when and at which price international hydrogen imports will be available to the market and affect prices. While

51 Note that this would include services provided by a bundle of products in the H2 system (such as for instance a joint combination of electrolyser and UHS contributing to balancing services to the electricity system)

52 Again, this underlines the importance of a system-wide perspective.

it is certain that storage can provide arbitrage opportunities, potential customers will find it difficult to assess the arbitrage value of a storage site in the current market environment. Storage operators will therefore find it difficult to obtain adequate remuneration for this benefit.

- **Environmental benefits** provided through storage are unlikely to be captured by storage operators. UHS enables a smooth supply of hydrogen, which is essential for the decarbonisation of a number of end uses. Industrial applications which are able to switch to decarbonised, hydrogen-based technologies have the opportunity to monetise the resulting emission savings – for example through selling EU ETS CO_2 allowances (otherwise needed if fossil fuels had been used). In contrast, the storage operators, who originally enabled the emission savings may not gain any immediate monetary benefit (because the financial benefits of CO_2 savings accrue to energy producers or consumers, but not those who store renewable and low carbon energy)[53].
- The **strategic value from security-of-supply** added through UHS is currently not valued by the market (or regulatory dispositions). UHS decreases immediate dependence from third-party, non-EU suppliers and protects energy end-users from unexpected dips in supply which could possibly cause major disturbances. This benefit of insuring the energy market against material harm is not yet systematically anchored in, or valued by European legislation. There is therefore no option for UHS operators to receive direct monetary compensation for the additional security they provide unless shortfalls in energy supply occur.

The absence of immediate remuneration opportunities discussed above makes it challenging for storage operators to fully reflect the values provided by UHS in their business plans. As a result, even though a UHS project may deliver significant added value to the system, it may not be commissioned or only at a reduced scale.

The lack of storage specific support mechanisms requires UHS operators to fully bear the risks arising from the current uncertainty in the market

There are currently no storage-specific support mechanisms available to bridge the funding gap between costs and expected revenues. European legislation has already recognised the need for support, coordination and integration across the Union, which has been formalised in the TEN-E Regulation, which defines the “project of common interest” (PCI) label. In a biannual process, projects that improve the connection between Member States can apply for PCI/PMI status. Projects awarded this status can then benefit from accelerated and simplified permitting processes and potential access to funding through the Connecting Europe Facility.

53 It is worth noting that the price signal from CO2 allowances remains in any case somewhat imperfect today, as it does in any case not capture the true social cost of climate change caused by additional emissions

While hydrogen storage facilities are eligible for PCI status, the current assessment criteria and methodologies used to grant PCI status are at risk of not reflecting the characteristics of storage and the specific value dimensions added to the energy system through UHS[54].

- Cross-border impact is a key criterion for PCI status, and in the past it has commonly been interpreted as a requirement for the infrastructure to provide a physical link between Member States. Sites for UHS are inherently bound to geological formations (salt caverns / aquifers / depleted gas fields) and are therefore often located on the territory of a single Member State. The focus on physical connections between Member States therefore makes it particularly difficult for storage operators to demonstrate cross-border impact.
- Similarly, key benefits that UHS can bring to the system are not well reflected in the PCI assessment methodology. In particular, benefits with regard to security of supply were barely acknowledged in the latest iteration of the PCI process (although the REPowerEU plan highlights the importance of UHS for security of supply and explicitly identifies investment needs for energy storage infrastructure[55]). As a result, the benefits of hydrogen storage projects were likely underestimated at the assessment stage, which may have had a detrimental effect on projects' chances to obtain the PCI label.

Today, there are insufficient opportunities for UHS operators to receive support to manage the risks of the emerging hydrogen market. It is worth noting that uncertainty surrounding the viability of UHS differs significantly from the developments in natural gas storage.

- Initially driven by inter-temporal arbitrage opportunities, natural gas storage became increasingly relevant for security of supply considerations[56]. Member States then started taking more explicit measures to intervene and address market failures.
- In contrast, given the current state of the hydrogen market and the challenges associated with the energy transition, UHS simply cannot wait for the maturing of the rest of the value before making investment decisions.

In summary, sub-optimal levels of investment combined with long lead times for storage will inevitably create negative implications for the future energy system. If sufficient storage facilities are not available when the system needs them most, the overall cost of energy will become significantly higher. This may, in turn create a domino effect of costly interactions that inhibit the necessary investment and progress towards net-zero for the system as a whole.

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54 We appreciate that the 6th PCI list, was the first list that included hydrogen infrastructure and that a range of assessment tools weren't yet fully developed when the candidate projects were analysed (e.g. a robust CBA methodology). As we describe in more detail below, policy makers should embrace the existing flexibility and learnings from this first round to ensure that the following call (expected at the end of 2024) does better reflect the benefits associated with these new types of infrastructure rather than try to implement a readacross from the natural gas market.

55 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 REPower EU Plan, available on https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=COM%3A2022%3A230%3AFIN&qid=1653033742483

56 It is worth noting that in the past, infrastructures were often part of vertically integrated groups, allowing for a form of internalization of the externalities generated by storage.

4.1.2 Complex coordination and approval

Lengthy approval processes

While natural gas storage in itself is an established process across Europe, there is little administrative (and technological – see section 4.1.3) precedent for underground storage of hydrogen.

Approval processes for the preparation of hydrogen storage facilities (in particular caverns, porous storage and aquifers) do not yet follow standardised procedures. They are therefore at risk of becoming very drawn-out and possibly further delayed through gaps in national regulatory and legal frameworks.

The complex nature of the permitting processes further prolongs the lead times of hydrogen storage facilities. Commissioning of UHS facilities may be held up by lasting approval proceedings, so that sufficient capacity is not available when demand emerges.

- By way of example, the approval process through the BNetzA for the first cavern in Germany to be repurposed from natural gas to hydrogen lasted for five months and required an additional expert opinion commissioned by the UHS promoter.
- The approval was further justified with the fact that the cavern was facing technical difficulties in the storage of natural gas. The cavern would therefore have required downtime for repairs and not been available for natural gas storage for a prolonged period in any case, so that the implications for security of supply of natural gas were very limited. It is thus likely that the administrative hurdle would have been even higher for a fully operational cavern[57].

Duality between hydrogen and natural gas storage

The complexity for hydrogen projects is further amplified by a certain level of duality with natural gas.

- Renewable and low carbon hydrogen is often seen as a natural successor to replace natural gas in the long-term or at least benefit from their chemical closeness (both are gases) in the required infrastructure roll-out.
- Indeed, as natural gas consumption decreases, both existing pipeline and storage facilities could in principle become available for repurposing, which would significantly lower the cost and lead-times for their commissioning as hydrogen infrastructure.

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57 Energie & Management (2023): Behörde genehmigt Umbau einer Kaverne für Wasserstoff, available on https://www.energie-und-management.de/nachrichten/recht/detail/behoerde-genehmigt-umbau-einer-kaverne-fuer-wasserstoff-202730;
Energate Messenger (2022): RWE plant Wasserstoffkaverne in Epe, available on https://www.energate-messenger.de/news/222075/rwe-plant-wasserstoffkaverne-in-epe

However, even if natural gas demand decreases, several studies[58] have shown that the need to ensure sufficient levels of natural gas supply and, in fact, high levels of security of said supply will likely remain in the EU over the medium term. The duality between natural gas and hydrogen may therefore persist for several years. This has direct implications for the available infrastructure for repurposing and storage facilities in particular.

As the impact of the Russian war of aggression in Ukraine has shown, natural gas storage facilities are a key enabler of security of supply and will need to continue to underpin the European energy system to guarantee a sufficient level of energy independence[59].

As a result, many currently-used cavities for natural gas will likely *not* be available for repurposing to hydrogen storage any time soon – at least not by the 2030 time horizon. Any capacity increases would therefore need to be covered by new cavities, which as discussed above are subject to longer development lead times and in particular stringent and complex approval processes.

4.1.3 Technological uncertainty

As the first of their kind, UHS promoters currently commissioning projects face technological and therefore cost uncertainty due to the novelty and innovative character of the technologies used for UHS. The sector expects there to be significant learning effects in the future, in particular for large-scale industrial projects – however, the trajectory and magnitude under which these will realise require additional testing on large-scale projects. This further adds to the uncertainty regarding potential future earnings.

While natural gas storage is an established technology, there is little to no experience with operation at an industrial scale and therefore a need for tests of large-scale underground storage of hydrogen.

- The chemical characteristics of the gas will certainly require some key technological alterations. However, with uncertainty on the future supply and demand of hydrogen remaining, this also implies uncertainty around required technical characteristics such as injection and withdrawal capabilities or necessary hydrogen purity levels.
- In addition, hydrogen storage facilities will likely be required to operate in a different mode to natural gas storage due to the different market requirements. Intermittent hydrogen

58 For instance, a December 2023 study from Frontier Economics for GIE title “*Maintaining security of supply while decarbonising our infrastructure with renewable and low-carbon gases*” pointed to a number of challenges associated with managing a cost-efficient energy transition to low carbon renewable gases while equally continue to ensure security of supply for CH4. Amongst others, challenges involve cross-vector coordination, cross-border coordination, an appropriate definition of SoS, governance arrangements for renewable and low carbon gases as well as the need to align incentives for the repurposing of infrastructure.

59 The current regulation ((EU) 2017/1938 of the European Parliament and of the Council of 25 October 2017 concerning measures to safeguard the security of gas supply and repealing Regulation (EU) No 994/2010) anchors these requirements until the end of 2025.

supply will make higher cycling rates necessary, which have not yet been tested at an industrial scale.

While a range of these parameters can be tested and simulated, the precise extent and in particular the associated cost of technological adjustments and steady-state hydrogen storage will only become clear when initial pilot plants have been in operation for a sufficient amount of time.

Indeed, as for hydrogen production, where small-scale electrolysers are nearing commercial viability (technology readiness level of 7 going onto 8[60]), larger-scale electrolysers remain at a less mature stage (5-6) with commercial viability expected, but remaining to be effectively demonstrated once the first projects have been established (today expected from 2025 onwards). UHS storage follows a similar trend – pilot projects have been tested and allowed to demonstrate a high level of maturity, however per definition remaining at a smaller scale. Important learning effects (cost savings, further technological development, efficiency, etc.) will therefore only materialise once projects have actually been implemented.

With existing barriers and slower investment, not only will these learning benefits be unlocked later, but also do their effects compound onto more hesitant investment decisions as higher uncertainty around future cost remains and projects may not be assessed as viable where – in fact – they would be.

In a nutshell, this uncertainty will contribute to the delay in the creation of additional storage volumes with substantial long-term side effects as explained above.

4.2 Efficient delivery of additional storage capacities may be hampered by a lack in coordination and planning at EU level

Even though we observe UHS operators and project promoters taking the risk to invest and commit to additional UHS capacities (as demonstrated by the H2 Inframap pipeline), the market outcome will likely fail to achieve the optimal capacity of storage facilities reported in section 3.

Individual storage operators can only optimise storage capacities based on their insights into the market. Their investment decisions can take into account observable market characteristics – such as the share of renewables in the electricity mix – and specific demands of potential customers they may have obtained through market screening or open seasons.

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[60] The "*technological readiness level*" or TRL is a scale of 1-9 with 1 being lowest and 9 being highest to describe a technology's development from basic theoretical principal (1) to full commercial viability and operation (9). Developed by NASA in the 1970s, it is typically grouped into four stages: Research Concept (1-3), Proof-of-Concept (4-5), Minimum Viable Product (6-7) and Commercial Product (8-9). The European Commission has adapted the TRL concept, quantifying (7) as "system prototype demonstration in operational environment" and (8) as "system complete and qualified., see h2020-wp1415-annex-g-trl_en.pdf (europa.eu).

This information will enable them to estimate local demand for storage and better assess the viability of their business case.

However, as long as key barriers persist, these assessments will remain imperfect estimations and projects that should go ahead (from a social, energy system point of view) in reality do not as the lack of information makes them too uncertain for a good investment case.

- As we have shown above, a key barrier for operators is the absence of a hydrogen price as well as associated valuations of the flexibility and security of supply that UHS can provide.
- The lack of recognition of these values by maintaining complex and lengthy approval processes further contributes to suboptimal levels of investment into UHS.

While in the long-term the market may well end up developing the required economic signals to foster investment on its own, this would almost certainly be too late to appropriately address the challenge of developing an integrated European hydrogen market in time to react and adapt to the climate urgency.

Policymakers therefore need to react and put in place measures that address the barriers and that send appropriate economic signals (or at least *simulate* these economic signals) to support market development. While individual Member state action is needed and valuable, coordination and support on the EU level will be particularly critical:

- Indeed, the optimal storage capacity from a societal perspective in the EU as a whole and in individual Member states separately adds values across a number of dimensions and needs to be assessed as a complex function of numerous variables. As outlined in section 2, not just hydrogen supply and demand, but also links with the electricity system, the costs of storage, the technology utilised and given the natural, geological constraints impact the ideal distribution of storage capacities. Beyond the developments within the emerging hydrogen market, the ramp up of UHS capacities is impacted by the need to hold significant capacities for natural gas storage to ensure security of supply. During the transitory period, storage operators are tasked with coordinating the ramp-up of UHS while maintaining natural gas storage facilities.
- As a result, the optimal outcome presented in section 2 is the result of an implicit merit order of storage costs across Europe, factoring in all other relevant conditions and constraints (which can indeed be quantified and stacked even if the market does not monetise them today). UHS operators cannot be expected to have the necessary market insights and the required internal capacities to carry out system-wide optimisations to ensure that their individual investment decisions are aligned with the societal optimum. This is further amplified by the risk of not receiving monetary compensation for storage sites which provide significant societal benefits, but are not necessarily met with immediate corresponding demand from customers.

Given the integrated nature and climate policy objectives of the European energy system, it is thus sensible to target European intervention early on rather than watching the emergence of a patchwork of individual, possibly disjointed national targets.

5 Targeted intervention will support a more cost-efficient, integrated European energy system

We have shown above that, absent intervention from policymakers, the hydrogen market is at risk of delivering far too little UHS capacity, which in turn curbs benefits – and system cost savings in particular – for the energy system and consumers as a whole.

But swift and decisive intervention can help overcome the barriers we described in the previous sections, and thereby foster optimal investment decisions, contributing to a more cost-efficient, integrated and decarbonised European energy system.

In this section, we present how different measures can accelerate the ramp-up of UHS capacity beyond currently planned projects. All of these measures seek to improve the extent to which the values provided by UHS can be more appropriately reflected in decision-making by storage operators, customers as well as policymakers.

We first present an overview of the proposed roadmap for intervention and then discuss additional detail for each individual measure.

- It is worth noting that the optimal intervention will likely reflect a portfolio of several of the proposed measures rather than a binary choice between one or another.
- Further, the appropriate way to implement each measure (or a combination thereof) across the EU will depend on the progress of the hydrogen ramp-up and the specific market circumstances, including preferences on the exposure to price and volume risk for storage operators / project promoters as well as other characteristics of energy markets and policies.
- Finally, given the provision of regulated third-party access (rTPA) by 2033 in the hydrogen and decarbonised gas market package, some of the proposed measures may only be transitory, and the actual design of measures will have to be driven by the way in which each Member state will choose to implement rTPA[61].

In other words, while the principles underpinning proposed measures and recommendations are valid at both the EU and national levels, one size does not necessarily fit all and specific market design questions will need to be addressed at a later stage and at the appropriate level. To illustrate this, we refer in this report to some of the H2 support mechanisms that are being discussed or implemented today, showing the diversity of mechanisms that could be introduced to apply our recommendations[62].

61 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), https://data.consilium.europa.eu/doc/document/ST-16522-2023-INIT/en/pdf

62 For instance, the use of economic regulation ahead of 2033 could be one possible approach, but not the only one, to further promote UHS. We discuss these in more detail below.

Finally, in our discussion, we primarily focus on the 2030 time horizon as a first important checkpoint, in line with the REPowerEU plan. However, market development will need to continue beyond this point, which makes ensuring continued and consistent support also important over the medium- to long-term.

5.1 A high-level roadmap of proposed measures to support additional and timely investment in storage capacity

The prevalent gap between planned hydrogen storages and the societal optimum will be best addressed through a portfolio of different interventions. The diversity of interventions across a range of measures is required so that the various obstacles outlined previously are each addressed in the most effective manner. Jointly, these measures can ensure that the total storage capacity and its distribution across Member states is as close to the societal optimum as possible.

Hence, we propose the following measures to support UHS going forward:

- Set an **explicit EU-wide target** and ambition for UHS capacity at (temporal) checkpoints, including 2030, to enshrine and **recognise the values of storage** and associated capacity needs in official EU policy (similar to REPowerEU).
- **Address administrative and complex approval processes** to facilitate project implementation.
- Introduce **targeted and tailored support mechanisms** for UHS projects with multiple objectives.
    - **Signalling mechanisms** – such as a UHS “project of common interest” label to formalise support from Member states and facilitate the attraction of third-party investments.
    - **Support mechanisms** – to support financing explicitly and reduce potential funding gaps for storage projects (e.g. financed by ETS revenues similar to the Innovation Fund programme, via existing mechanisms like CEF, but could also be via low/zero interest loans from public financing bodies).
- **Monitor the market** via the regular (e.g. annual) assessment of a range of EU-wide KPIs on both the pipeline of projects of planned/commissioned capacity and UHS needs, fostering the agility to react to possible changes in market needs and the wider system environment.

Any intervention to support UHS should and can never be implemented in an isolated vacuum: we have previously shown how UHS is not only closely-linked to the rest of the H2 value chain, but also to the wider energy system and the electricity sector in particular. As a result, the **implementation of the proposed measures needs to be consistent with wider policy**

objectives[63] and mechanisms on the development of the H2 market[64] as well as on the transition of the energy system as a whole.

More generally, we focus our discussion on measures that could be implemented by policymakers to support the UHS sector. In addition to these, other, market-based or "hybrid" instruments may emerge that could also drive a more explicit recognition of the values of UHS. For instance, these could involve the development of more complete flexibility markets for electricity grids, which may in turn also drive the development of "new" hydrogen business cases such as electrolyser + storage bundles.

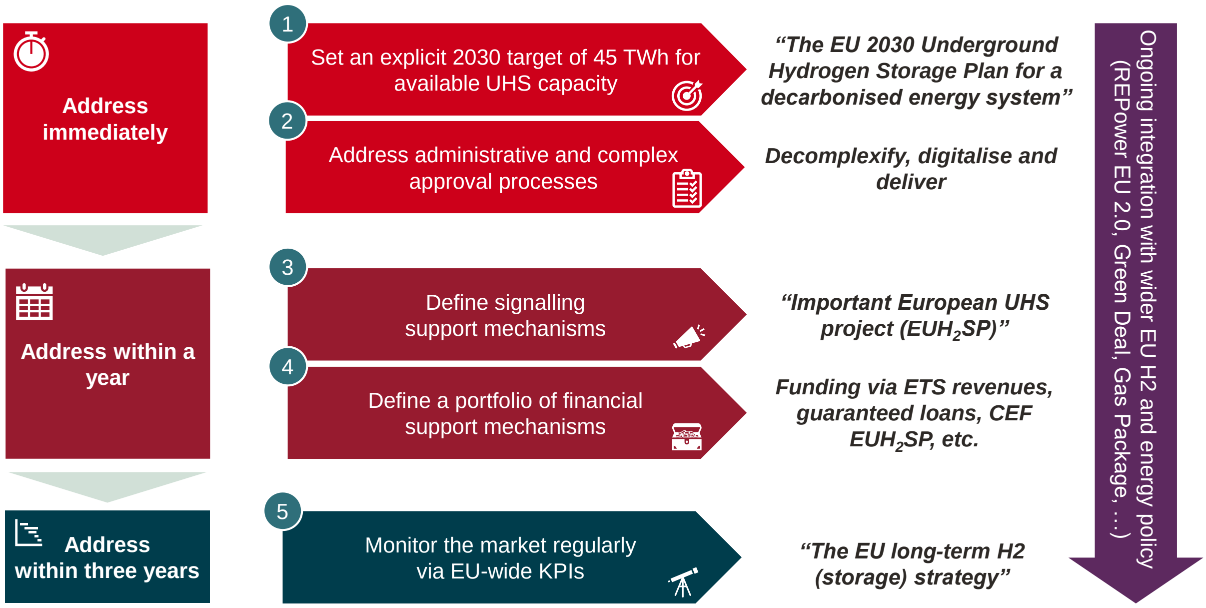
It is for this reason that, as we have pointed out repeatedly, a system-wide approach will be best-suited to obtain the most efficient and resilient European energy system in a net zero world.

In our roadmap, we group measures into three categories:

- Those that should be addressed immediately;
- Those that should be addressed within a year; and

  Those that should be addressed within the next three years (e.g. because they require some legislative changes)

Figure 23 Roadmap of proposed measures to promote investment into additional UHS capacity



Source: Frontier Economics

63 E.g. on further support of RES generation

64 E.g. on storage obligations, minimum filling-levels or strategic reserves – similar to what exists for natural gas across a range of EU countries.

We describe each proposed measure in more detail below.

5.2 Measures which need to be implemented immediately

5.2.1 Set an explicit 2030 ambition of 45 TWh for available UHS capacity

Why is a target useful?

Setting an explicit, aspirational target for UHS capacity should be front and centre of European hydrogen and energy policy. A target will

- Provide a clear and effective signal to the entire energy system and associated investment ecosystem;
- Acknowledge the values and benefits provided by underground hydrogen storage to the system;
- Create a focal point for potential hydrogen end users.

In other words, a target will **provide assurance that policy makers are aware** of the need to provide sufficient hydrogen storage capacities not only to secure a continuous supply of hydrogen, but also support the electricity system via the interlinkages from electrolysis and hydrogen turbines (in the future). Uncertainty around the demand, and indeed needs for storage can be reduced, which, alongside a combination of other types of interventions, can ensure a more efficient outcome for the European energy market.

Additionally, joint European targets **facilitate coordination** between market participants.

- As set out above, absent a clear price signal, project promoters and investors only have access to imperfect information and likely only capture a partial valuation of the true social (and private) benefits provided by their projects to the system.
- This asymmetry in information and lack of opportunity for coordination between market participants will in turn lead to inefficient underinvestment.

While a target does not fully replace a price signal, it does go a long way to “simulate” a signal on the market’s need for storage – in particular in a nascent immature market environment. The target will act as a signpost in the market, encouraging investment and coordination at an appropriate scale and pace, thereby facilitating the development of a common European market.

Finally, jointly with explicit targets for the ramp-down of natural gas storage capacities, European UHS targets can also **facilitate the transition** from fossil to renewable security-of-supply reserves. Coordinated targets between natural gas and hydrogen storage ensure that sufficient underground storage capacities are available to be repurposed for hydrogen while equally maintaining security-of-supply for methane. Storage operators are thereby enabled to plan the (de-)commissioning of their assets accordingly and provide capacities to the market as and when they are needed, while overall energy policy consistency is also guaranteed[65].

Setting the target value

We would recommend that the **2030 EU UHS capacity target should be set at the optimal, system cost-minimising UHS capacity of 45 TWh** as determined by our modelling (presented in section 2 above). This would maximise the benefit of achieving the target for European energy consumers, at c. 32 billion euros over 20 years (as detailed in section 3 above).

- While this target is likely ambitious given both the currently planned projects and lead times associated with any new UHS projects, it would serve as an unambiguous signal on the importance of the need for UHS in a decarbonised and efficient integrated European energy system, and on the urgency associated with developing further UHS project across the Union.
- A 45 TWh target will also serve as a useful checkpoint for the market monitoring and will help to identify and assess both the development trajectory and potential remaining gap in UHS capacity once 2030 is here. In turn, this will allow to react swiftly and implement any further support mechanisms – should these be required. After all, 2030 will likely not be the future steady state of the energy system, but rather a first milestone that will provide increased clarity on the relative importance and system needs on the way to net zero.

Concretely, the target could be implemented in a wider EU plan on UHS similar to the REPowerEU plan (alongside several others of the measures proposed here) and could then subsequently be formalised in EU legislation, which could include the hydrogen and gas market package[66] or specific regulations such as the regulation on the deployment of alternative fuels infrastructure[67] or wider energy policy regulation like TEN-E or TEN-T[68].

Why we need formal recognition of the five values alongside the target?

The definition of a target will also allow policymakers to formally recognise and enshrine the five values of storage in their policymaking. Current market outcomes (i.e. the currently

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65 Indeed, the aforementioned Frontier Economics study for GIE on the need to maintain security of supply for CH4 throughout the energy transition clearly demonstrates that coordination of intervention will be key in order to ensure that significant investment risks can be mitigated and the ramp-up of the H2 market realised as efficiently as possible.

66 European Commission (2023): 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).

67 European Commission (2023): REGULATION (EU) 2023/1804 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the deployment of alternative fuels infrastructure, and repealing Directive 2014/94/EU.

68 REGULATION (EU) 2022/869 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 30 May 2022 on guidelines for trans-European energy infrastructure, amending Regulations (EC) No 715/2009, (EU) 2019/942 and (EU) 2019/943 and Directives 2009/73/EC and (EU) 2019/944, and repealing Regulation (EU) No 347/2013; REGULATION (EU) No 1315/2013 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 11 December 2013 on Union guidelines for the development of the trans-European transport network and repealing Decision No 661/2010/EU (currently under revision)

planned projects based on H2 Inframap data falling very short of system needs) and associated lack of explicit policy support clearly demonstrates that these values are not widely known today or appropriately reflected in decision-making across all levels.

Similarly to the explicit ambition for a target UHS capacity, recognising the values and system benefits formally will deliver both, an important signal to investors, project promoters and storage operators and also further support market development and integration.

In other words, the definition of storage business cases will be able to more appropriately reflect the whole spectrum of the storage value dimensions and more generally reinforced, on the back of an explicit acknowledgement of the values in EU and national energy policy. Recognising the need for storage on the back of the values will drive quantification and ultimately monetisation, bringing the storage sector as well as the whole H2 ecosystem much closer to a world with clear and liquid price signals.

Recognising the values and benefits from UHS will go hand-in-hand with an explicit ambition on a target UHS capacity. The values motivate the need of storage and ultimately justify the place that UHS should take in an integrated energy system.

5.2.2 Facilitating administrative and complex approval processes for UHS

While intervention focused on signalling effects to the market (like the capacity target and the recognition of values) is an important first step, these measures will likely become most impactful over the medium-term only, i.e. as investment decision-making evolves and new projects are developed.

- However, storage operators and project promoters also face a number of operational barriers today, which means that projects face longer than necessary lead times, even where a favourable investment decision was already taken. As a matter of fact, a number of storage operators have already developed plans for additional projects, which could progress swiftly once these barriers are resolved.
- In particular, given the novelty of UHS, no standardised procedures are in place for the administrative processes in the lead-up to the commissioning of storage sites. Similarly, the necessary legislative frameworks are yet to be finalised.
- As a result, projects hurt themselves at complex administrative processes, often handled by different, and not joined up authorities, which place both an unnecessarily high workload for the development of requests for approval on project developers and also lead to inefficient delays in the run-up to project commissioning.

Addressing these processes and simplifying the administrative hoops that projects need to jump through for approval should therefore be a key focus for policy intervention looking to support the increased development of UHS.

In a nutshell, the following principles should be reflected when developing updated approval processes:

- **Decomplexify.** Administrative processes should be transparent and well-understood by all stakeholders and project promoters. This will not only allow to simplify the workload for UHS operators that will be in a position to plan and anticipate better, but also ultimately support investment and third-party support as the probability of getting approval (or not) will be better understood and easier to estimate upfront.
- **Digitalise.** Increasingly moving approval processes into the digital space will further increase transparency and can also speed-up the treatment of requests by being able to use standardised templates that can be assessed (at least at an initial stage) automatically. Digitalisation can also support increased alignment of processes across Member states and support market integration for both the actual projects and third-party support and investment (e.g. by systematically proposing an English-speaking interface).
- **Deliver.** Administrative approval processes can be handled on an isolated standalone basis, with the sole focus being put on assessing the specific project landmark at hand (building permits, environmental impacts, etc.), in a rather disjointed manner across the various approval processes a project will need to go through. Instead, the assessment and approval of administrative process should be integrated with the wider policy objectives and focused on *delivering* the projects. Increased integration and supportive documentation on the process as a whole to ease the burden on operators and investors should allow to significantly improve the lack of coordination currently faced by projects[69].

For the avoidance of doubt, decomplexified, digitalised and delivery-focused administrative processes should not renege on the requirements for projects to comply with environmental needs or the respect of biodiversity, quality-control or best practice. Sustainability is a key dimension of a truly decarbonised energy system and can and should not be put aside for the benefit of increasing the speed of infrastructure delivery.

Nevertheless, any available margins of improvement should be exploited to ensure that friction from these administrative processes is kept to a minimum. We note in this context, that there is indeed a relevant track record for such an approach, as projects that qualify of the PCI label already benefit from sped up and simplified administrative approval processes today. An immediate first step could therefore be to simply extend these dispositions to UHS projects (possibly combined with an adjustment of the PCI assessment process for UHS as well).

5.3 Measures to be implemented within a year

5.3.1 Define signalling support mechanisms for UHS

Similar to the explicit storage target and recognition of values in a global European plan for UHS, specific support mechanisms can serve as important signals to the market. In practice, these mechanisms would serve as important complements to the signals on overall market

69 For instance, this could involve more continuity between different stages of the overall approval process, the possibility to easily transfer relevant information on the project as well as ensuring consistency of demands placed on projects to achieve compliance with the various administrative requirements.

development (associated with e.g. the capacity target) as they would allow to select and support *specific* flagship projects within the emerging UHS market.

We note that similar support mechanisms already exist in the EU energy policy landscape today. These are notably the “Projects of common interest” (PCI) or “Important Projects of Common European Interest” (IPCEI), with the latter being directly associated with financial support from Member states.

As a result, the PCI label in particular as well as the underlying TEN-E regulation would be natural stepping stones to more explicitly support UHS projects and foster investment. It is worth noting that improved support for UHS does not necessarily require a complete overhaul of the existing mechanisms, but could already be achieved by amending specific aspects of the methodologies used to assess candidate projects[70].

For instance, possible intervention could include the following:

- **Reviewing the PCI assessment methodologies** to appropriately reflect the properties of UHS and specific benefits brought to the system through storage. During the 6th PCI process (the first under the revised TEN-E regulation), substantial uncertainty amongst storage operators was caused through the missing explicit representation of storage in the assessment process.

  In the end, PCI status was awarded to seven storage projects only – of which only four plan to be operational by 2030 based on the Inframap dataset. The four projects cover a capacity of about 800 GWh – less than 15% of the total planned projects for 2030. In addition, several flagship UHS projects unsuccessfully applied for PCI status and can therefore not benefit from the signalling effects associated with being labelled as a PCI. We understand that the key reason for not being retained for PCI status lies in the inability of the CBA and project assessment methodology that were used to appropriately reflect the flexibility and security of supply benefits that would nevertheless have been vital for the energy system.

- Alternatively, **a separate “PCI-type” qualification specifically focused on UHS** and less bound to the physical connection of Member States could be implemented to support the sector.
  - This programme, which could be labelled “Important European UHS project” (EUH_2SP), could for instance be linked to the 2030 ambition for a target capacity.
  - Most crucially, this separate qualification would not be associated with a strong focus on cross-border integration or, indeed, geographic closeness of a given project to an interaction point, which imposed a first strong filter and pre-emptively excluded a range of strategic and important storage projects from the ability to be labelled as a PCI.

70 Indeed, UHS projects are already eligible for the PCI label.

- In addition, other KPIs (e.g. inspired by the existing PCI KPIs, such as the reduction in GHG emissions or the reduction of price volatility for hydrogen and/or electricity in a specific bidding zone) to select and support the projects that best address the needs of the energy system as a whole could be used as a complement. Some of these proposed KPIs are presented in the table below.

Table 5 Proposed KPIs that could address the shortcomings in the CBA methodology used to assess projects for the 6th PCI list

Value	Proposed KPIs	Corresponding benefit in existing PCI methodology
System Value	Levelised cost of hydrogen (LCOH)	B2: Social Economic Welfare for hydrogen sector
Arbitrage Value	Share of hydrogen supply routes, Electrolyser load factor	
Insurance Value	Hydrogen production capacities	B5: Reduction in exposure to curtailed demand
Kick-start value	Investments in on-site renewables and electrolysers	B3: Renewable Energy integration
Environmental value	Carbon footprint of hydrogen, avoided RES curtailment	B1: Societal benefit due to GHG emissions variation

Source: Frontier Economics

As for the standard PCI, this would allow to reflect both the whole systems view and could also feature improved and simplified administrative approval processes. For overall consistency, the *EUH_2SP label* could be linked to a specific funding mechanism to also directly address the risk of underinvestment.

5.3.2 Defining storage-specific financial support mechanisms

As previously demonstrated, additional public funding may be needed to improve the viability of socially-desirable business cases, especially in the short-term where information remains imperfect and price signals are missing.

During the ramp-up of the decarbonised energy market, funding for UHS is needed to overcome potential market failures arising from **uncertain and unstable business cases** in an emerging hydrogen market (that is politically desired). Public support may also be necessary to compensate for societal benefits provided through UHS which are at risk of not being fully captured by UHS operators or their customers (e.g. such as improvements in security of supply).

As the precise shape, form and future of all the parts of the emerging H2 value chain remain uncertain, the exact requirements for UHS cannot be predicted today. Combined with the inherent uncertainty associated with the new technologies employed for UHS, a substantial financial risk from the operation of storage sites persists and may hinder investments. Projects that would be commercially viable are at risk of not being realised.

A range of different of support mechanism types could be designed to create an appropriate level of certainty on price and volume of UHS to enable sufficient prospects of investment recovery and long-term remuneration for promoters. By way of example, **government investment guarantees**, the introduction of **a merchant market with a backstop**[71] or **subsidies to UHS end-users** could create additional certainty for investors:

- Through actively taking a stake in UHS projects through a **guarantee** and particularly through taking on a share of the investment risk, governments can effectively decrease the uncertainty promoters are facing. Similarly, long-term bookings through governments (for example to ensure security of supply) could create additional certainty for storage operators.
- In a **merchant market model** with a set backstop, UHS promoters operate under similar conditions as when supported through a revenue floor. The backstop introduces a minimum return for UHS projects, creating certainty with regard to the projects commercial viability.
- **Subsidies to UHS end-users** can indirectly create additional certainty for UHS operators. Funding available to end-users will encourage and likely increase demand for UHS, alleviating uncertainty regarding the utilisation of projects and the attainable revenues.

The funding provided would help overcome the market failures outlined above and ensure that storage capacities which provide benefits to the energy market are indeed commissioned. This would pave the way for the transition in the mid- to long-term to steady-state regulation and market-based intervention.

Additionally, as long as the future energy market has not reached sufficient maturity and a long-term steady-state, the benefits associated with certain values from UHS may not be unlocked. For instance, without a robust market price for renewable and low carbon hydrogen, market participants will not be able to benefit from arbitrage opportunities. As a result, they will not compensate UHS operators for providing the opportunity to do so.

Hence, during market ramp-up, financial support mechanisms could address issues arising at both the technological or commercial level. Potential funding could be provided in the form of **R&D/demonstrator support** or through **short-term funding support,** which help to overcome initial uncertainty during the ramp-up. For example, this type of funding could take the form of **lump-sum payments** (such as these delivered via the Innovation Fund that is

[71] In this case, the market is predominantly left without regulation. However, a minimum level of return is introduced to « backstop » a certain degree of volume and price risk that projects are protected against.

financed via ETS income) or **fixed premia associated with certain volumes** (such as those provided via the EC's RFNBO auction for electrolysers).

In summary, financial support would always be linked to an analysis of the costs of financing and operating new UHS projects. In other words, support would be required where expected commercial revenue does not allow to cover at least lead Capex, fixed Opex and an appropriate level of return (cost of capital) – noting that the financing gap may either arise because commercial revenue and associated market value are uncertain and/or because the technology may not yet be competitive compared to a fossil alternative.

For the avoidance of doubt, it is worth noting that we include both "*funding*" as well as "*financing support*" measures in this category. Indeed, proposed financial measures can both provide direct financial support (just like the example measures presented in the previous paragraphs) and/or improve the access to financing as well as associated cost of capital for a project, e.g. by reducing the financial exposure to a certain number of financial risks. The measures presented in the following sub-section represent a combination of both types of financial support mechanisms.

Specific financial support mechanisms already considered for UHS projects

More recently, we have observed specific mechanisms that are used in various countries to financially support hydrogen projects. Primarily these are:

- The introduction of a **minimum revenue floor** by the Department for Energy Security and Net Zero (DESNZ) in the UK;
- The potential introduction of **contracts-for-difference ("CfDs")** in Germany.

We present both approaches in more detail below.

Revenue floors for UHS operators

Revenue floors can be set by regulators to ensure commercial viability of projects, for example during the ramp-up phase of a new market. In a nutshell, they ensure that projects receive a minimum revenue, irrespective of the actual utilisation and market revenues earned – in other words, the mechanism removes a significant degree of volume (and price) risk. Through ensuring this minimum return, barriers to investment decisions resulting from uncertainty regarding market developments can be overcome.

This type of funding support is commonly designed to ensure that the subsidies provided cover the project's CAPEX, fixed OPEX as well as a set return on capital investment. The floor thus ensures that the overall business model is viable to begin with as well as that the project can remain operational across its lifetime.

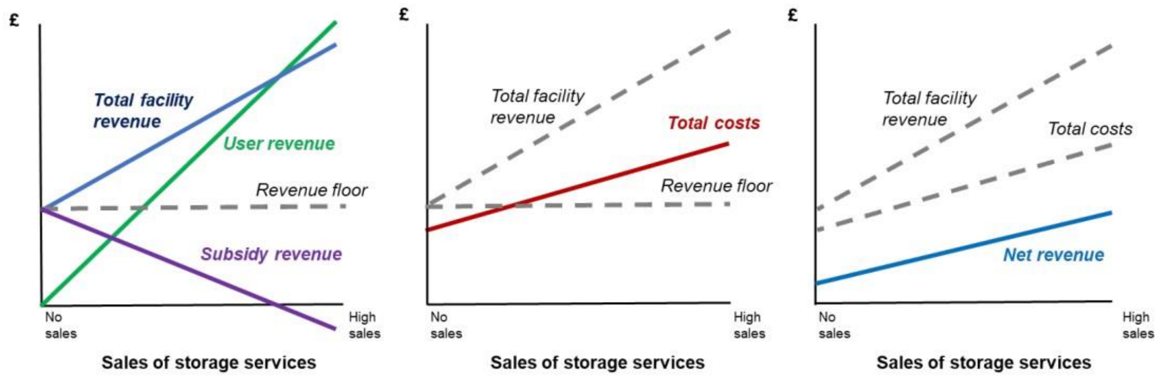
The concrete subsidy amount paid out thereby depends on the actual revenues achieved by the project on the market:

- If the facility was not used at all and no market revenues were generated, the subsidy provider would pay sufficient subsidies so that the revenue floor is covered
- As market revenues obtained from users increase, the subsidy amount decreases proportionally.

Revenues and therefore subsidy payouts are commonly assessed over a longer period of time (such as a full business year) to account for potential cyclicality of demand and therefore revenues achieved on the market. Revenue floors are commonly guaranteed for a significant duration of the operating lifetime of the respective asset. This ensures that promoters are provided with sufficient certainty to take investment decisions, particularly in emerging markets.

As promoters do not receive a fixed payment but rather a guaranteed minimum return, revenue floors still encourage operators to continue to engage in revenue-maximising behaviour. Capturing market demand to generate additional revenue remains beneficial for operators even with a revenue floor in place, as Figure 24 illustrates.

Figure 24 Illustrative revenue floors and sales incentive



Source: DESNZ (2023), Hydrogen transport and storage infrastructure: Minded to position.

Revenue floors can be further refined to ensure smooth operation of the market and an efficient allocation of subsides. By way of example, an availability factor can be incorporated into the revenue floor to ensure that capacities which receive funding are actually available to the market.

Similarly, mechanisms to participate in the upside achieved by particularly successful facilities (with high revenues) which received funding through the subsidy can be included. This “clawback” mechanism could take different shapes, such as.

- a cap on total revenues paid by the subsidy provider;
- a gainshare arrangement between the project and the subsidy provider;
- an equity stake for the subsidy provider to receive potential upsides as dividends

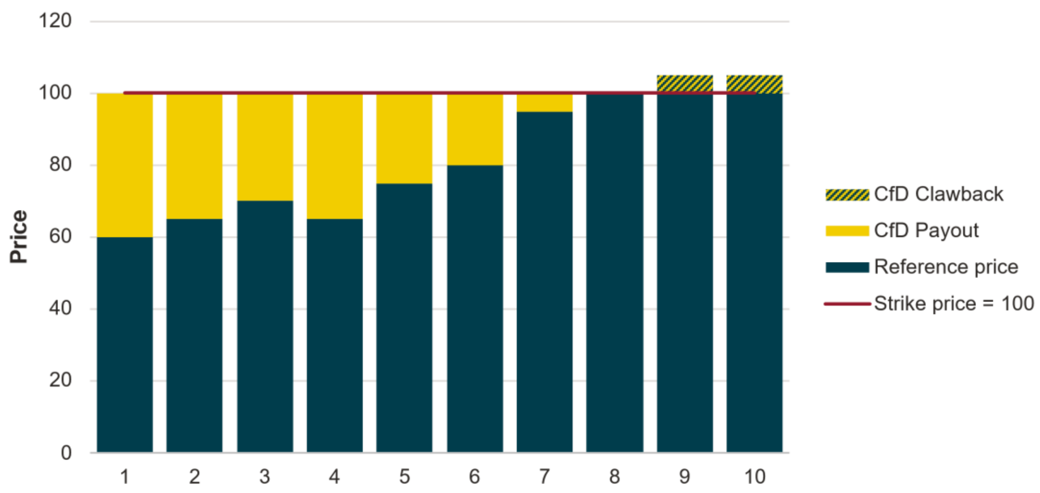
Introducing a revenue floor for UHS can lead to substantial benefits. Through guaranteeing a minimum return, UHS promoters can be provided with the certainty necessary to take investment decisions promptly. Jointly with an explicit target for UHS capacity, this would not only accelerate the ramp-up of the UHS market, but also ensure that sufficient capacities are available in the medium and long term.

Contracts-for-Difference Model for UHS projects

Contracts-for-Differences (CfDs) are an instrument available to governments to hedge private entities against volatile or uncertain market revenues. The contracting authority guarantees to reimburse the difference between a set price and the actual or expected revenues achieved by the entities on the market where these are lowered than the reference price. In contrast, if the actual revenues exceed the set price, authorities can claim the premium obtained by the partner ("clawback"). CfDs thus present a de-facto revenue guarantee for the affected parties.

The CfD strike price forms the key element of the measure. It is set such that suppliers are able to operate (sufficiently) profitably, but efficiently. There are various potential approaches to determine the price, including benchmarking processes among all beneficiaries or cost-plus methodologies.

Figure 25 Overview of the CfD mechanism



Source: Frontier Economics

CfDs are particularly appealing in nascent markets (such as hydrogen), which are inherently prone to a higher degree of uncertainty with regard to market size and efficient price signals. Under these conditions, a regulatory authority is well-placed to ensure that sufficient volumes are provided to the market and providers operate profitably at the same time.

For UHS, CfDs present an opportunity to accelerate the market ramp-up. A European target for storage capacity can enable national regulatory authorities to support numerous projects through CfD schemes. Storage operators are thereby provided with additional certainty regarding their projects' financial viability, while the availability of sufficient storage volumes to the market is ensured. In a recent position paper[72], the association of German gas and hydrogen storage system operators (INES) has therefore proposed the introduction of a CfD based support mechanism for hydrogen storage in Germany.

The optimal definition of a financial support mechanism will depend on precise policy objectives and risk appetite

In a nutshell, funding would look to attach an explicit monetary value to the various ways in which underground hydrogen storage supports the European energy system. Efficiency, sustainability and sovereignty would be rewarded where these values may not (yet) be sufficiently reflected in the default revenue streams that projects would receive from customers.

Prospectively, legislators can draw from the toolbox that has been effective in ensuring the continued contribution of underground natural gas storage to the security of supply in the EU energy system. Specific policy instruments at EU and national level can then be combined according to specific circumstances.

As noted before, the ultimate design of each measure, will also depend on the specific degrees of risk-sharing and risk exposure that policymakers and project promoters are looking to implement. For instance, the various measures set out above all deliver significantly different levels of exposure to volume risk, which could in turn different target levels of profitability – the specific optimal solution will as a result depend on circumstances and longer-term regulatory policy objectives that are set by each Member state.

Finally, we recall that support for UHS could also come from the development of additional market-based measures on both the hydrogen, but also the electricity side. For instance, the further development of remuneration mechanisms for providing (various durations) of flexibility on the electricity side (possibly with public funding as a complement to enhance the competitiveness and viability of business cases) can also promote increased investment into UHS projects and could even lead to the development of new business models, such as a combined electrolyser + storage facility.

5.4 Measures to be addressed within three years

5.4.1 Ongoing market monitoring

Finally, any intervention needs to acknowledge that the hydrogen market and indeed the energy system as a whole are in a state of flux with several different trajectories for future development as of today. The realisation of one or another of these trajectories will depend

72 INES (2023): Positionspapier – Vorschläge für einen Marktrahmen zur Entwicklung von Wasserstoffspeichern.

on both investment decisions, but also technological developments or EU and national political direction.

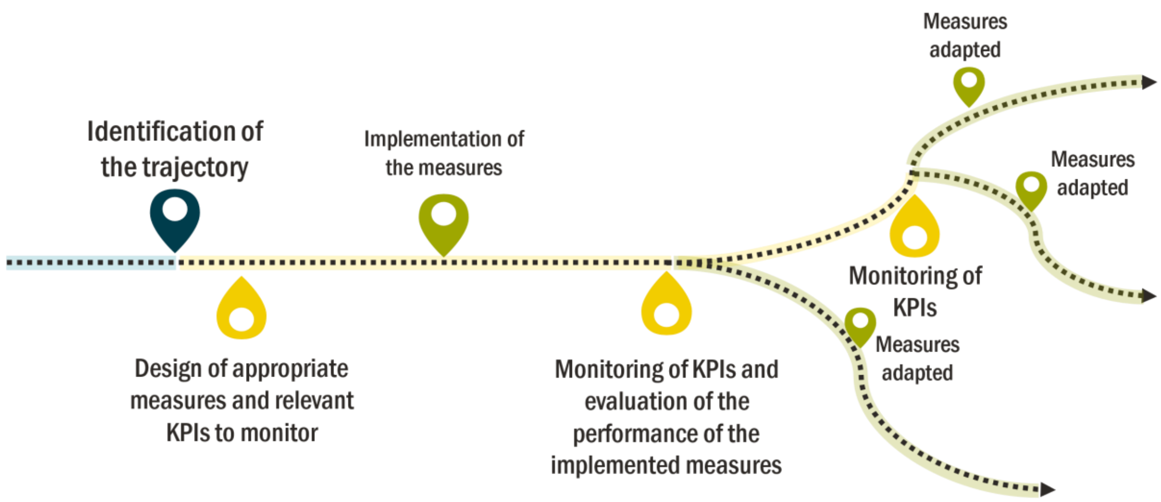
As a result, it will be important to ensure that any intervention is not set in stone, but remains optimised in relation to the actual market environment and risks and barriers that are effectively faced by UHS project at a specific point in time. Remaining flexible to adapt policy support will ensure that the most efficient projects are realised (with respect to the target) and that both inefficient underinvestment as well as overinvestment are avoided, which will ultimately benefit system costs and European consumers.

Market monitoring is a helpful tool in this context. For UHS specifically, market monitoring could feature a range of key performance indicators, which, when assessed regularly, would subsequently serve as a basis to possibly adjust the support strategy. These KPIs could cover:

- Overall UHS capacity available (possibly with respect to the 2030 target)
- Number of projects per Member state
- Pipeline of projects
- Average project lead times to commissioning / supply chain stress indicators
- Ratio of H2 storage capacity to H2 production capacity and imports where relevant[73] (on EU level and on Member State, or even electricity bidding-zone level).
- Ratio of H2 storage capacity to H2 demand (on EU level and on Member State level)

The figure below presents a stylised overview of how the intervention strategy could be adapted and assessed over time.

Figure 26 Exemplary overview of a long-term monitoring process



Source: Frontier Economics

[73] We note that some countries will structurally remain net-importers. For the Member State or bidding-zone level, an assessment including imported volumes may therefore be more relevant.