Artelys | OPTIMIZATION SOLUTIONS

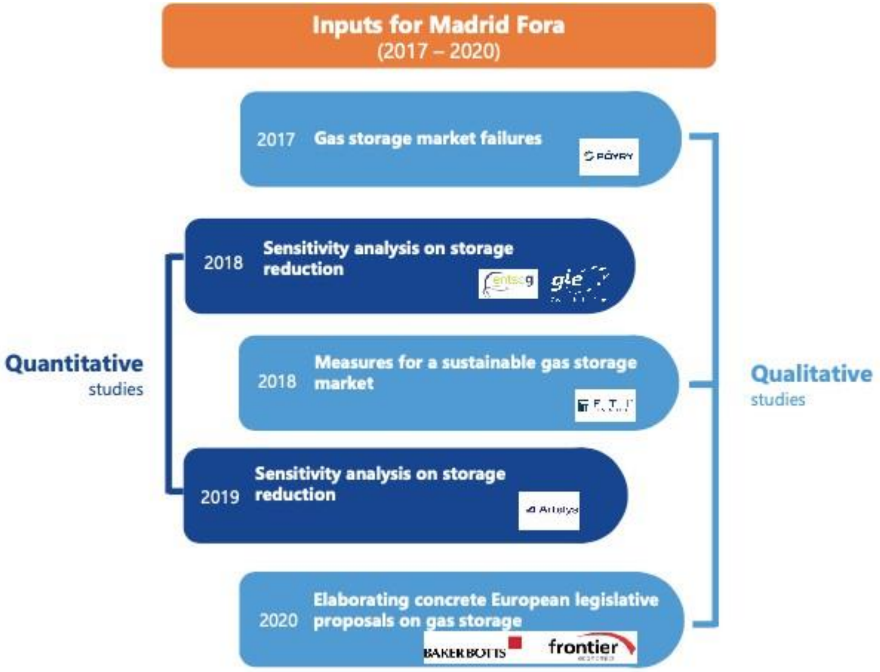
Gas Infrastructure Europe

Showcasing the pathways and values of underground hydrogen storages

Final report

September 2022

Objectives of the study



GSE has identified the need for a robust assessment of the role underground hydrogen storage can play in the European energy transition.

This study has two key objectives:

1. Identification and description of the **values** of underground hydrogen storage, and notably the identification of services that are specific to hydrogen storage,
2. Quantitative **evaluation of the benefits** brought by underground hydrogen storage in a series of four territorial use-cases.

The results of this study can inform the design of policy recommendations, and their respective priorities, to support the emergence of underground hydrogen storage that can help kick-start the hydrogen ecosystem.

Contents

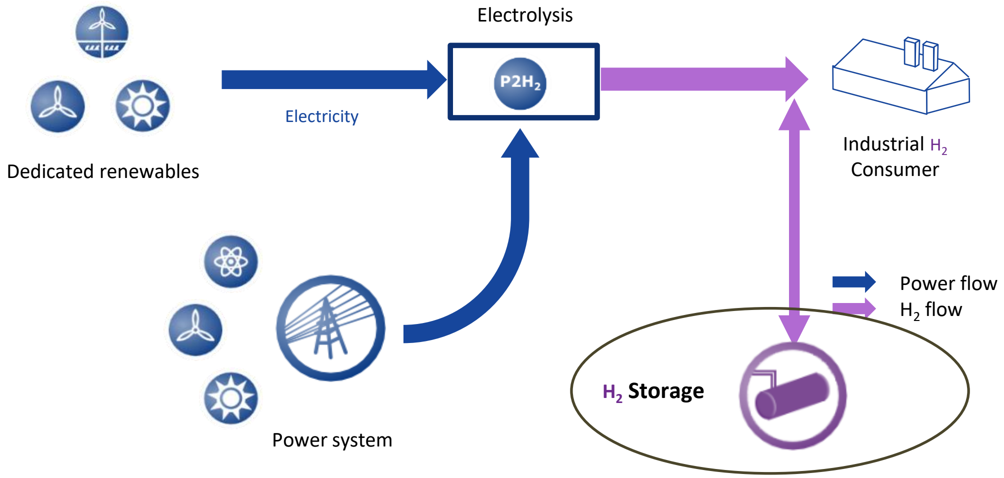
Executive summary (1/2)

- Hydrogen storage is a **key enabling technology** required for the emergence of a hydrogen ecosystem, as it provides an essential bridge between variable electricity supply options (dedicated RES and grid withdrawals) and the dynamics of hydrogen demand.
- **More precisely, five values of hydrogen storage** have been identified in this study, each corresponding to a set of services that hydrogen storage brings to the entire energy system, including from a cross-sectoral perspective:

Arbitrage value	Ability of storage assets to make a better use the cheapest hydrogen sources in competitive markets, reducing the consumers' exposition to the volatility of prices.
System value	Ability of storage assets to avoid over-investments in other infrastructure elements, across the entire energy sector, to ensure the energy demand can be met in a secure and efficient way.
Insurance value	Ability of storage assets to ensure sufficient volumes and injection rates are available to end-uses subject to uncertain demand levels (e.g. H2 turbines, H2 heating technologies).
Specific to H2 Kick-start value	Ability of storage assets to optimally size investments in RES capacity in order to comply with transition targets, thereby facilitating the emergence of an hydrogen ecosystem.
Specific to H2 Environmental value	Ability of storage assets to help avoid electric redispatch and fossil-based hydrogen production and to avoid RES curtailment.

Executive summary (2/2)

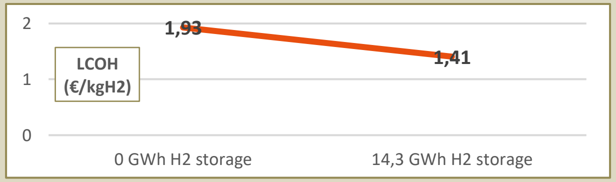
- **Four territorial use cases** representing different configurations of **local hydrogen ecosystems** have been analysed. The use cases differ by the hydrogen supply options, consumer profiles, connection to networks, and geographical locations. The **analysis** reveals **the various services** that hydrogen storage provides.



One of the four territorial use cases considered in the study:
On-site green hydrogen production for an industrial consumer

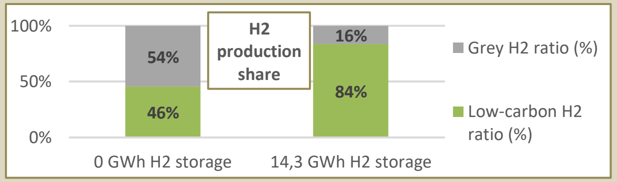
System value

Hydrogen storage enables to better use the cheapest hydrogen sources and to decrease full cost of hydrogen production.



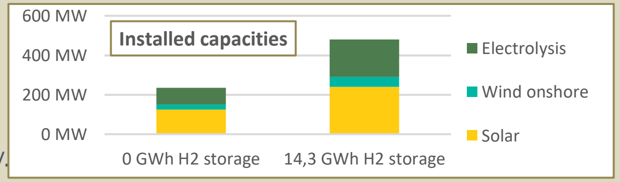
Arbitrage value

Hydrogen storage fosters renewable hydrogen production by allowing a better use of local RES resources.



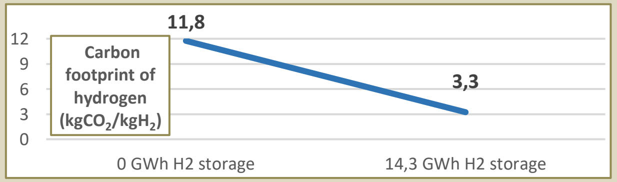
Kick-start value

Hydrogen storage allows for a system-level optimization of electrolysis and RES sources, facilitating the emergence of a hydrogen economy.



Environmental value

Hydrogen storage allows the system to withdraw decarbonised electricity for hydrogen production, thereby reducing carbon emissions.

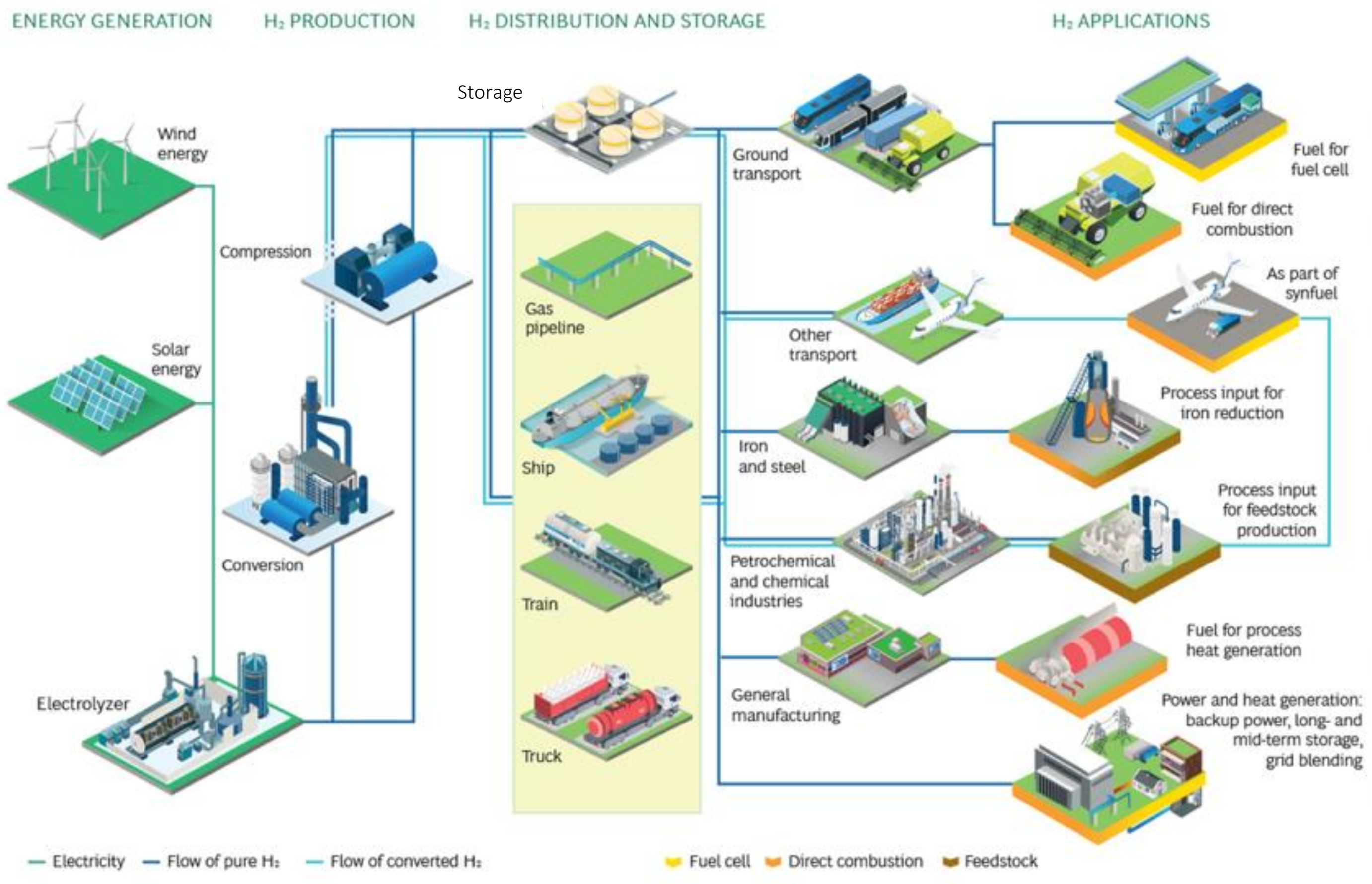


The full results are available in Section C (including the assessment for the insurance value)

Contents

The role of hydrogen in the future EU energy system

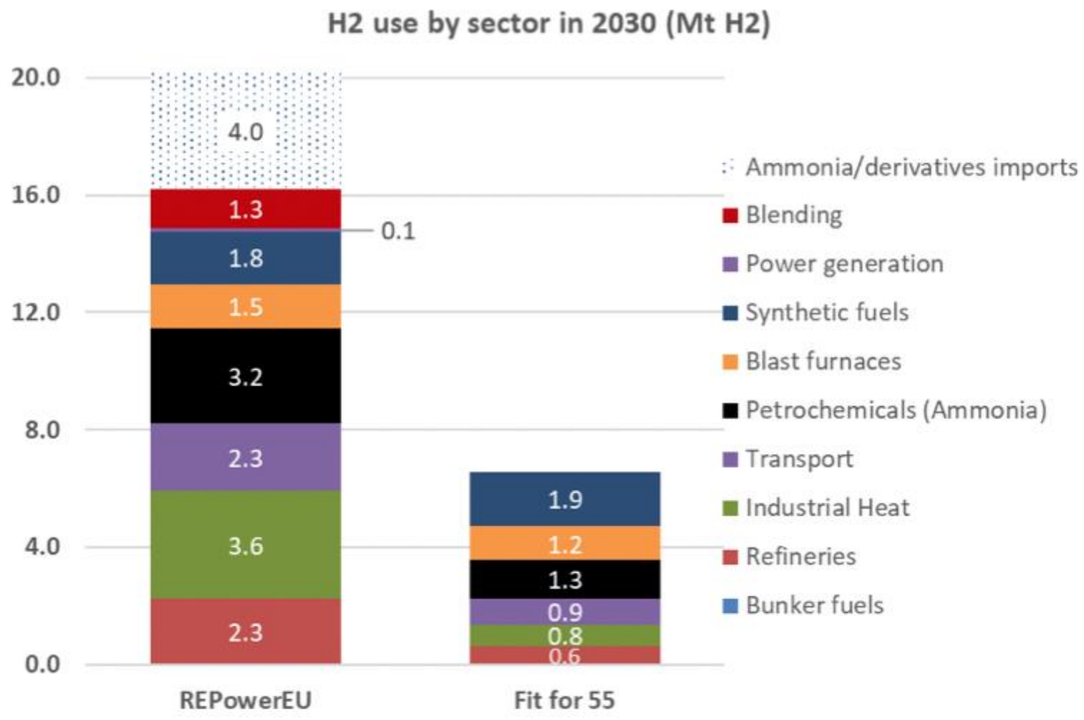
- Hydrogen is an essential building block of a decarbonised future
  - Whilst it is recognised that energy efficiency efforts and the development of renewables will play a major role in the decarbonisation of the European economy, a number of end-uses will need to use renewables gases or renewable fuels to abate their emissions.
  - Hydrogen is one of the most promising options to decarbonise hard-to-abate sectors such as long-haul trucking and shipping, aviation, maritime, fertiliser industry, steel making, etc. and could also play a role in heating and power generation. The emergence of hydrogen could be facilitated by the repurposing of part of the existing gas infrastructure.
  - Electrolytic hydrogen is one of the solutions well suited to provide flexibility to the energy system, via e.g. smart management of electrolysers, storage assets directly connected to the electricity grid, or the use of hydrogen in H2-fired turbines for power generation.



Source: BCG analysis

What is the outlook for hydrogen in Europe?

- The need to rely on hydrogen to reach the EU energy and climate objectives has been robustly established
  - The European Commission’s Hydrogen Strategy recognises that hydrogen will play a key role in decarbonising hard-to-abate sectors.
  - In the scenarios underpinning the Climate Target Plan, the European Commission foresees an important role for hydrogen, through a deployment of circa 500 GW of electrolysers in Europe by 2050 (see figure).
  - The REPowerEU plan proposed by the Commission considerably increases the level of ambition for 2030 compared to the Fit-for-55 package, with 65 to 80 GW of electrolysis capacity being required to help meet a projected demand of 16 Mt of hydrogen (of which 6 Mt will be imported according to the Commission’s analysis).
  - Harnessing the flexibility of the infrastructure, and of underground hydrogen storage in particular, will be key to deliver energy and climate targets in a cost-efficient and secure way, be it in areas close to offshore wind projects or in areas with high solar potentials.

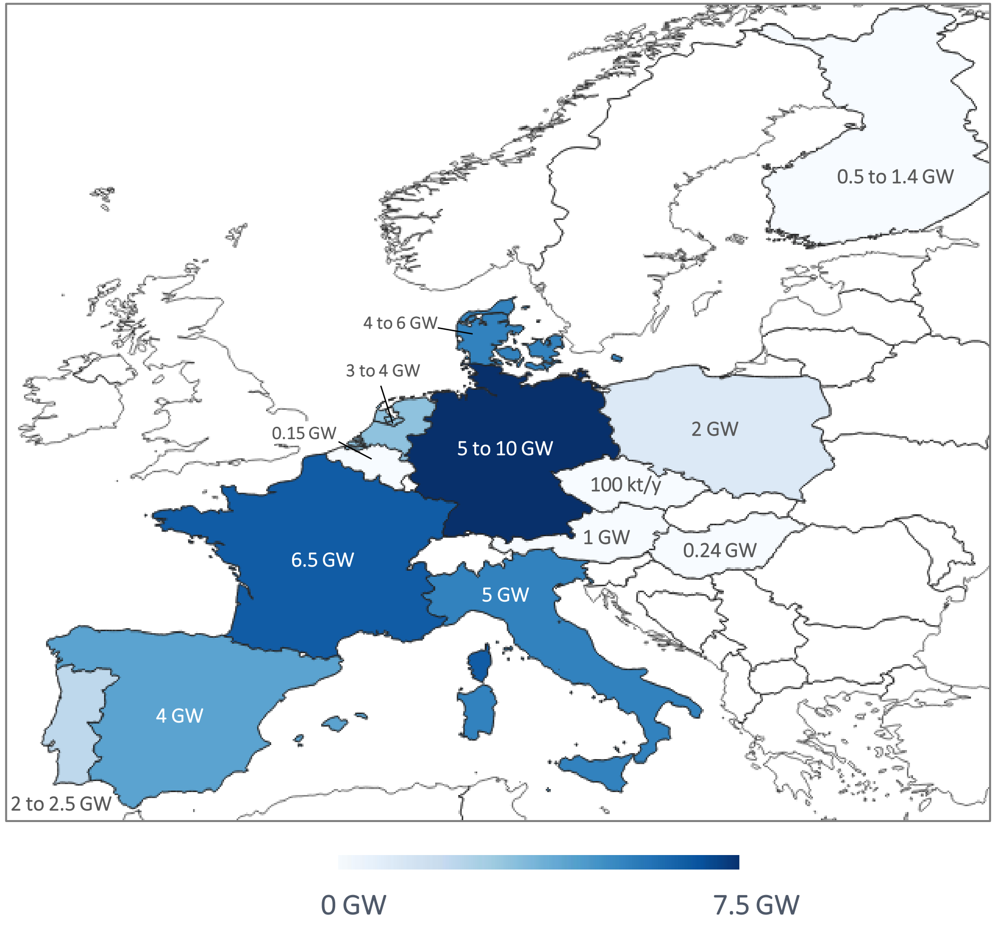


Source: SWD(2022) 230 final

“Impacts” of the EU Hydrogen Strategy

- Following the European Commission’s hydrogen strategy, numerous Member States and regions are developing their hydrogen strategies
  - National strategies may include targets for sectors, objectives for electrolysers, funding commitments, etc.
  - Most of the currently published national strategies identify **electrolytic hydrogen** as the key hydrogen production technology, while some also consider blue hydrogen (steam methane reforming combined with CCUS), methane pyrolysis, etc.
  - A number of Member States have already adopted **ambitious targets** related to the deployment of electrolysers at the 2030 time horizon (see map)
- At the EU and MS level, work has been ongoing to clarify rules and regulations on the following topics
  - Delegated Act on additionality principle (RED II)
  - EU taxonomy related to hydrogen production
  - Cross-border adjustment mechanism (CBAM) and other support mechanisms such as CCfDs
  - Gas decarbonisation package

National electrolysis targets for 2030



Components of an hydrogen system & interlinkages

- The energy infrastructure has always played a key role in ensuring the demand for energy services can be met in a secure and cost effective way
  - The infrastructure, and in particular storage, provides **flexibility services** on numerous timescales, from infra-hourly to multi-annual levels.
  - In the hydrogen ecosystem, the infrastructure includes numerous components, providing a **cross-sectoral link** between variable and low carbon energy sources and hydrogen consumers: pipelines, import terminals, and storage technologies.
  - Taking into account the interlinkages with other sectors (see right-hand side for a list of key interlinkages) is essential when identifying and charactering the **roles** of the infrastructure, evaluating the **needs** for infrastructure, and building the **business cases** for particular infrastructure projects.

Key interlinkages between a hydrogen ecosystem and the gas, electricity and heat systems

Operational level	Planning level
✓ Electrolysis (grid-connected and/or with dedicated renewables) and other conversion processes ✓ Steam methane reforming and other conversion processes ✓ Hydrogen boilers, fuel cells, hybrid heat pumps ✓ Hydrogen turbines	✓ Coordinated planning for the use of the current gas infrastructure via repurposing/retroffiting ✓ Trade-offs between co-locating RES and electrolysis and subsequent transport of hydrogen, and transporting electricity

Contents

Storage is a key provider of flexibility services

- 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 need for flexibility will be structurally different in the case of hydrogen, as drivers differ considerably. The extent of the need for hydrogen storage will depend on the sectors being supplied with hydrogen and the way electricity is sourced.

	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)	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)	RES production variability (wind power in particular) , network congestions
Drivers of seasonal flexibility needs (and higher)	Thermosentivity (mostly residential)		Thermosentivity (mostly residential)	RES production variability (hydro, wind and solar PV), network congestions

Additional drivers of flexibility needs, specific to electrolytic hydrogen

How to identify the values of hydrogen storage?

- Hydrogen storage provides different services to the energy system. In order to (a) identify these services and to characterise them and (b) extract a set of values from this analysis, we follow the procedure below.

Description of the way hydrogen storage operates in a future integrated energy system

Ask the following question: "What would differ in the absence of hydrogen storage, or with a regulatory regime hampering the provision of flexibility?"

Economic impacts	Environmental impacts	Social impacts
Key metrics: Investments and operational costs	Key metric: GHG emissions, RES curtailment	Key metrics: Security of supply, prices for consumers

"What would differ in the absence of H2 storage?" (1/2)

- The first impact of an absence of hydrogen storage would be the inability to perform arbitrage operations, i.e. to store hydrogen produced by a cheap source and to withdraw it at a later stage
  - Economic impacts: higher operational costs as arbitrage enables the use of the cheapest resources, lower level of liquidity
  - Environmental impacts: uncertain as the cheapest supply source is not always the one with the lowest level of emissions
  - Social impacts: higher prices and higher volatility for consumers

- The second impact of an absence of hydrogen storage would be the potential inability to withdraw gas for hydrogen turbines/boilers or for industrial end-uses, leading to potential disruptions of electricity and heat supply and of industrial processes
  - Economic impacts: higher operational costs and higher investments costs in alternative (non-H2) technologies
  - Environmental impacts: uncertain as the cheapest supply source is not always the one with the lowest level of emissions
  - Social impacts: higher prices for consumers and potential demand curtailment

- The third impact of an absence of hydrogen storage would be the inability to scale the operations of electrolysers up and down to provide flexibility services to the electricity system without disrupting the supply of hydrogen
  - Economic impacts: higher operational costs and higher investments costs in alternative flexibility solutions
  - Environmental impacts: higher emissions (due to simultaneously generating hydrogen and using carbon-intensive resources to meet the electricity demand)
  - Social impacts: higher prices for consumers

“What would differ in the absence of H2 storage?” (2/2)

- The fourth impact of an absence of hydrogen storage would be the over-dimensioning of RES capacity to comply with an additionality* principle and the curtailment of large volumes of renewables
  - **Economic impacts:** higher investment costs (RES or alternative H2 sources), potentially impacting the business case of P2X
  - **Environmental impacts:** higher curtailment volumes
  - **Social impacts:** higher prices required to recover the extra investment costs

- The fifth impact of an absence of hydrogen storage would be higher GHG emissions to meet a given hydrogen demand with grid-connected electrolysers (as the dynamics of electrolysis would be dictated by the dynamics of the hydrogen demand)
  - **Economic impacts:** higher operational costs (more fossil-based generation) or higher investments costs (additional investments in RES – see fourth impact)
  - **Environmental impacts:** higher overall emissions as electrolysers would run with electricity generated from fossil sources
  - **Social impacts:** higher prices for consumers

*A principle of additionality aims at ensuring that the electricity being used to produce electrolytic hydrogen is additional to the one that would have been produced without the demand from electrolysers.

Contents

The values of hydrogen storage

Arbitrage value	Ability of storage assets to make a better use the cheapest hydrogen sources in competitive markets, reducing the consumers' exposition to the volatility of prices.
System value	Ability of storage assets to avoid over-investments in infrastructure elements, across the entire energy sector, to ensure the energy demand is met in a secure and efficient way.
Insurance value	Ability of storage assets to ensure sufficient volumes and injection rates are available to end-uses subject to uncertain demand levels (e.g. H2 turbines, H2 heating technologies) and ability to reduce security of supply risks in case of large share of imported H2.
Specific to H2 — Kick-start value	Ability of storage assets to optimally size investments in RES capacity in order to comply with transition targets, thereby facilitating the emergence of an hydrogen ecosystem.
Specific to H2 — Environmental value	Ability of storage assets to help avoid fossil-based hydrogen production, RES curtailment and fossil-based electric redispatch.

NB1: These values emerge for new hydrogen storage sites as well as for retroffited/repurposed ones.
NB2: The ability to stack revenue streams corresponding to the different values depends on the future hydrogen market design. This list could be used to benchmark market design proposals.

Contents

Overview of the methodology

Definition

- Characterisation of 4 territorial use-cases
- Ensuring coverage of all identified values

Procedure & KPIs

- Definition of a simulation framework and a set of KPIs
- Ensuring clear link between KPIs and values

Simulations

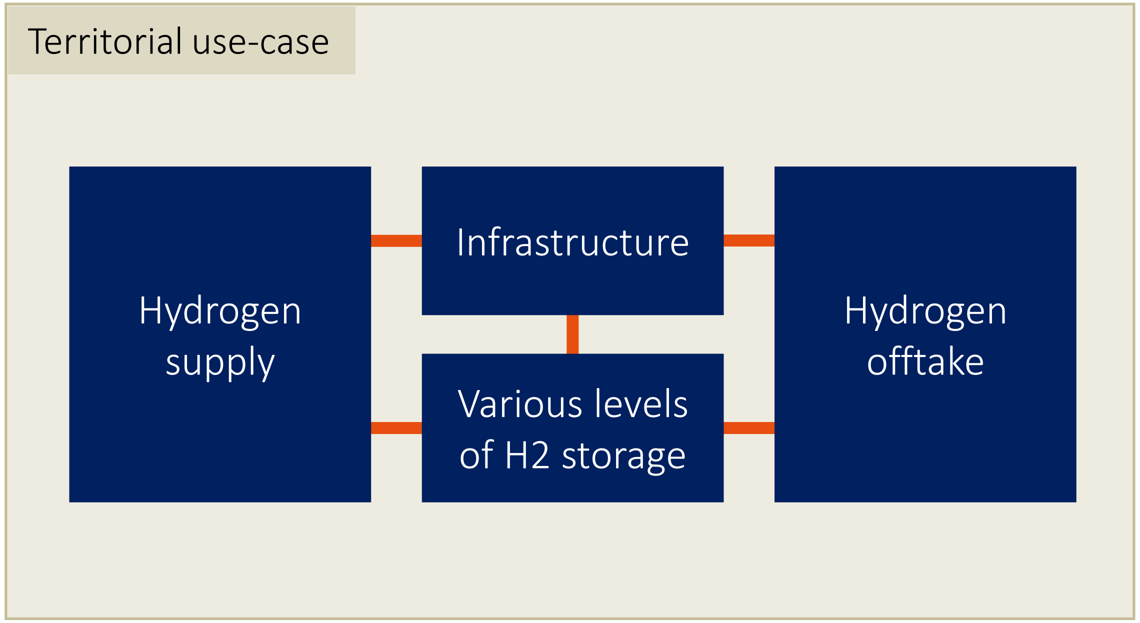
- Simulation of all territorial use-cases
- Sensitivity analyses to relevant parameters

Analyses

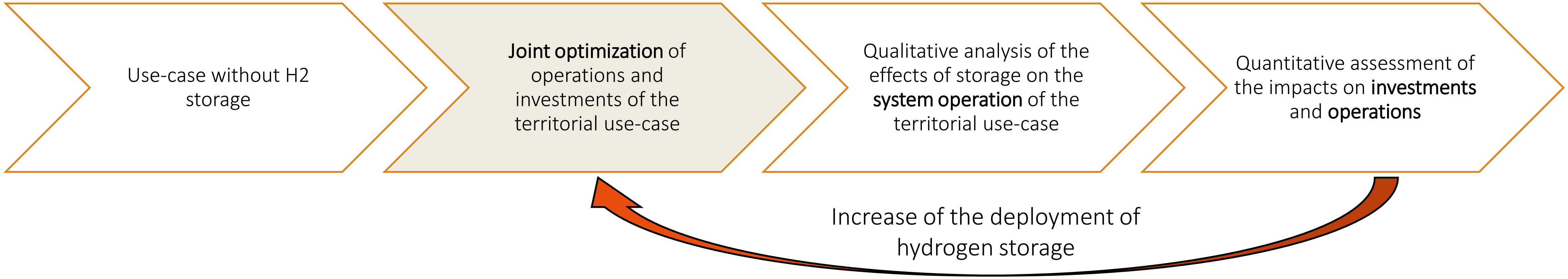
- Analysis of all simulations and sensitivity analyses
- Extraction of key messages and identification of policy recommendations

What is a territorial use case?

- A territorial use-case is a **virtual** configuration representing a hydrogen ecosystem.
- A territorial use-case is characterised by:
  - A hydrogen **demand** (volume and dynamics of the offtake)
  - Hydrogen **supply** options (e.g. grid-connected electrolyser, electrolyser with dedicated renewables, hydrogen imports from other regions, blue hydrogen, etc.)
  - **Infrastructure** connecting the use-case to other systems (e.g. to the electricity grid or to a hydrogen pipeline)
- The role of hydrogen storage is then investigated by **progressively adding hydrogen storage capacity** into the territorial use-case configuration and measuring the impacts on operations and investments via a set of KPIs.
- The set of territorial use-cases has been built to showcase the key benefits of underground hydrogen storage, but does not aim at representing all possible configurations.



Overview of the modelling framework

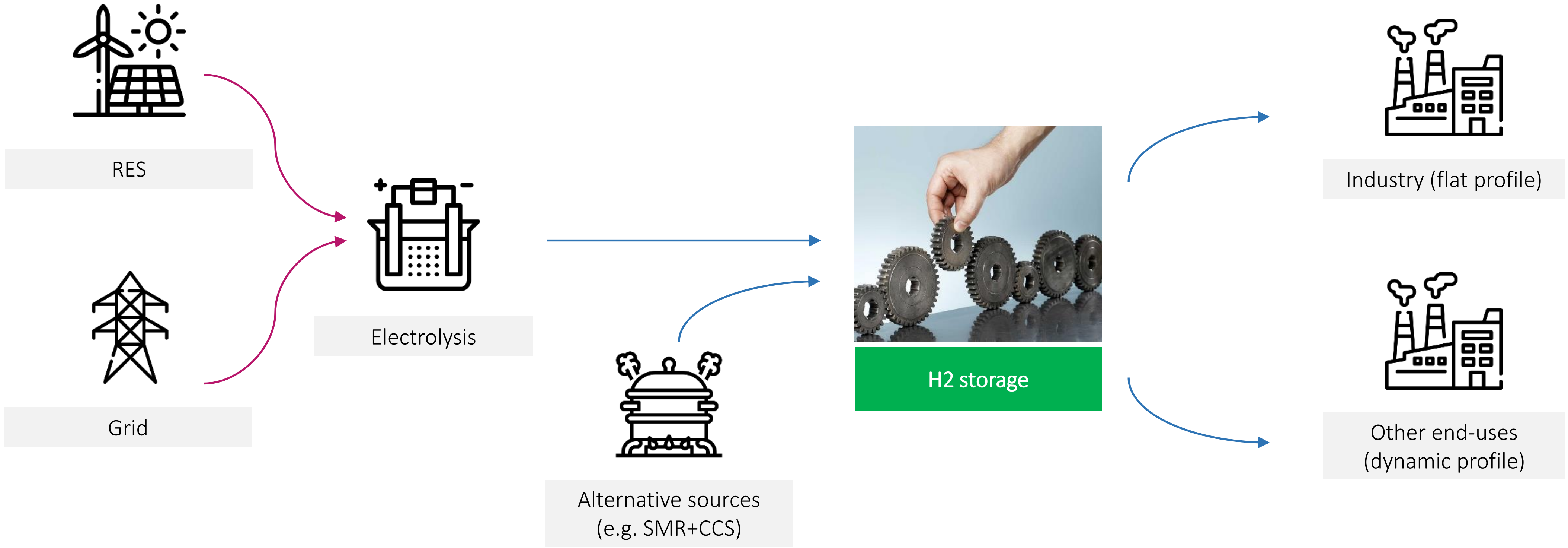


- We start by considering the territorial use-case **without hydrogen storage**, in a situation where the balance between hydrogen supply and demand can be met.
- **As hydrogen storage is progressively added** to the territorial use-case, we measure its impacts on operations and investments, and extract key performance indicators such as RES deployment, RES curtailment, CO2 emissions, investment costs, operational costs, reliance on non-electrolytic sources of hydrogen, etc.

Contents

List of selected territorial use-cases

- The study is based on the analysis of 4 territorial use-cases, focusing on different **sources** and different **uses** of hydrogen.



List of selected territorial use-cases

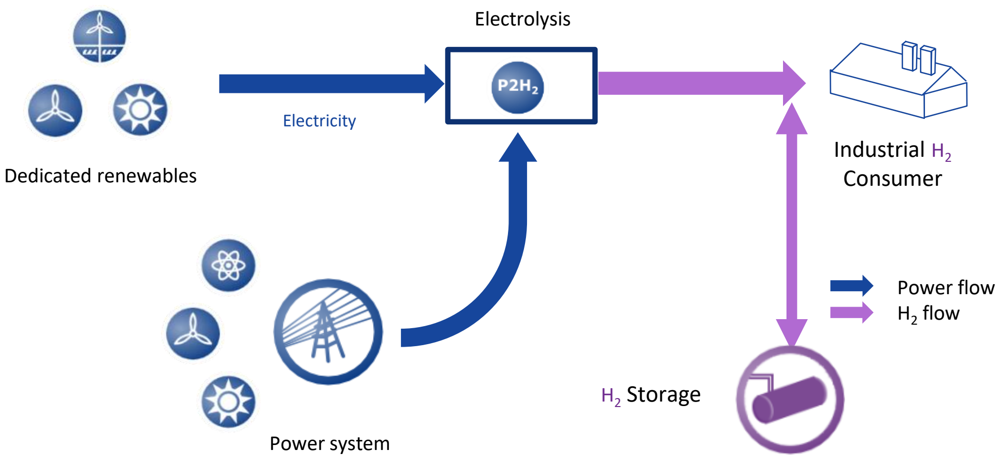
- The study is based on the analysis of 4 territorial use-cases, focusing on different **sources** and different **uses** of hydrogen.

#1	On-site green hydrogen production for industrial consumer
#2	Hydrogen production from grid-connected electrolysis for thermosensitive consumer backed-up by an alternative supply option

#3	Hydrogen production from grid-connected electrolysis for industrial consumer backed-up by an alternative supply option
#4	On-site renewables for green hydrogen production and power injection/consumption into/from the grid

Territorial use case #1 – Definition

On-site green hydrogen production for industrial consumer

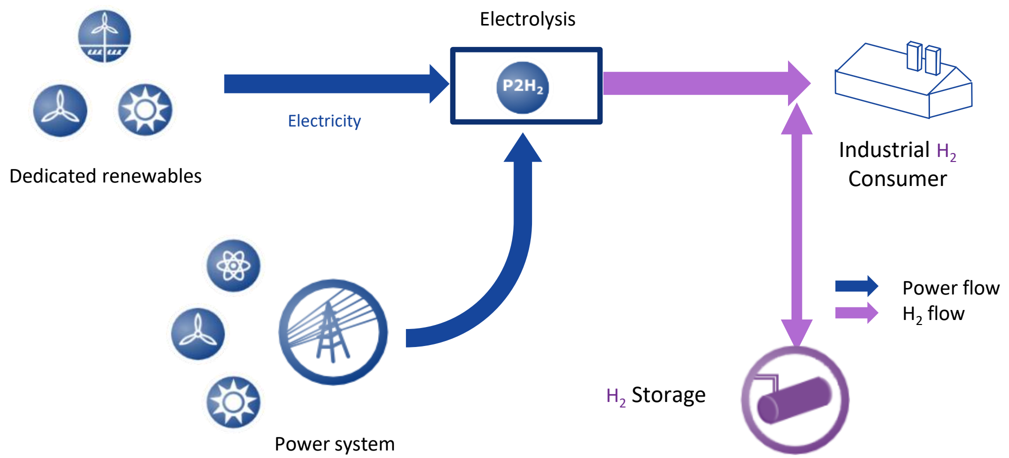


Key characteristics	
Demand	Flat industrial demand
Production	Electrolytic hydrogen from dedicated renewables and grid connection: - The power system is modelled via an hourly electricity price time-series - Dedicated renewables are modelled by investment, fixed O&M costs, and hourly load factors time-series
Flexibility needs	Driven by the variable electricity sourcing options considered (hydrogen demand is assumed to be flat)

Objective: Demonstrate that hydrogen storage is enabling a reduction of the level of on-site RES curtailment, and results in reduced levelised costs of hydrogen.

Territorial use case #1 – Methodology

On-site green hydrogen production for industrial consumer

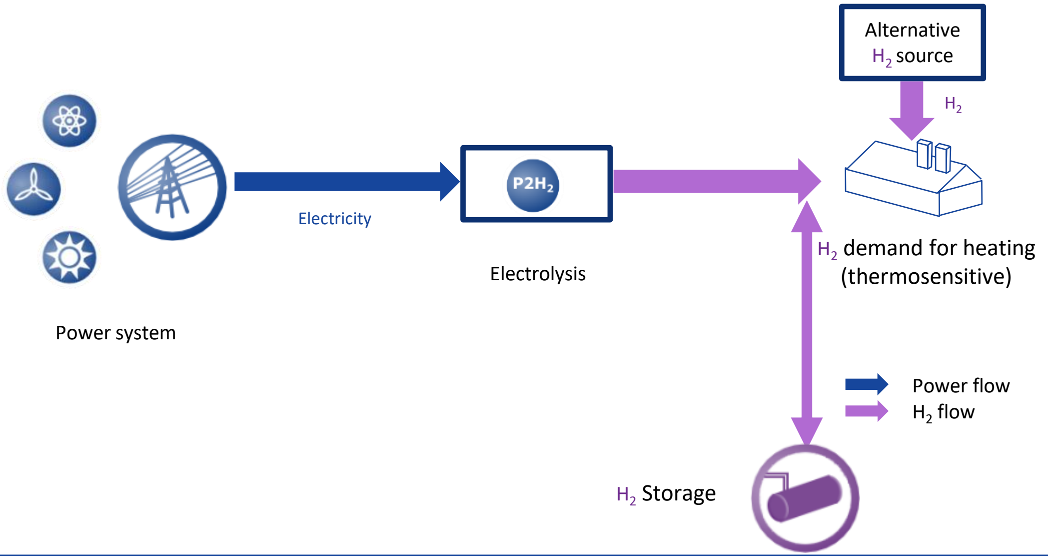


Methodology		
Starting point	Demand	Flat demand of 2 tonnes H2 / hour*
	Production	Electrolysis and renewable power plants are optimised in order to reach an **80/20 %** share of solar and onshore wind production respectively Electricity price curve results from the simulation of the EUCO3232.5 2030 scenario for a country of Southern Europe.
Gradual introduction of storage	H2 storage	Withdrawal/injection capacity increases from 0 to the electrolysis capacity with a 10% step. A **1-week** discharge time of storage is assumed.
Sensitivities	Geographical location	Northern Europe price curve is used and the dedicated renewables are offshore wind + solar

*derived from the GIE-Guidehouse study on the value of underground gas storage

Territorial use case #2 - Definition

Hydrogen production from grid-connected electrolysis for thermosensitive consumer (heating) backed-up by an alternative supply option

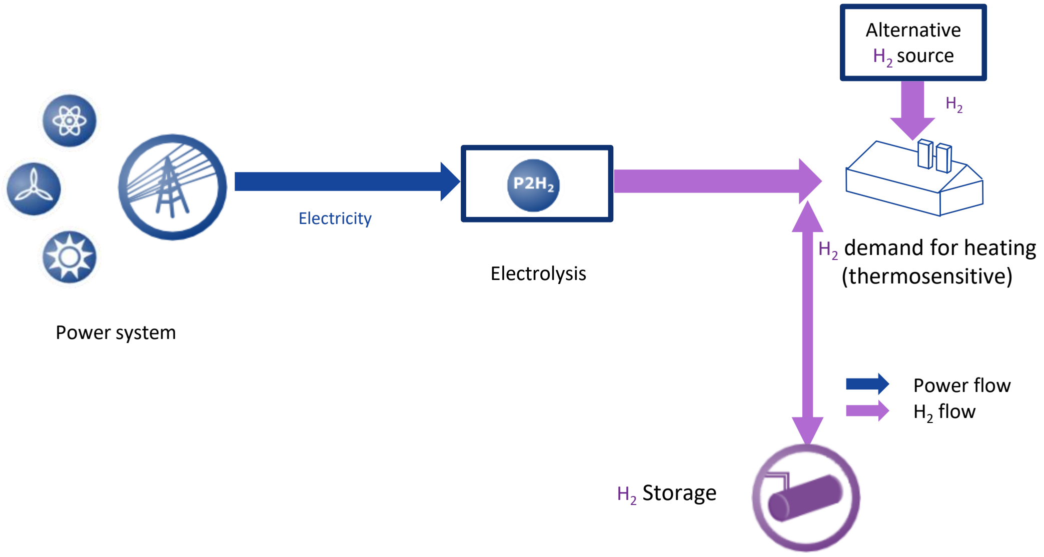


Objective: Demonstrate that hydrogen storage is allowing best use of the grid connection and enabling a reduction of alternative hydrogen supply and CO2 emissions (depending on the nature of the alternative supply option), and results in reduced investment costs in on-site electrolysers and alternative hydrogen suppliers.

Key characteristics	
Demand	Heating profile with seasonal variations
Production	Shared production between grid-connected electrolysis and an alternative source (SMR, pipeline, etc.): - The power system is modelled via an hourly electricity price time-series - The alternative source is modelled by investment, fixed O&M and commodity costs
Flexibility need	Driven by both the variability of electricity price and a temperature-driven hydrogen offtaker

Territorial use case #2 - Methodology

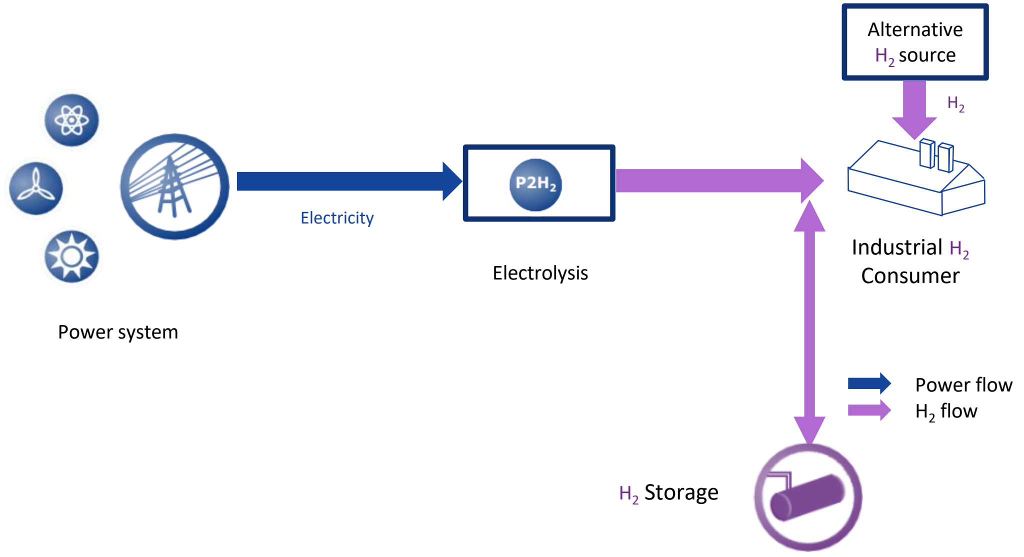
Hydrogen production from grid-connected electrolysis for thermosensitive consumer (heating) backed-up by an alternative supply option



Methodology		
Starting point	Demand	Thermosensitive gas demand for a thermosensitive profile (average consumption of 2 tonnes H2 / hour) for a country of Southern Europe.
	Production	Electricity price curve results from the simulation of the EUCO3232.5 2030 scenario for a country of Southern Europe. Alternative hydrogen source is modelled by **SMR + CCS** costs (investment and operation)
Gradual introduction of storage	H2 storage	Withdrawal/injection capacity increases from 0 to the electrolysis capacity with 10% step. A **1-week** discharge time of storage is assumed.
Sensitivities	Market supply	Grid connection capacity: 100/250/400/450 MW

Territorial use case #3 - Definition

Hydrogen production from grid-connected electrolysis for industrial consumer backed-up by an alternative supply option

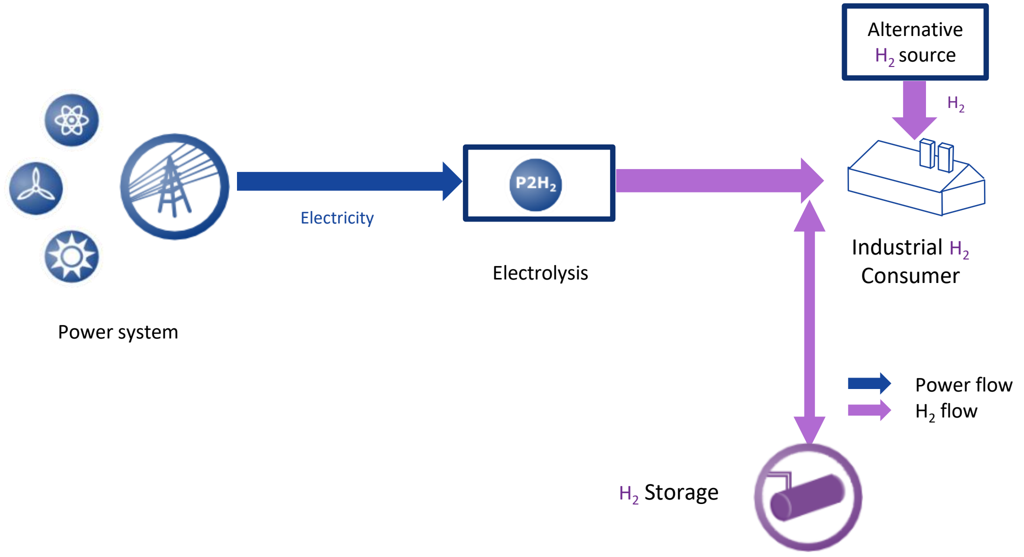


Key characteristics	
Demand	Flat industrial demand
Production	Shared production between grid-connected electrolysis and an alternative source (SMR, pipeline, etc.): - The power system is modelled via an hourly electricity price time-series - The alternative source is modelled by investment, fixed O&M and commodity costs
Flexibility need	Driven by the availability of favourable periods of the power system

Objective: Demonstrate that hydrogen storage is allowing best use of the grid connection and enabling a reduction of alternative hydrogen supply and CO2 emissions (depending on the nature of the alternative supply option), and results in reduced investment costs in on-site electrolysers and alternative hydrogen suppliers.

Territorial use case #3 - Methodology

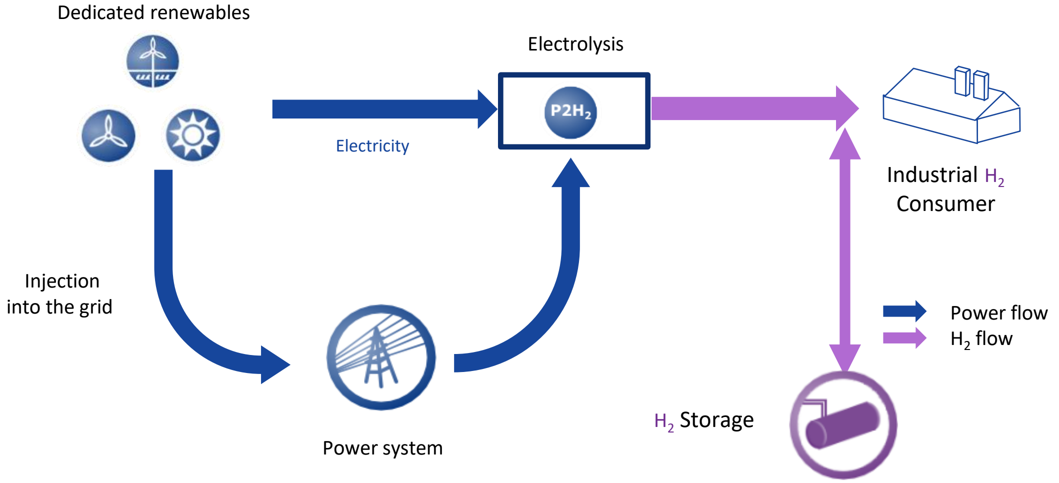
Hydrogen production from grid-connected electrolysis for industrial consumer backed-up by an alternative supply option



Methodology		
Starting point	Demand	Flat demand of 2 tonnes H2 / hour
	Production	Electricity price curve results from the simulation of the EUCO3232.5 2030 scenario for a country of Southern Europe. Alternative hydrogen source is modelled by **SMR + CCS** costs (investment and operation)
Gradual introduction of storage	H2 storage	Withdrawal/injection capacity increases from 0 to the electrolysis capacity with 10% step. A **1-week** discharge time of storage is assumed.
Sensitivities	Geographical location	Northern Europe price curve is used

Territorial use case #4 - Definition

On-site renewables for green hydrogen production and power injection/consumption into/from the grid

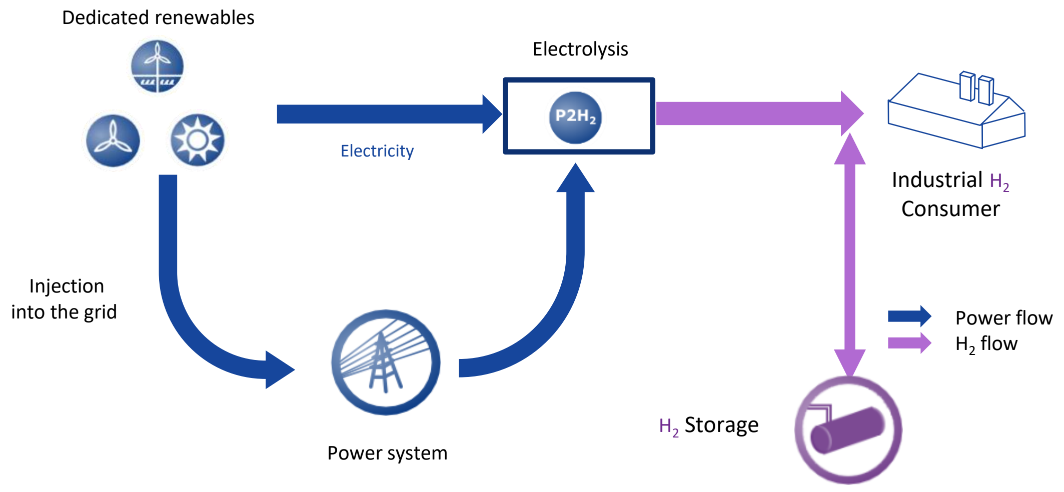


Objective: Demonstrate that hydrogen storage is enabling an optimal use of dedicated renewables prodution, and results in reduced levelized cost of hydrogen and increased additional incomes due to injection into the grid.

Key characteristics	
Demand	Flat industrial demand
Production	Electrolytic hydrogen from dedicated renewables and grid connection: - The power system is modelled via an hourly electricity price time-series - Dedicated renewables are modelled by investment, fixed O&M costs, and hourly load factors time-series
Flexibility need	Driven by the variable electricity sourcing options considered (hydrogen demand is assumed to be flat) and possibility to sell electricity to the market.
Sensitivities	Share of wind and solar in the dedicated renewable mix

Territorial use case #4 - Methodology

On-site renewables for green hydrogen production and power injection/consumption into/from the grid



Methodology		
Starting point	Demand	Flat demand of 2 tonnes H2 / hour*
	Production	Electrolysis and renewable power plants are optimised in order to reach an **80/20 %** share of solar and wind production respectively Electricity price curve results from the simulation of the EUCO3232.5 2030 scenario for a country of Southern Europe. The system can buy and sell electricity to the market.
Gradual introduction of storage	H2 storage	Withdrawal/injection capacity increases from 0 to the electrolysis capacity with a 10% step. A **1-week** discharge time of storage is assumed.
Sensitivities	Dedicated renewable mix	Solar/wind shares are adjusted (50/50 and 20/80)

*derived from the GIE-Guidehouse study on the value of underground gas storage

Sensitivities- Definition

- As underground hydrogen storage facilities are foreseen to store **electrolytic hydrogen** produced from renewable electricity, the sensitivities focus on the ability of the territorial use cases to produce and store green hydrogen. The effects of **connection to the electricity grid (#1)** and **the geographical location (#2)** (northern/southern European countries) have therefore been assessed.

- #1 The **level of electrical interconnection capacity** impacts the ability to **deploy on-site electrolysis capacities**, and to withdraw electricity from the power system to produce hydrogen.

  In cases with on-site renewables, the connection capacity also impacts the ability to **inject power back into the grid**, and therefore the arbitrage between using local electricity for hydrogen production or supplying the power system.

- #2 The **geographical location** impacts the electricity sourcing for hydrogen production, whether it is **the operation of the power system** or **the on-site renewable mix**:
  - European countries have national power systems with local specificities, with **periods of surplus renewable power** and **cheap electricity prices** differing by location, resulting in different dynamics for the operation of electrolysers.
  - These local specificities can impact the operations of underground hydrogen storage assets, and on which timescales they bring most benefits.

Sensitivities - Methodology

Territorial use case		Sensitivity dimension	Reference case	Sensitivity case(s)
#1	On-site green hydrogen production for industrial consumer	Geographical location	**Southern Europe country** with a **solar/onshore wind** dedicated RES mix	**Northern Europe country** with an **offshore wind/solar** dedicated RES mix
#2	Hydrogen production from grid-connected electrolysis for thermosensitive consumer backed-up by an alternative supply option	Grid connection capacity	100 MW	100/250/400/450 MW
#3	Hydrogen production from grid-connected electrolysis for industrial consumer backed-up by an alternative supply option	Geographical location	**Southern Europe country**	**Northern Europe country**
#4	On-site renewables for green hydrogen production and power injection/consumption into/from the grid	Geographical location (share of wind and solar in the dedicated renewable mix)	**80/20%** share of solar and wind in the dedicated renewable generation mix	Solar/wind shares are adjusted (**50/50** and **20/80**)

Contents

Results – Foreword

- Results are presented for each territorial use case:
  1. The impacts of introducing hydrogen storage into the territorial use case are showcased by identifying relevant effects on **system operations** (dynamics of production and storage, activation of flexibility, etc.)
  2. The values of hydrogen storage are evaluated through **a series of KPIs** (listed below). These indicators are provided for several storage sizes in order to showcase how they scale with the size of storage.
- Then the **impacts of sensitivity options** on the benefits brought by hydrogen storage are assessed. The full sensitivity results are available in Appendix.

KPIs used to measure the values of underground hydrogen storage*	
System value	Levelized cost of hydrogen (LCOH)
Insurance value	Hydrogen production capacities
Arbitrage value	Share of hydrogen supply routes, Electrolyser load factor
Kick-start value	Investments in on-site renewable and electrolysers
Environmental value	Carbon footprint of hydrogen, Avoided RES curtailment

*The list of indicators can be slightly amended/modified to take into account the specificities of some use-cases.

Territorial use case #1 – Effects of hydrogen storage

A system without UHS (left): balance between dedicated renewables and grid electricity

1. Without storage, the electricity sourcing is balanced between investment in dedicated renewables and the costs of electricity consumption from the grid. The grid provides the flexibility, even when electricity is expensive.

2. Surplus renewable generation is curtailed.

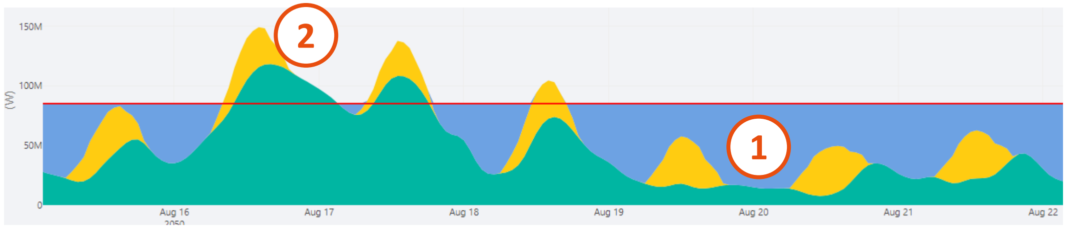
A system with UHS (right): better use of RES and better capture of low electricity prices

3. Hydrogen storage enables to increase the electrolysis capacity and to produce more hydrogen than the instantaneous demand during low electricity price periods. Surplus renewable electricity generation is better exploited.

4. When the grid electricity prices are high, electrolysis reduces its operations and hydrogen storage discharges to meet the hydrogen demand.

Hourly supply-demand balance over 1 week **without** H2 storage

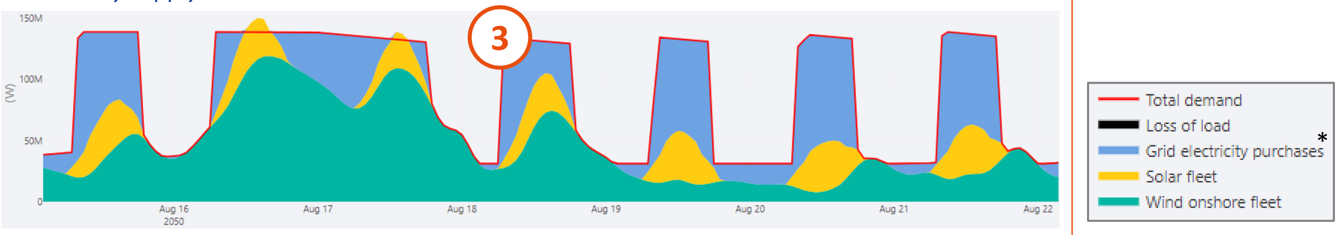
Electricity supply



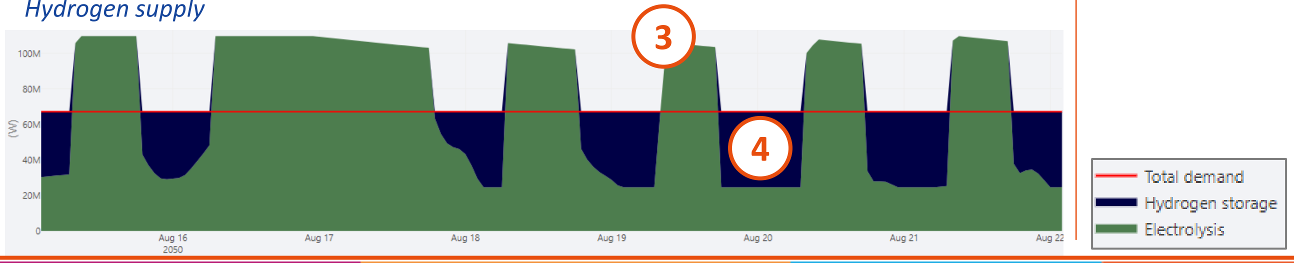
Hydrogen supply

Hourly supply-demand balance over 1 week **with** H2 storage

Electricity supply



Hydrogen supply

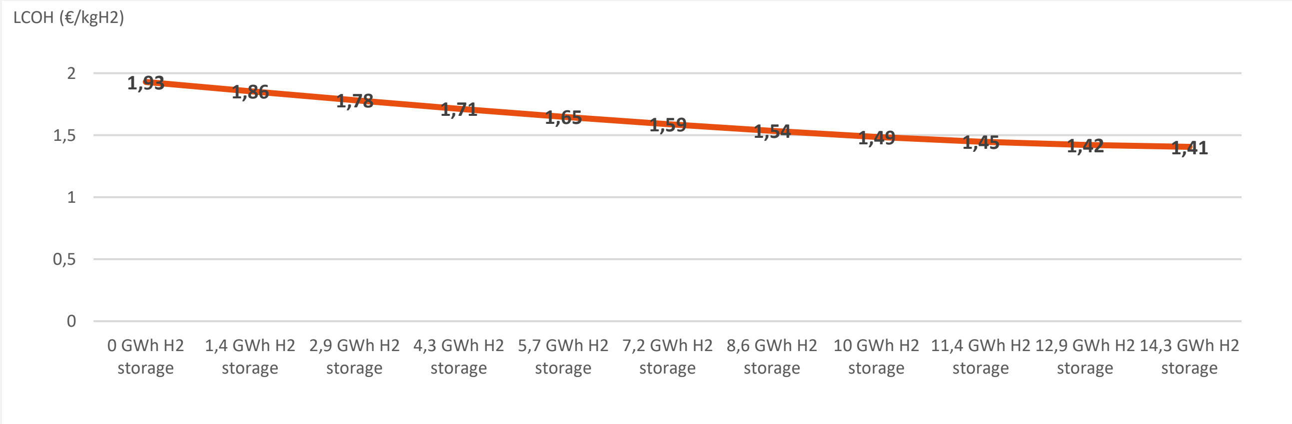


*The purchase of electricity from the grid (in blue on the charts) can be either renewable or fossil. The introduction of storage reduces the carbon footprint of the electricity withdrawn.

Territorial use case #1 – Results (1/2)

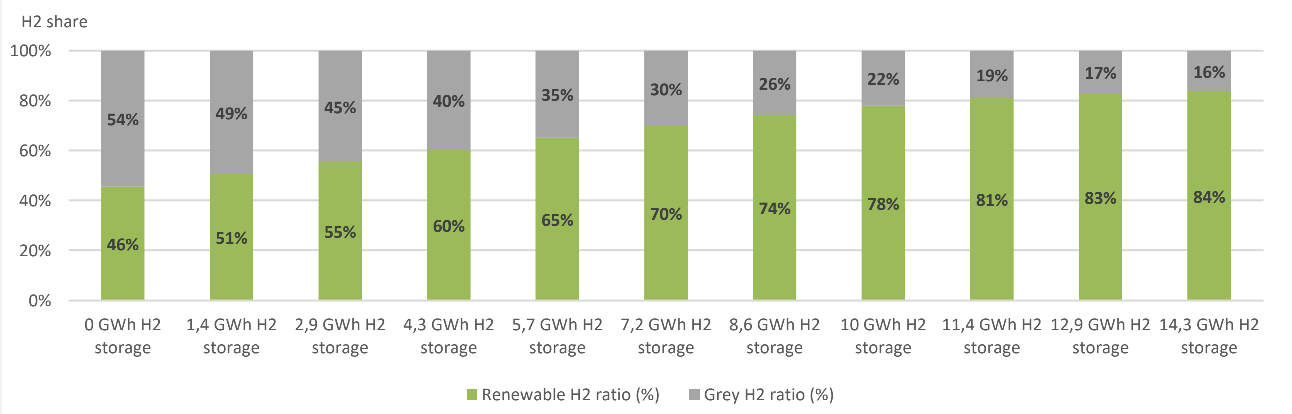
System value

By allowing for a better use of RES resources and for a reduction of grid withdrawals, H2 storage **reduces the hydrogen costs** by circa 25%*.



Arbitrage value

By enabling a better use of the cheapest hydrogen sources, the deployment of hydrogen storage technologies results in up to 38% more renewable H2 in the H2 mix.

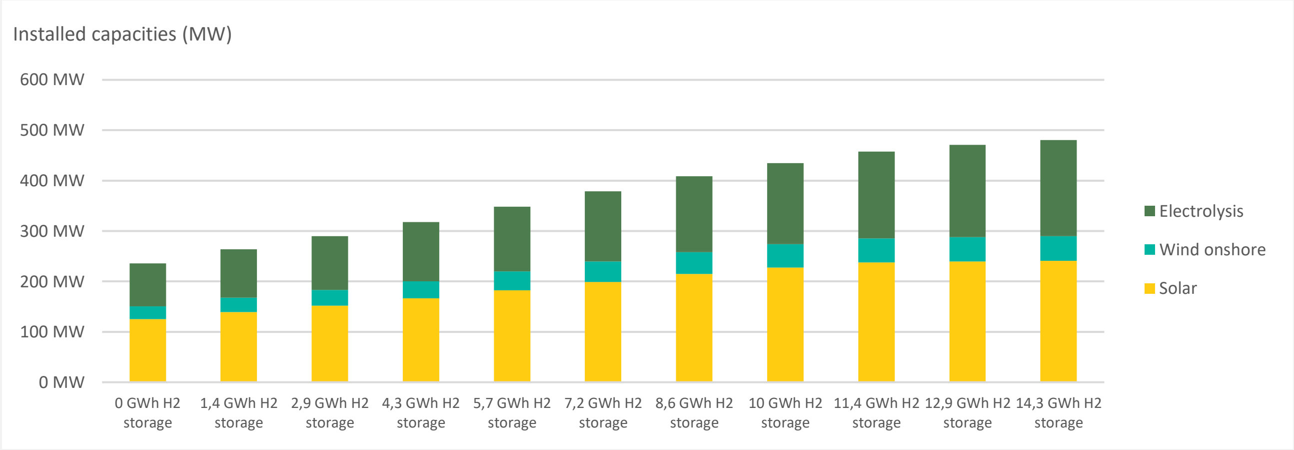


*storage investment cost are not included

Territorial use case #1 – Results (2/2)

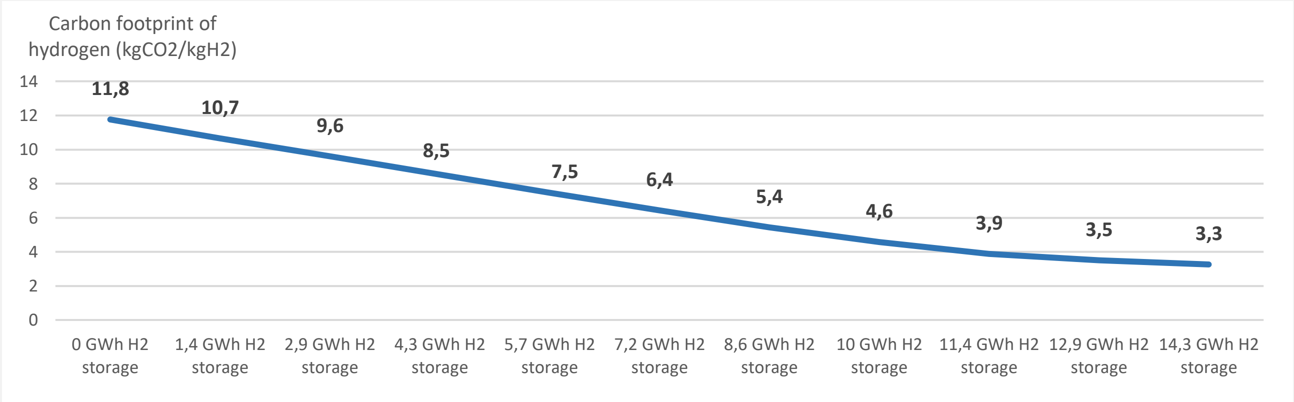
Kick-start value

In order to exploit at best the dedicated renewables and the cheap prices of power market, H2 storage is key to meet criteria related to **additionality** and to facilitate the emergence of a hydrogen ecosystem.



Environmental value

By promoting the use of decarbonised electricity for renewable hydrogen production, H2 storage **reduces the average carbon emissions of hydrogen** by more than **70%.**



Territorial use case #2 – Effects of hydrogen storage

A system without UHS (left chart) : balance between SMR+CCS and electrolytic hydrogen

1 Without storage, SMR + CCS is producing when electrolysis is not sufficient to cover the hydrogen demand (peak period of hydrogen demand, high electricity prices)

The introduction of hydrogen storage (right chart) brings flexibility to the energy production mix. It enables to:

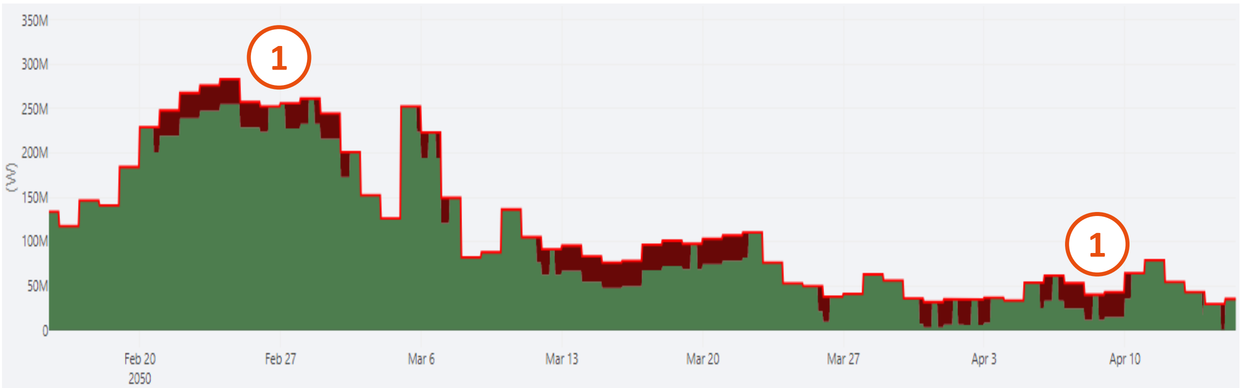
2 store electrolytic hydrogen that has been produced when electricity prices are low ;

3 provide hydrogen during high demand periods or when electricity prices are high ;

4 lower SMR+CCS production capacity.

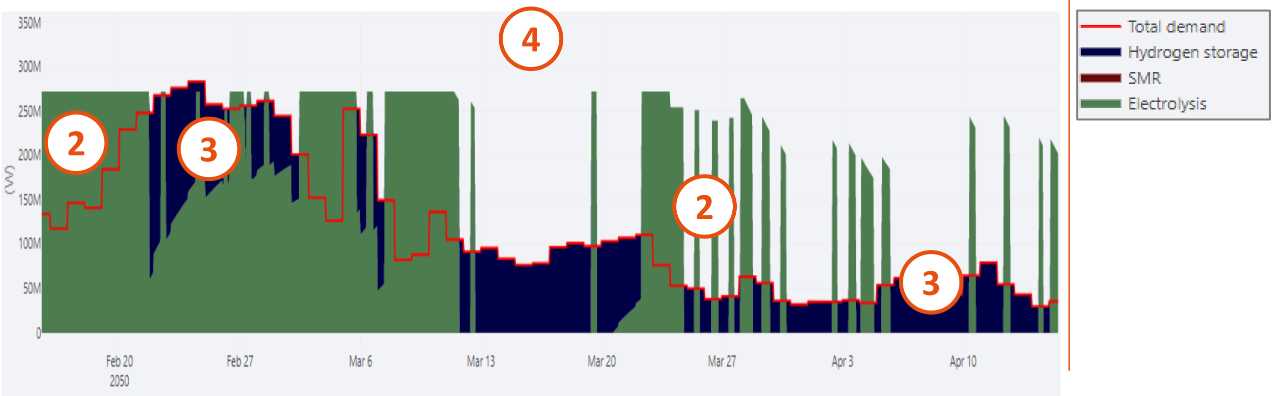
Hydrogen supply-demand balance over 2 months

without H2 storage



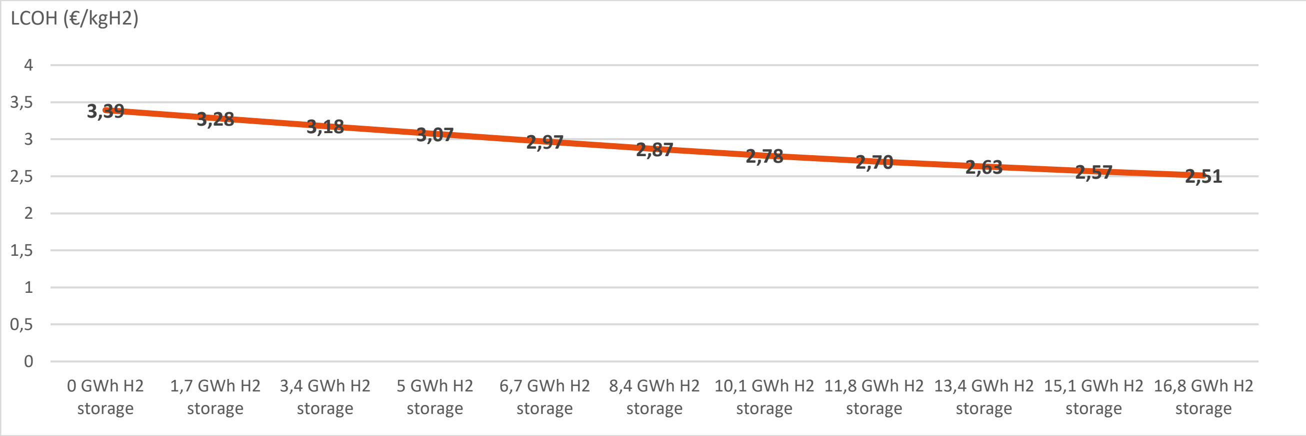
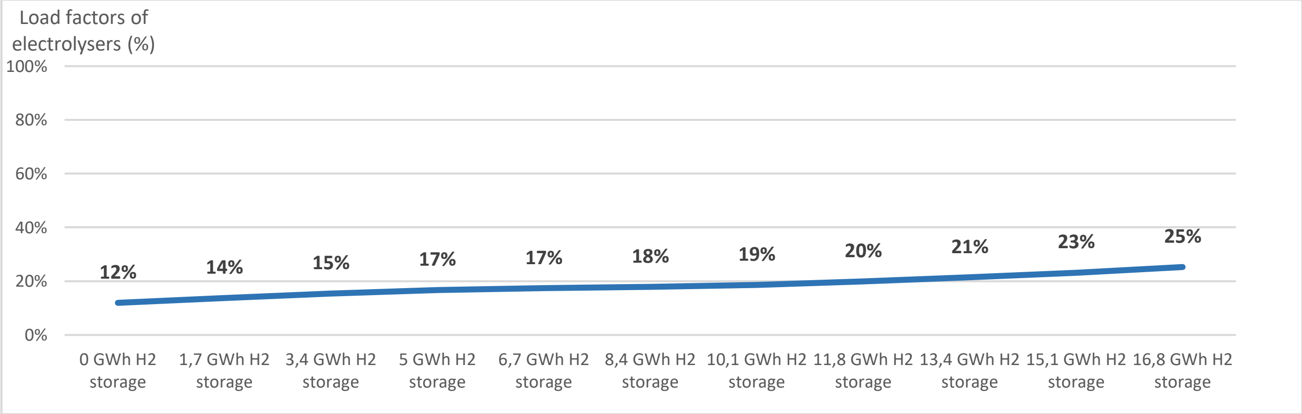
Hydrogen supply

with H2 storage



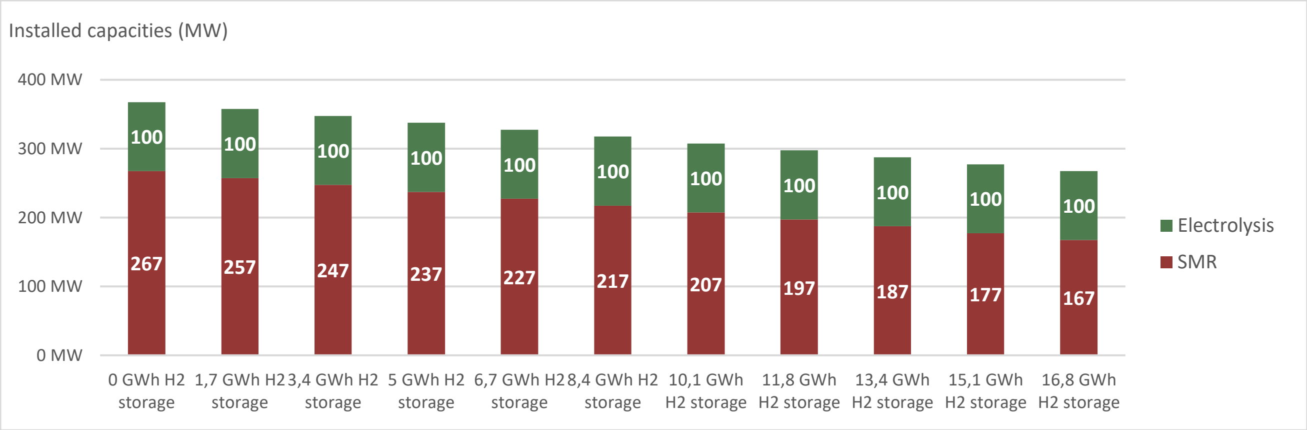
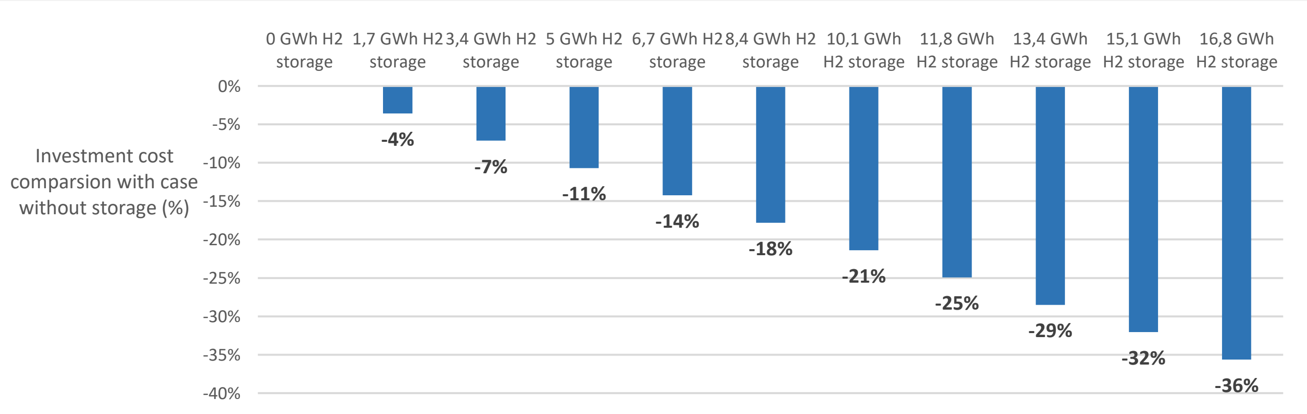
Hydrogen supply

Territorial use case #2 – Results (1/2)

System value	H2 storage allows to decrease investment in SMR+CCS by purchasing more electricity from the grid. This trade-off has a positive system impact as it **reduces LCOH by up to 26%***	
Arbitrage value	H2 storage allows a **better use of grid electricity** by favouring the consumption during low electricity price periods. Thus, the **load factor of the electrolysers increases** (up to x2), which reduces the production share of alternative hydrogen suppliers.	

*storage investment cost are not included

Territorial use case #2 – Results (2/2)

Insurance value	By securing hydrogen supply, at a low cost, hydrogen storage **decreases the capacity needs of a back-up hydrogen supplier** (here SMR+CCS) by up to **36%.**	
Kick-start value	Hydrogen storages allows to **decrease investments in hydrogen production capacities**, thereby facilitating the emergence of an hydrogen system (up to **36%**)	

NB: the results are presented in a low grid connection configuration

Territorial use case #3 – Effects of hydrogen storage

A system without UHS (left chart) : balance between SMR+CCS and electrolytic hydrogen

1. Without storage, hydrogen production is driven hourly by the flat demand.

2. There is an economical balance of hydrogen production between SMR + CCS and electrolysis. The power system prices are therefore a key parameter driving the operations and investments in this configuration.

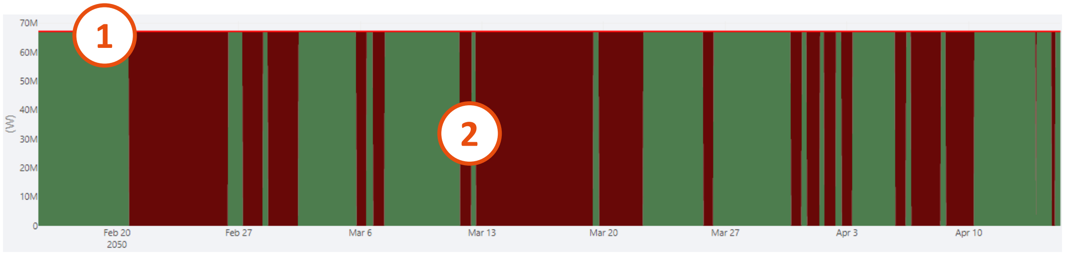
The introduction of hydrogen storage (right chart) brings flexibility to the energy production mix.

3. Hydrogen storage enables to increase the electrolysis capacity and to produce more than the instantaneous hydrogen demand during low electricity price periods.

4. Hydrogen is provided by storage when electricity prices are high.

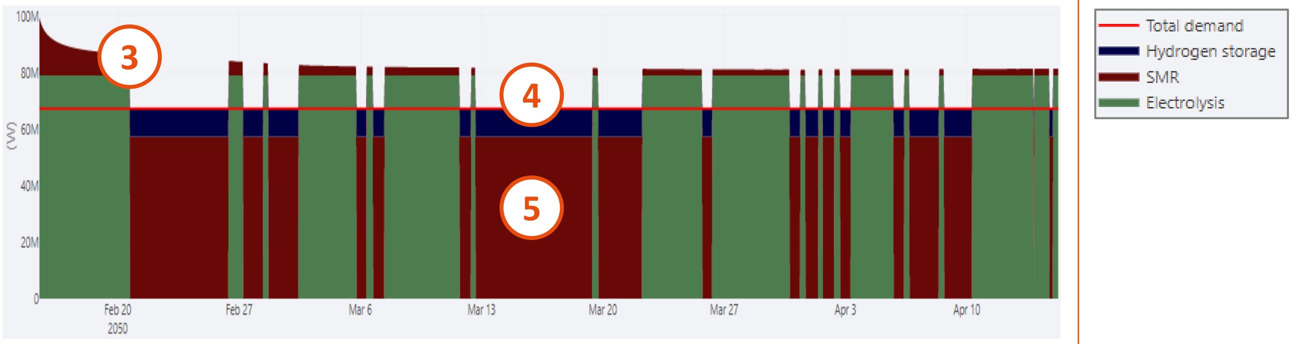
5. SMR+CCS production capacity is lowered.

Hydrogen supply-demand balance over 2 months **without** H2 storage



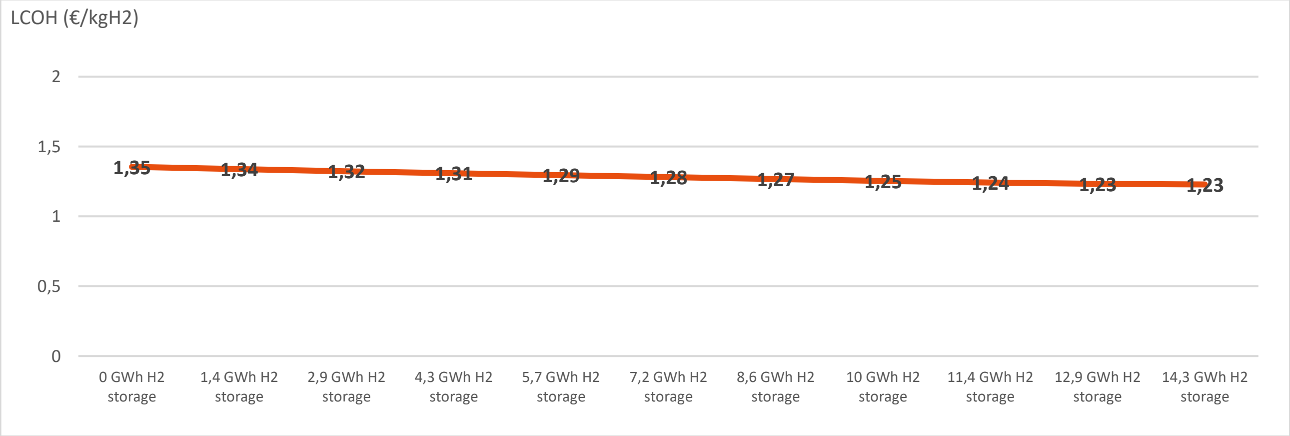
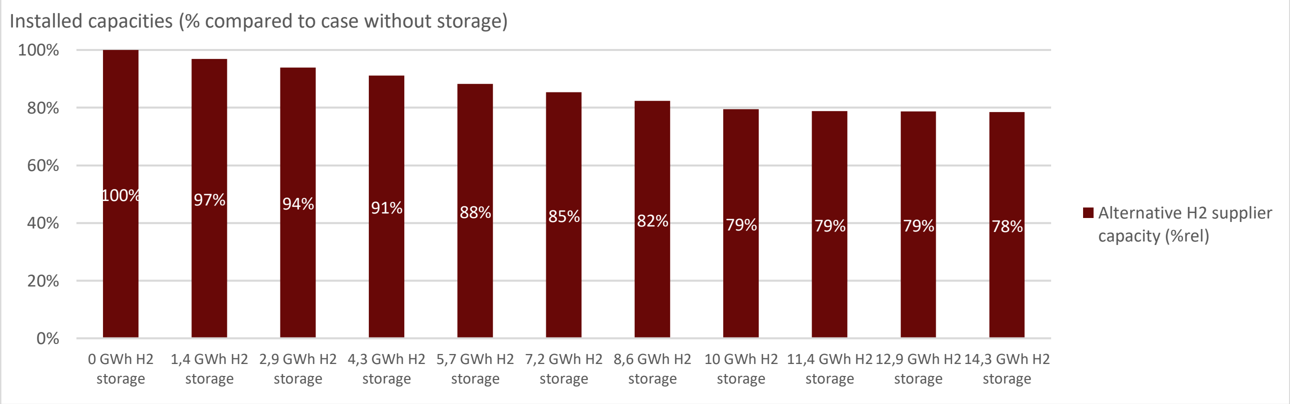
Hydrogen supply

Hydrogen supply-demand balance over 2 months **with** H2 storage



Hydrogen supply

Territorial use case #3 – Results (1/2)

System value	H2 storage allows to decrease investment in SMR+CCS by purchasing more electricity from the grid. This trade-off has a positive system impact as it **reduces LCOH by up to 9,3%***.	
Insurance value	By securing hydrogen supply, at a low cost, hydrogen storage **decreases the capacity needs of a back-up hydrogen supplier** (here SMR+CCS) by up to **22%.**	

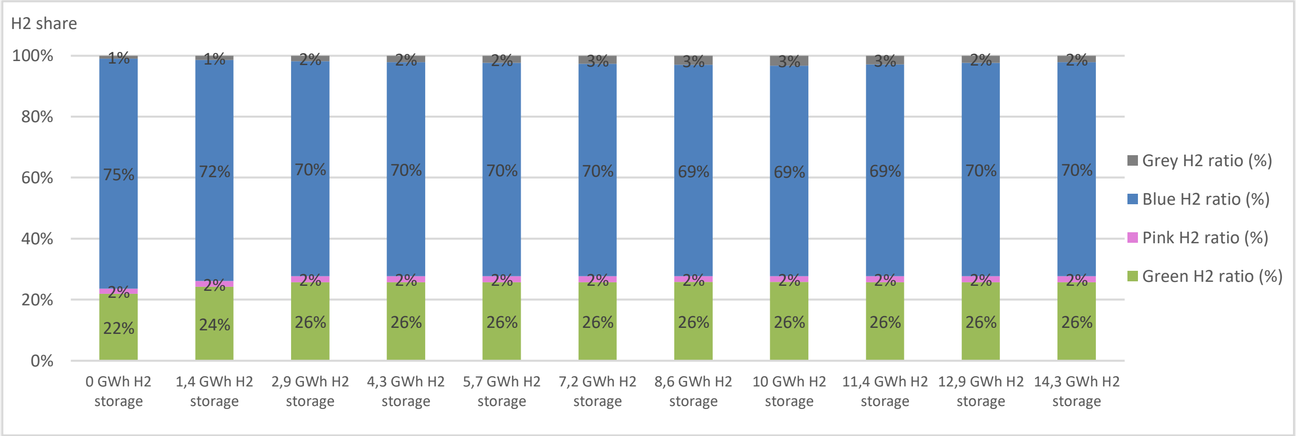
*storage investment cost are not included

Territorial use case #3 – Results (2/2)

Arbitrage value

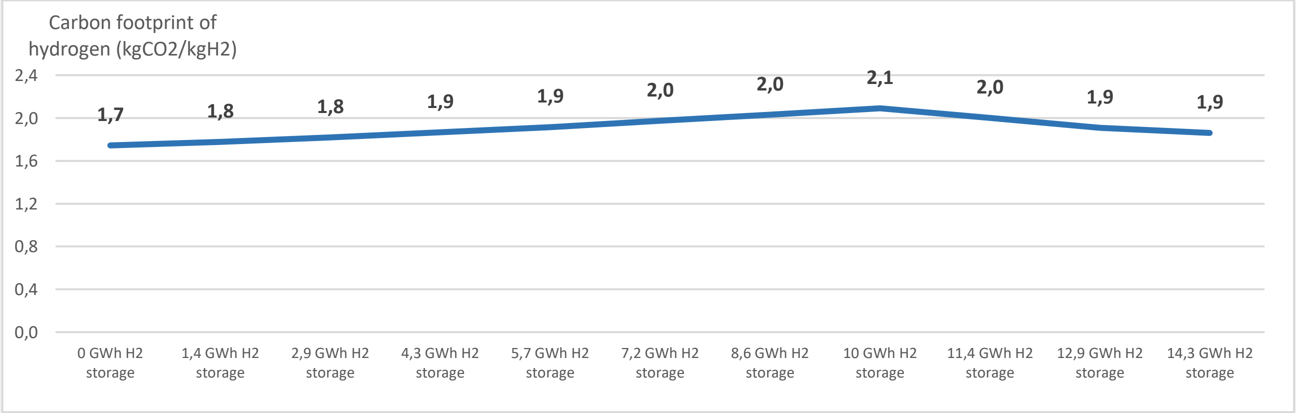
In order to exploit at best the cheap prices of power market, H2 storage allows to **increase the renewable electrolytic hydrogen production by up to 4%** (green/pink H2).

Electrolytic hydrogen production is also slightly increased since it is more economical to consume electricity during additional high-price hours (carbon intensive) than to invest in SMR + CCS.



Environmental value

Increasing the storage size has **limited impacts on CO2 emissions** since it is more economical to consume electricity during additional high-price hours (carbon intensive) than to invest in SMR + CCS.
However, the overall carbon intensity remains low, as the alternative H2 supply is not carbon intensive (SMR+CCS).



Territorial use case #4 – Effects of hydrogen storage

A system without UHS (left charts) : balance between dedicated renewables, grid purchases and sells to the grid

1 Without storage, the electrolytic hydrogen production is balanced between investment in dedicated renewables and the costs of grid electricity. The grid provides the flexibility, even when electricity is expensive.

2 The ability to inject power onto the grid increases the penetration of dedicated renewables, valuing surplus renewable generation through injections. The importance of these benefits is limited by the grid congestion due to connection capacity.

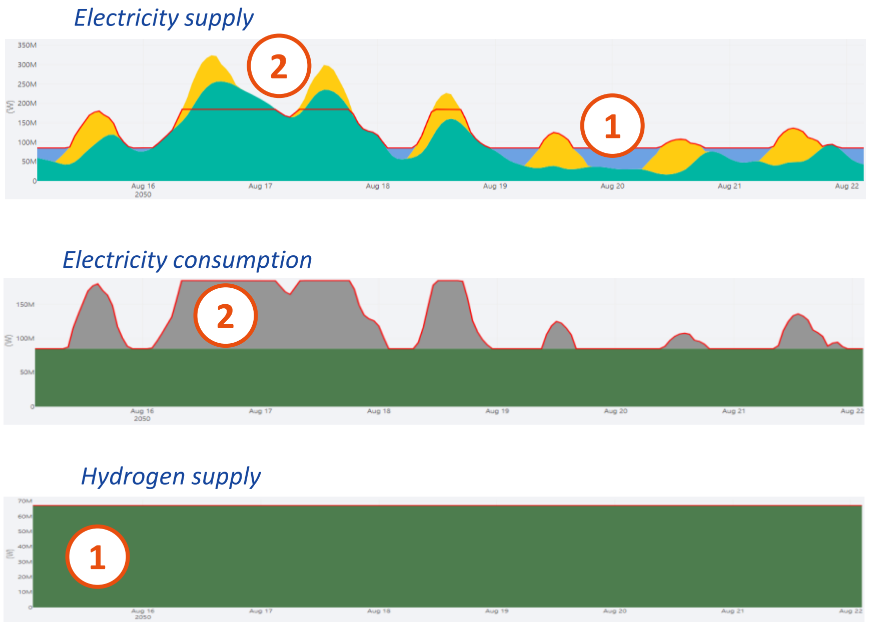
A system with UHS (right charts) : more flexibility enables a more profitable managment of dedicated RES and electricity market

3 The introduction of hydrogen storage brings flexibility in the production, based on grid electricity prices.

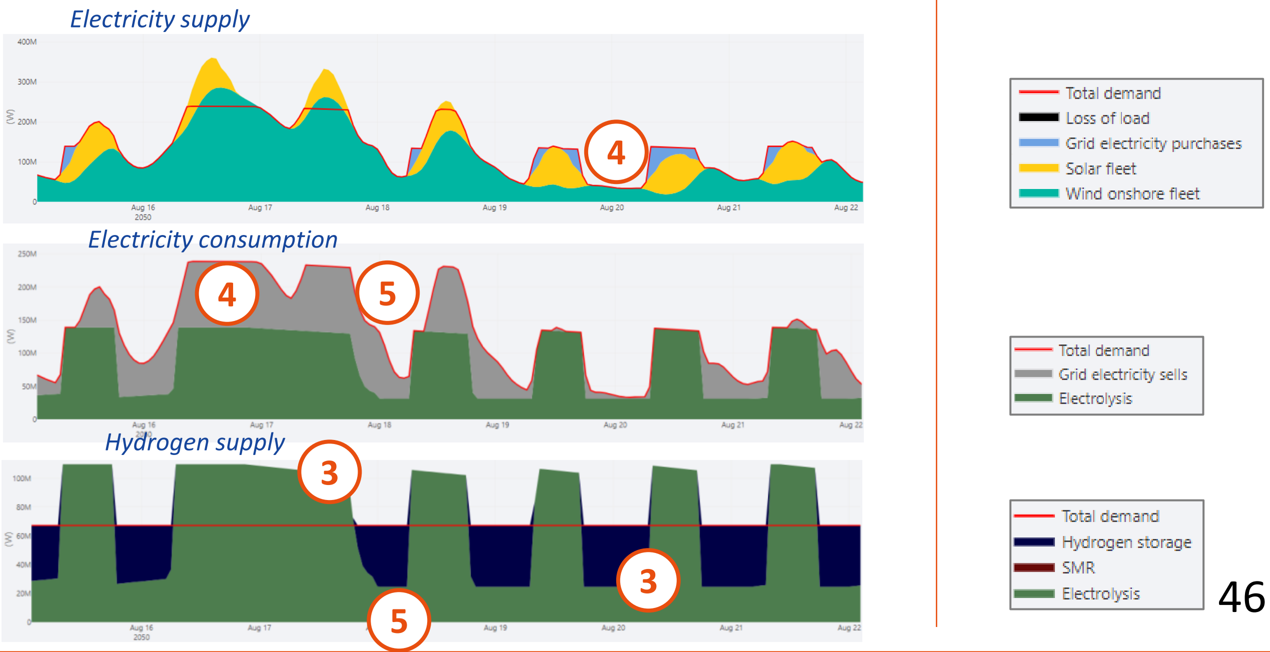
4 Electricity withdrawal from the grid decreases with storage and injections increase. Curtailment is lowered.

5 During periods of high electricity prices, the system sources hydrogen from storage assets to fully allocate the production of dedicated renewables for injection onto the grid.

Hourly supply-demand balance over 1 week **without** H2 storage



Hourly supply-demand balance over 1 week **with** H2 storage

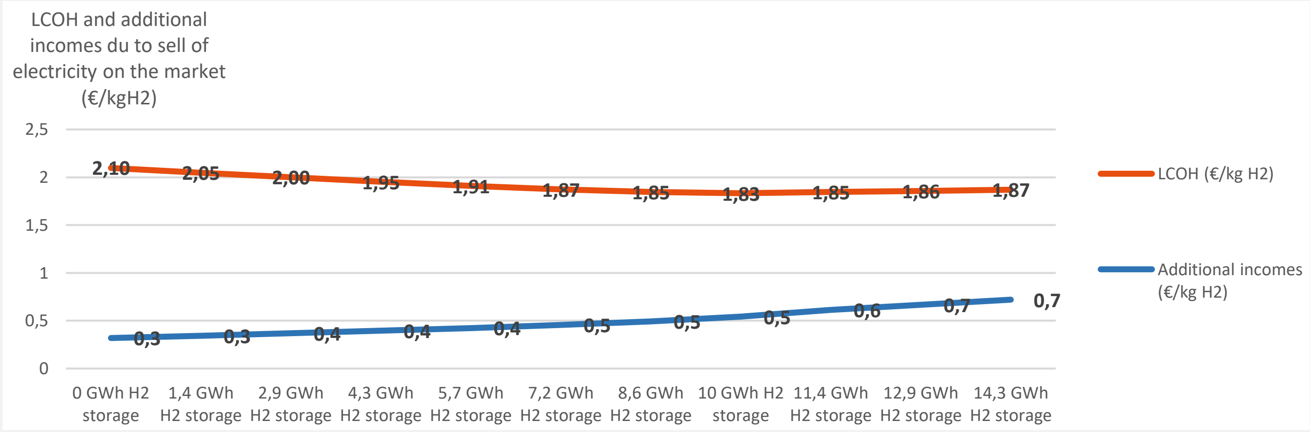


Territorial use case #4 – Results (1/2)

System value

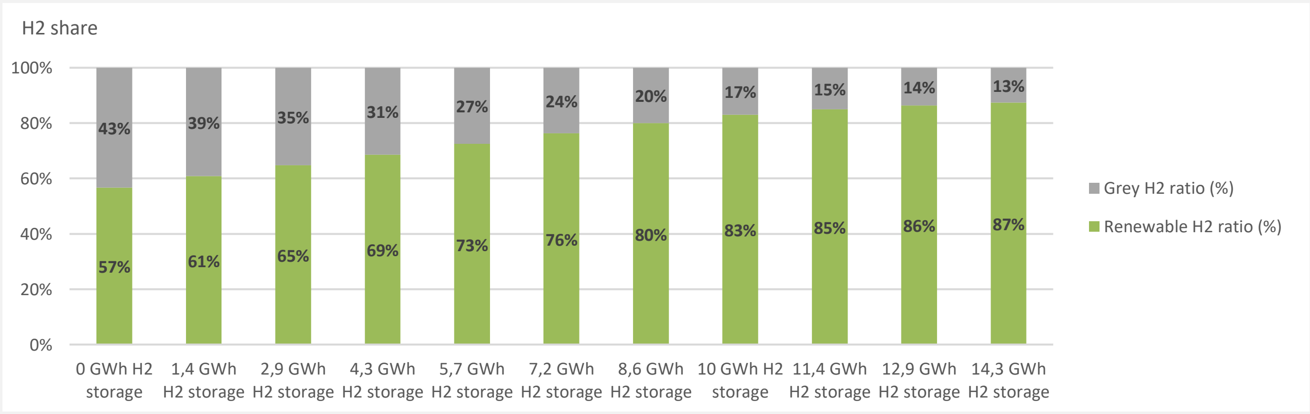
By reducing the cost of the electricity being withdrawn from the grid, H2 storage **reduces the hydrogen costs** by up to 13%*.

The amount of electricity sold to the market increases with storage, providing additional incomes to the use case including storage.



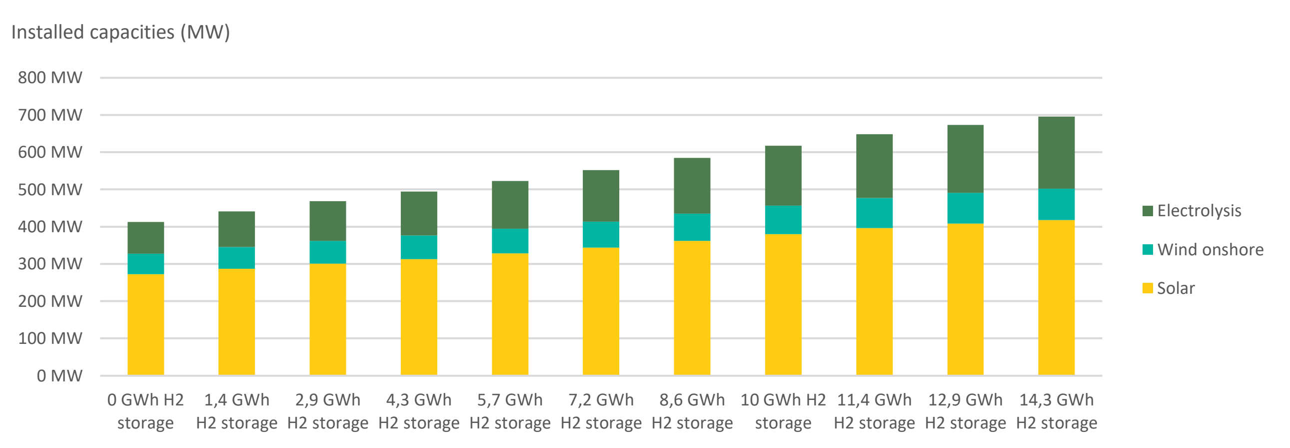
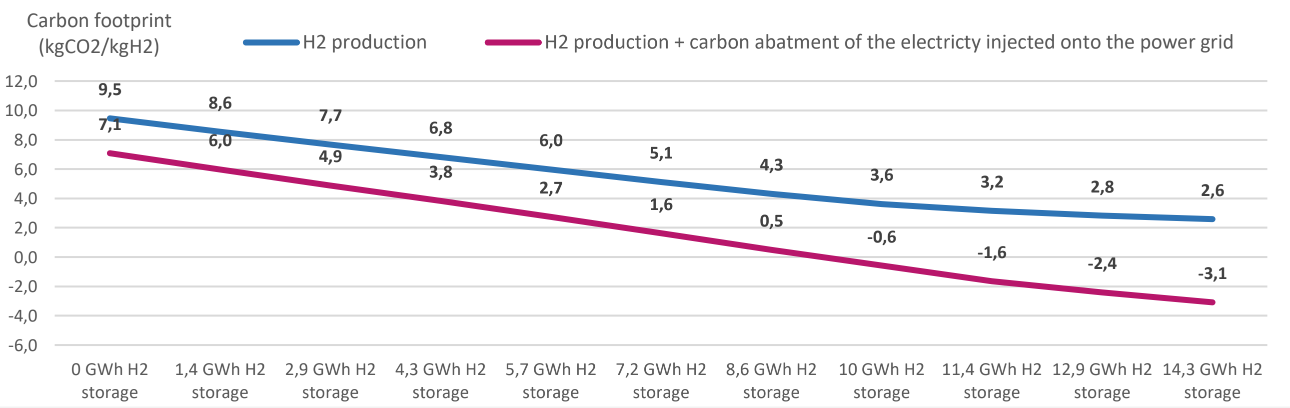
Arbitrage value

By making **a better use of the cheapest hydrogen sources,** hydrogen storage increases the penetration of renewable hydrogen suppliers (up to 30%).
Hydrogen storage also ables a least-cost arbitrage between withdrawal and injection of electricity from/onto the grid.



*storage investment cost are not included

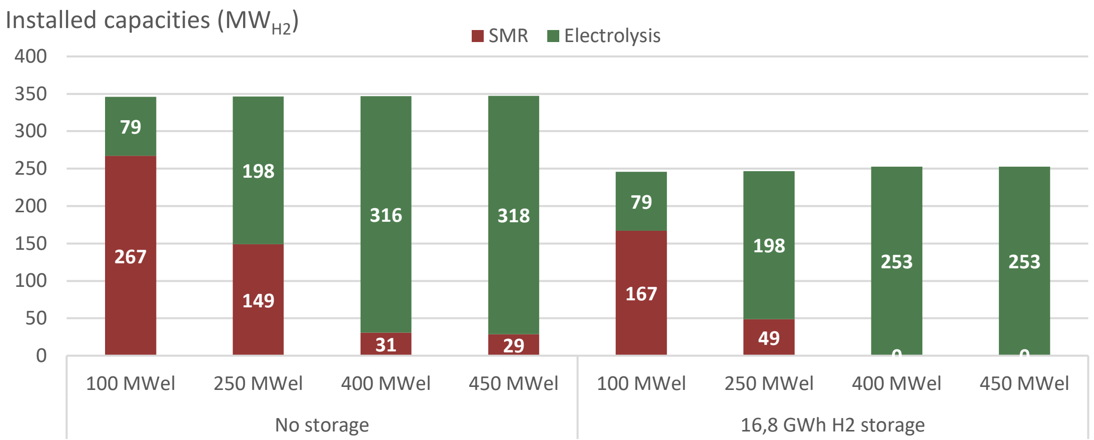
Territorial use case #4 – Results (2/2)

Kick-start value	The electrolysis capacity and renewable generation capacity increase when hydrogen storage increases. The load factor of electrolysers drops as a consequence: storage allows for a system-level optimisation of electrolysis and renewable electricity production.	
Environmental value	By increasing the power injection from the on-site renewables onto the grid, **hydrogen storage contributes to GHG abatement** in the power system.	

Sensitivities – Result (1/2)

Effects of **the grid connection capacity** on the values of underground hydrogen storage

- A greater grid connection allows a higher **sizing of electrolysis** (with or without storage), the benefits brought by the storage of renewable electrolytic hydrogen are accentuated
  - The flexibility provided to the electricity and hydrogen systems increase, and the capacity needs of a back-up hydrogen supplier decrease
  - The contribution of hydrogen storage to GHG abatement of the power and hydrogen systems increase



Capacity mix for the sensitivities of use case #2, for the base case without storage (left) and a case with storage (right)

How to read the chart

#1 The greater the connection to the power grid, the smaller the back-up capacity (e.g. SMR), both for cases without and with storage.

#2 For all levels of grid connection capacity, hydrogen storage reduces the need for back-up capacity. Back-up is not necessary in the case of a high grid connection, the combination of electrolysis + storage is sufficient to meet the demand.

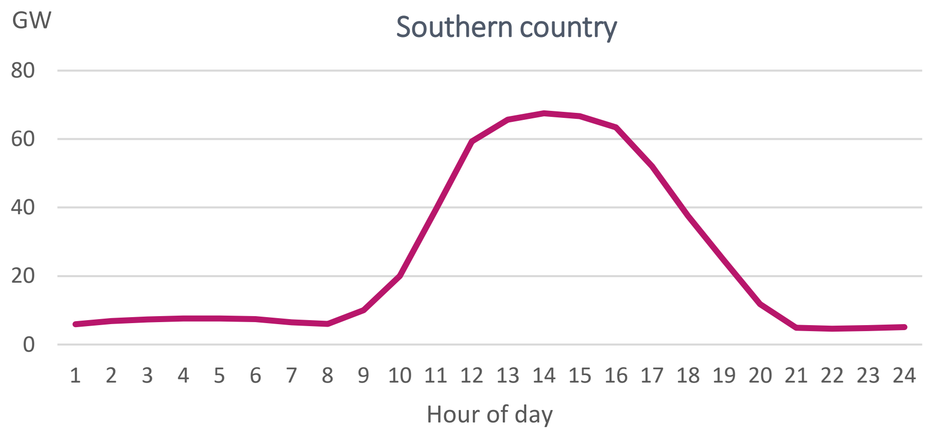
- In the analysis of territorial use cases, the values of underground hydrogen storage are found to be **more important** with a higher grid connection capacity. The optimal sizing of the connection should be determined through a multi-sectoral cost-benefit analysis.

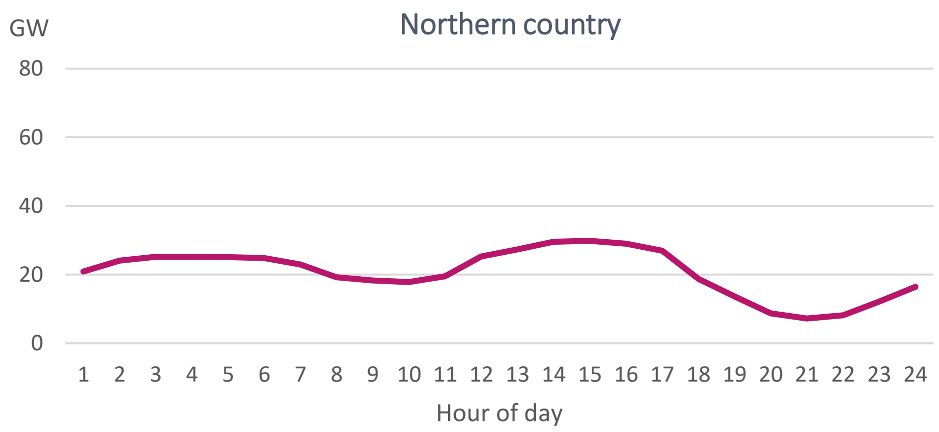
Sensitivities – Result (2/2)

Effects of **the geographical location** on the values of underground hydrogen storage

- The sensitivities regarding the geographical location confirm that hydrogen storage brings benefits in a Southern or a Northern European country, with differentiated impacts on operations and investments:
  - The **consumption/production patterns** of hydrogen storage are affected by **the dynamics of renewable production** (for example the injection/withdrawal cycles have a clear daily pattern for countries with high solar penetration, cf. figures below).
  - The geographical location and the **available renewables sources** (solar or wind) have therefore an impact on the optimal sizing of electrolysers and underground hydrogen storage.

Average daily hydrogen storage injection profile for a Southern and a Northern European country (use case #1)





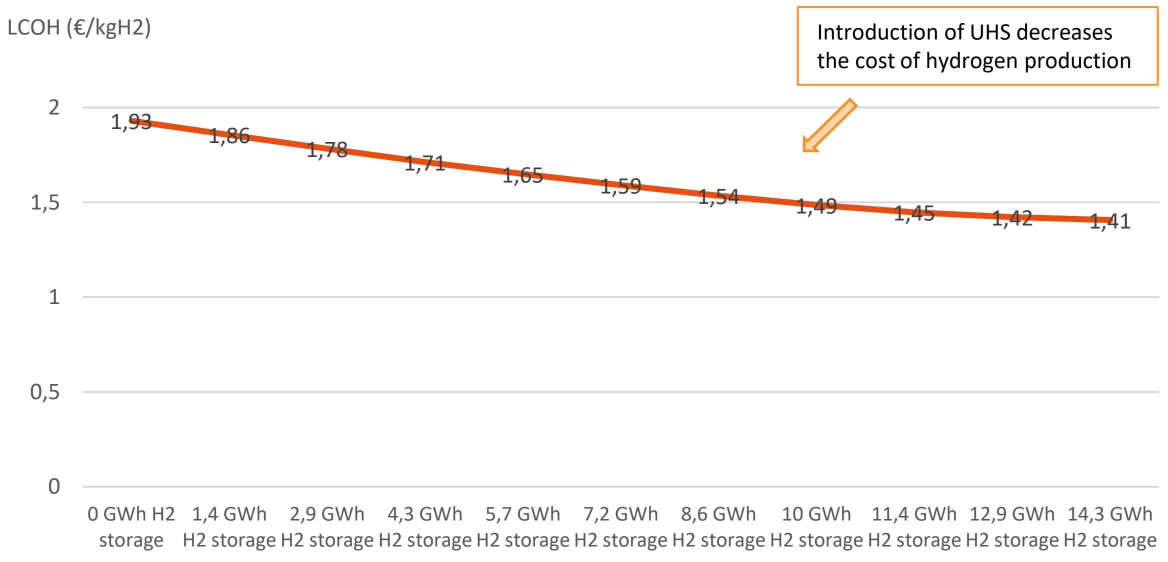
- For territorial use cases with grid connections, the geographical location can have major impacts on electrolytic hydrogen production. **The number of hours of cheap electricity prices** is essential for deploying cost-effective electrolysers.

Contents

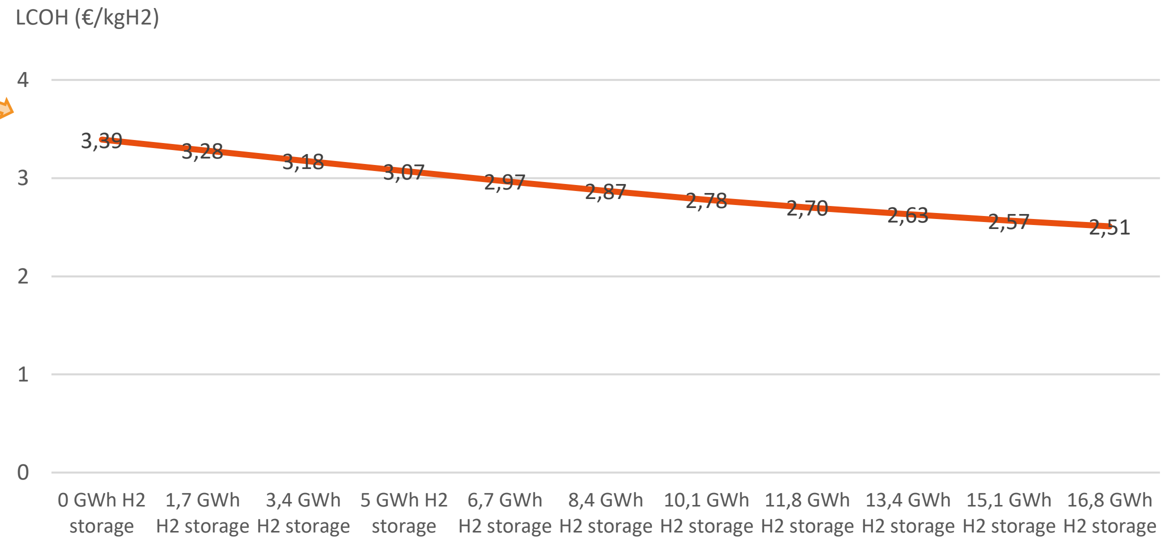
System value

By enabling a better dimensioning of the overall system, UHS helps **avoid over-investments** in other infrastructure elements, and thereby **to minimize the overall cost of hydrogen production*:**

- The flexibility services provided by storage is the key element driving the system value of UHS
- Depending on the configuration of the territorial use case, UHS may increase investment in electrolysis in order for the overall system to be more flexible and better exploit periods of high renewable production and/or low electricity prices.
- Thanks to UHS, the hydrogen system can also be shown to be less dependent on other systems (and their volatility)



Use case 1 (dedicated renewables + grid-connected)



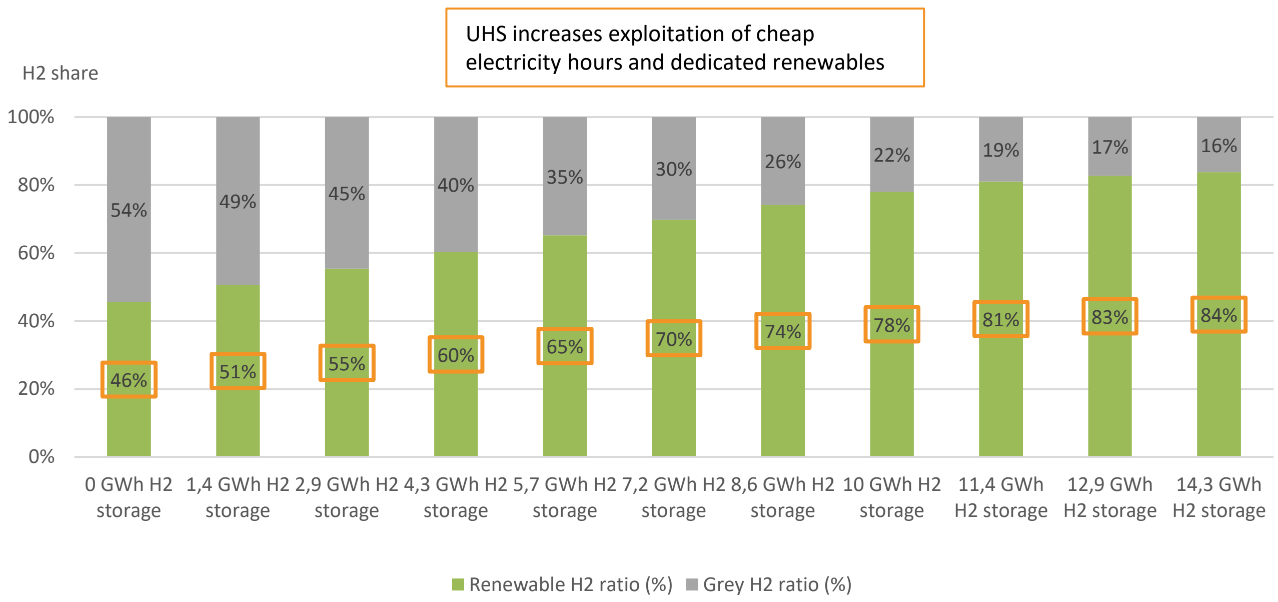
Use case 2 (electrolytic hydrogen with high connection to the grid + alternative supplier for thermosensitive suppliers)

*LCOH is computed as $\frac{totalProductionCost(investment+fixed\ O\&M+operationnal\ cost)}{totalHydrogenProduction}$

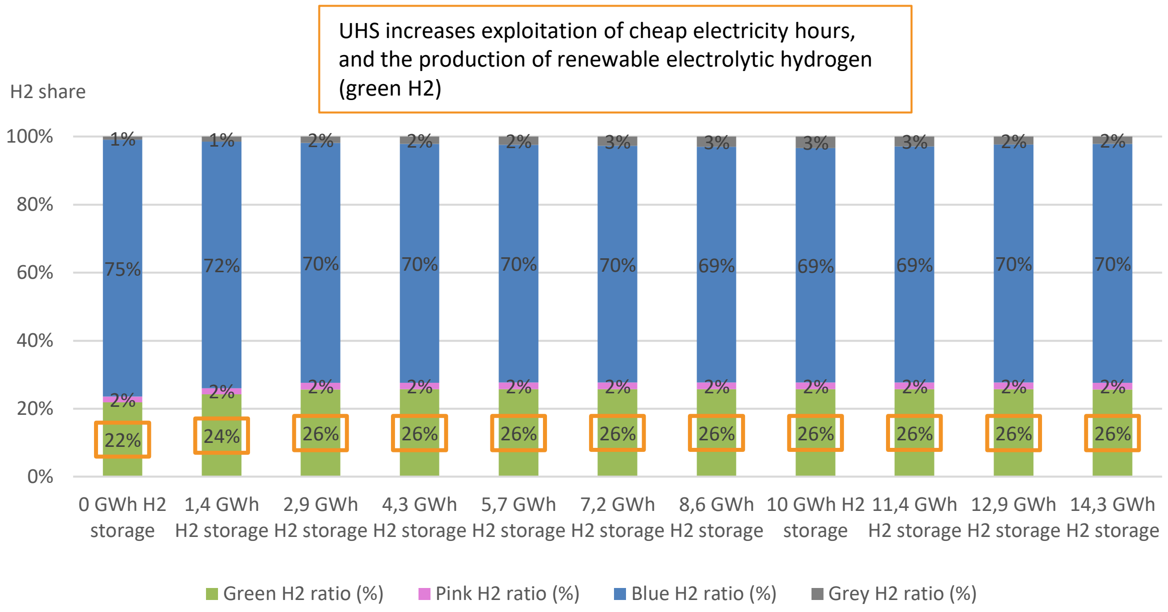
Arbitrage value

By reducing the risks associated with the intermittency of electrolytic hydrogen production, UHS enables to make a **better use of the cheapest hydrogen sources** and to **better exploit the synergies between hydrogen suppliers**.

- When several variable electricity sources compete to power electrolysers, the electricity supply trade-off depends on the size of hydrogen storage. The impacts on renewable hydrogen penetration are found to always be positive.
- When grid-connected electrolysers compete with alternative suppliers, UHS enables a maximal use of grid connection



Use case 1 (dedicated renewables + grid-connected)

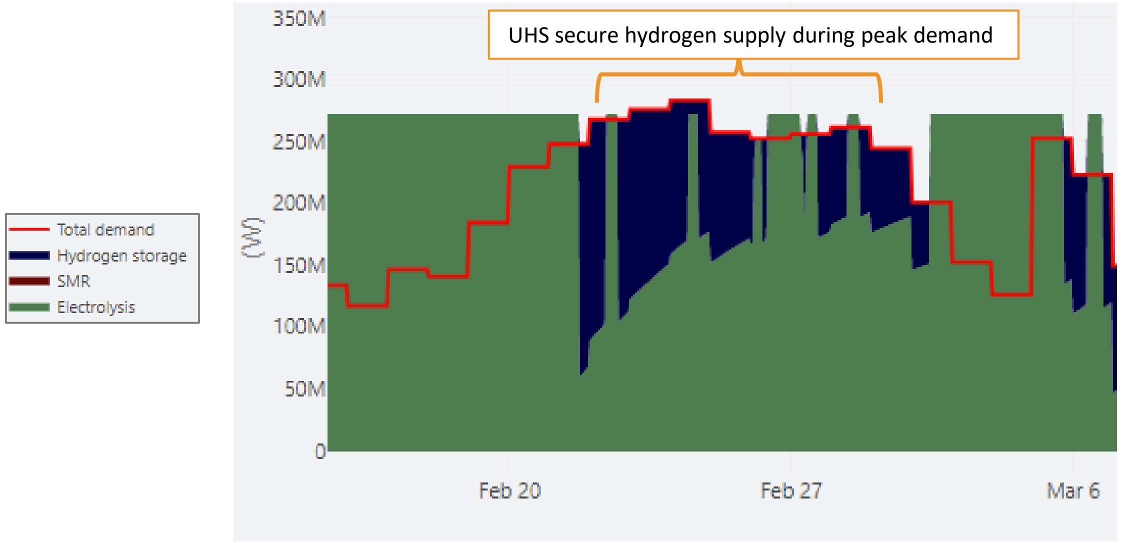


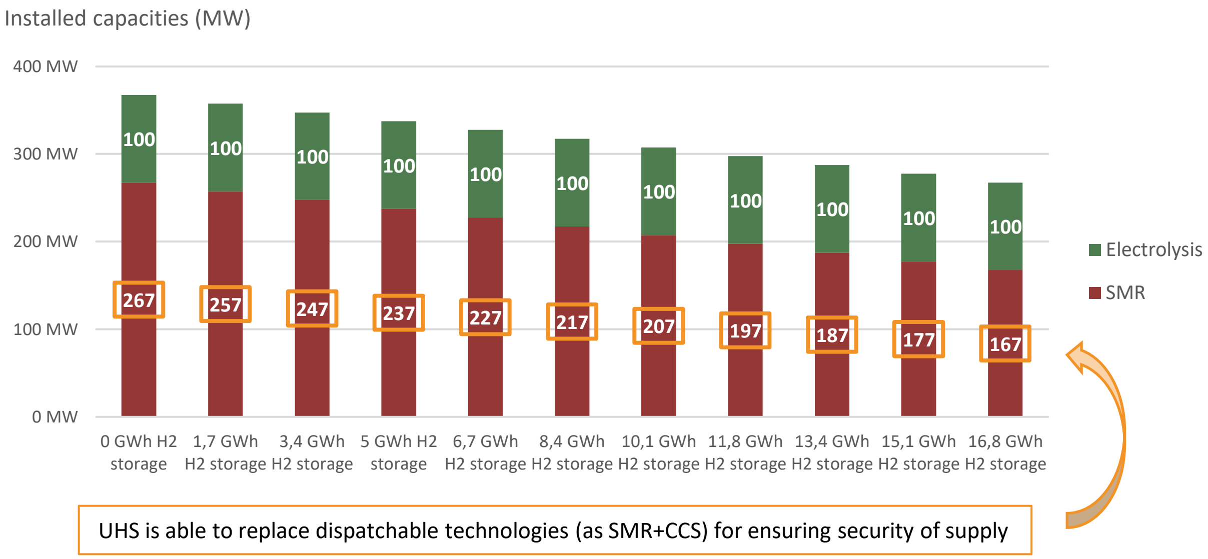
Use case 3 (grid-connected electrolytic hydrogen + alternative supplier (SMR+CCS))

Insurance value

By securing hydrogen supply, at a low cost, in situations of variable/intermittent hydrogen demand (e.g. to supply H2 peakers or H2 boilers), UHS **provides insurance** to the hydrogen system and decreases **the risk of scarcity and unserved energy in the electricity sector:**

- UHS enables to store and deliver hydrogen during high hydrogen demand episodes
- Insurance value of UHS increases when uncertainty occurs on the side of offtakers (e.g H2 turbines, H2 heating technologies) or suppliers (variable renewable generation)





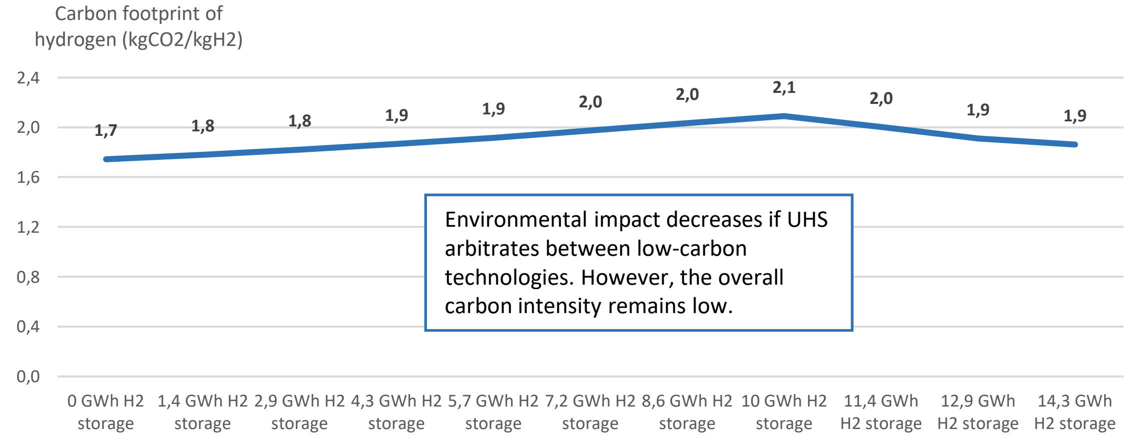
Use case #2 (electrolytic hydrogen with connection to the grid + alternative supplier for thermosensitive consumers)*

*For illustration purposes, the graph on the left features the 450 MW sensitivity of use case #2 and the one on the right the 100 MW sensitivity

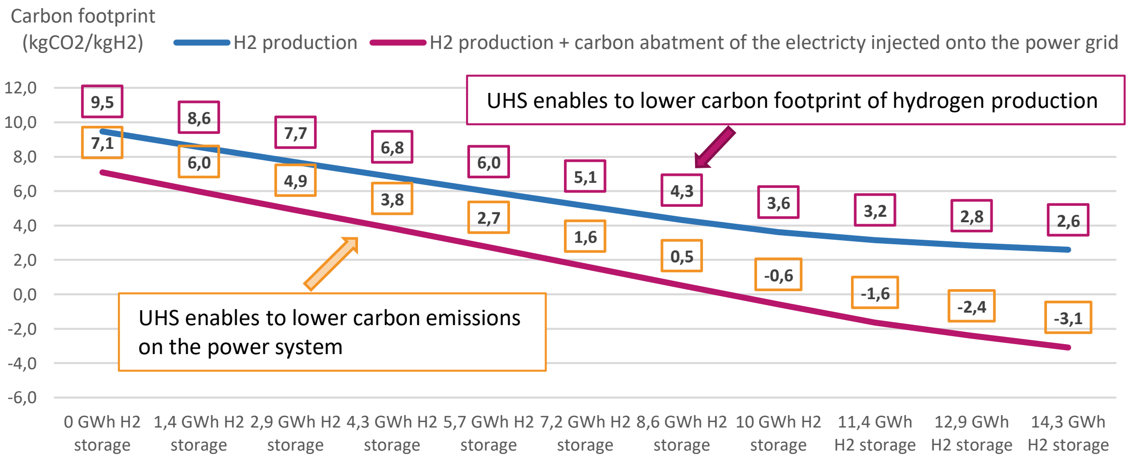
Environmental value

By fostering the production of low-carbon hydrogen, **UHS helps avoid GHG emissions**

- UHS **promotes the use of decarbonized electricity** for green hydrogen production (either increasing withdrawal of neutral-carbon electricity from the grid or developing dedicated renewables production – see use-cases #1 and #4)
- The environmental impact of UHS is **lower** if hydrogen storage enables **arbitrages between low-carbon technologies** (use cases #2 and #3)
- The flexibility of UHS does not only result in environmental benefits within the hydrogen system, but also contributes to **GHG abatement in the broader energy system** (use case #4)



Use case #3 (electrolytic hydrogen with connection to the grid + alternative supplier - here SMR + CCS)

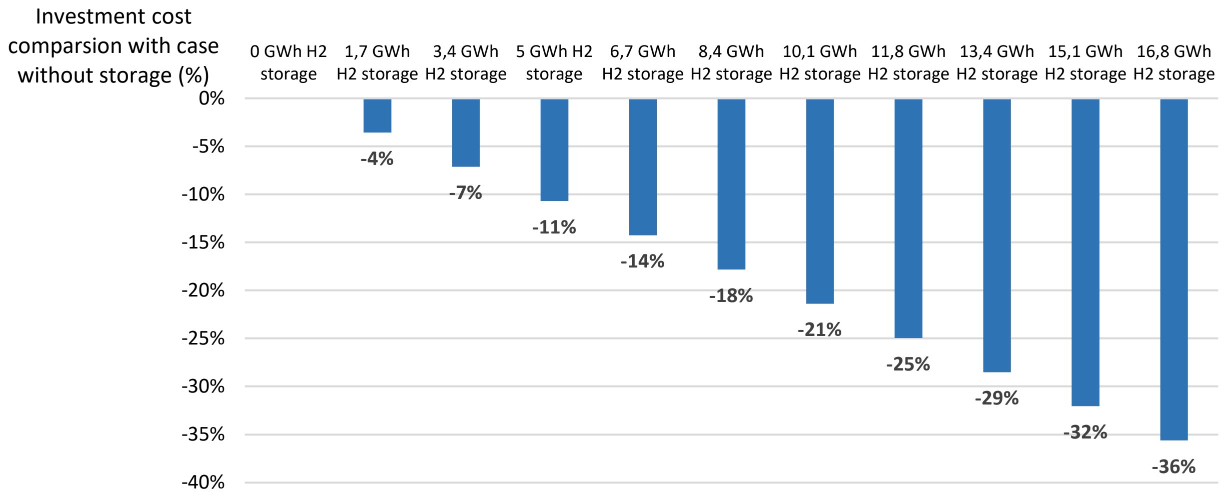


Use case# 4 (dedicated renewables + grid-connected and ability to inject on the grid)

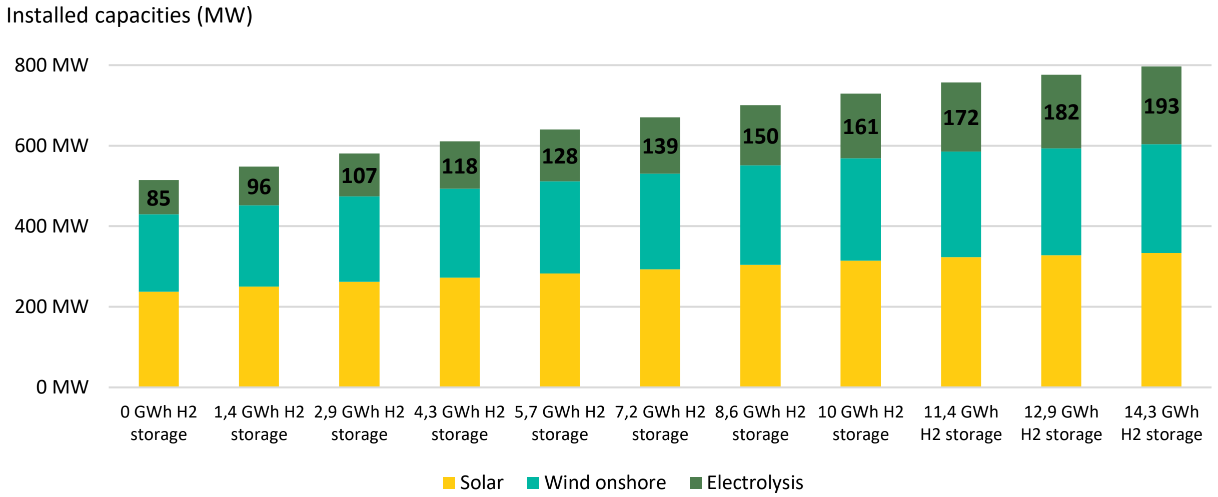
Kick-start value

By reducing overall hydrogen costs and optimizing the size of RES capacity, UHS enables **to facilitate the emergence of a hydrogen ecosystem**

- In all territorial use cases, the introduction of UHS results in lower hydrogen production cost (investment + operational costs, excluding the storage component).
- Several configurations show that **this reduction in costs is accompanied by an increase in the installed capacity of electrolysers** so as to enable a flexible operation of the entire system.
- Other configurations show that UHS allows to **decrease investments in alternative hydrogen production capacities**, thereby helping the emergence of a hydrogen ecosystem



Use case #2 (electrolytic hydrogen with connection to the grid + alternative supplier for thermosensitive consumers)



Use case #4 (dedicated renewables + grid-connected and ability to inject on the grid)

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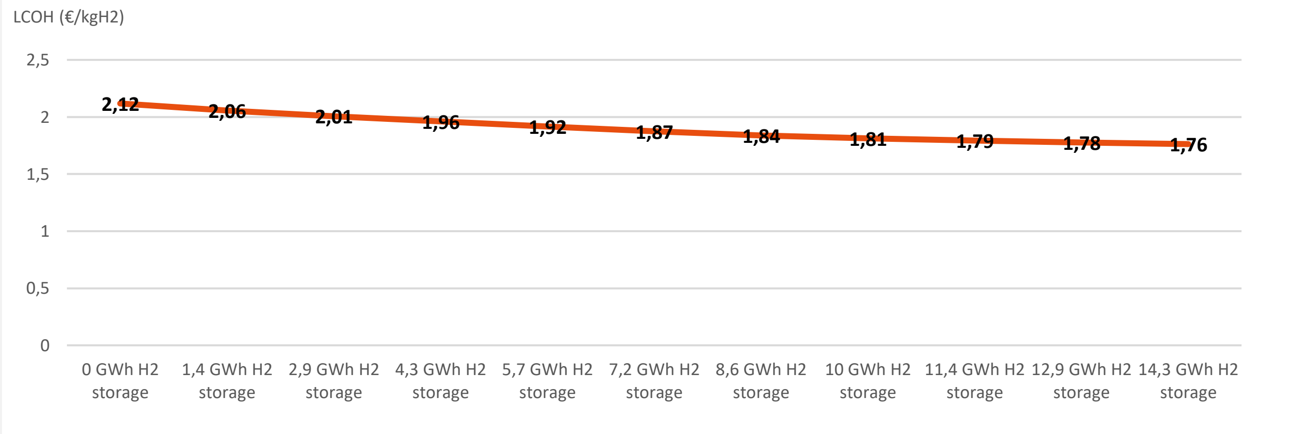
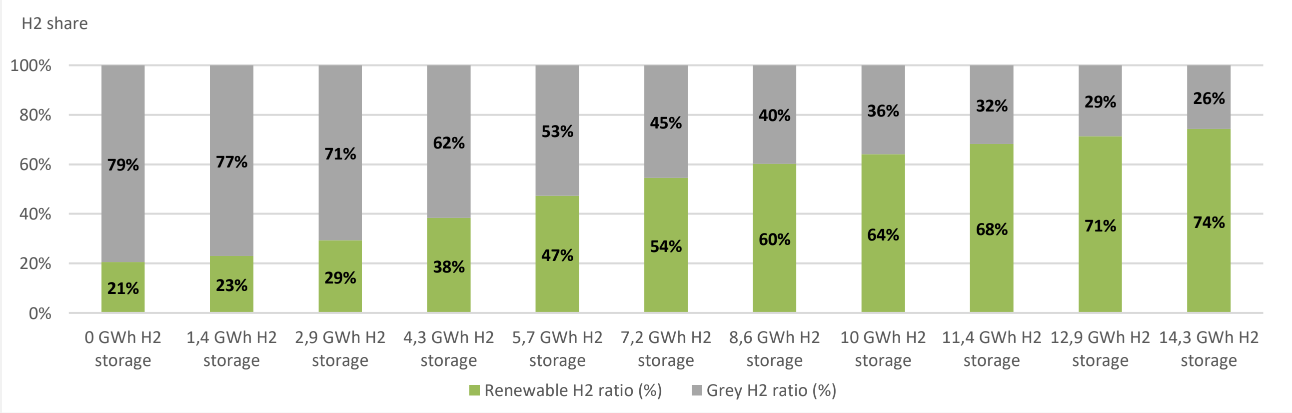
Appendix

Sensitivity for use case #1 – Results (1/2)

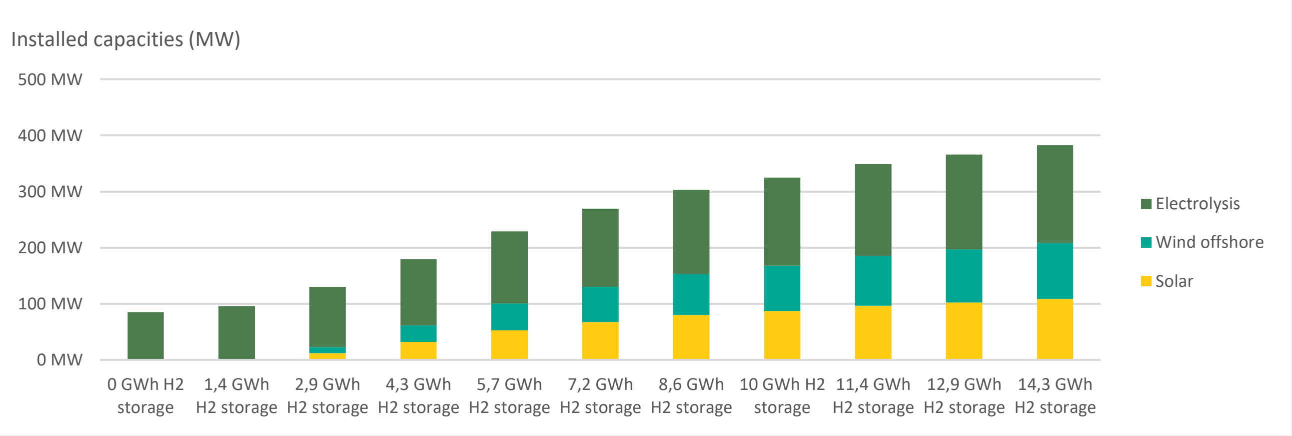
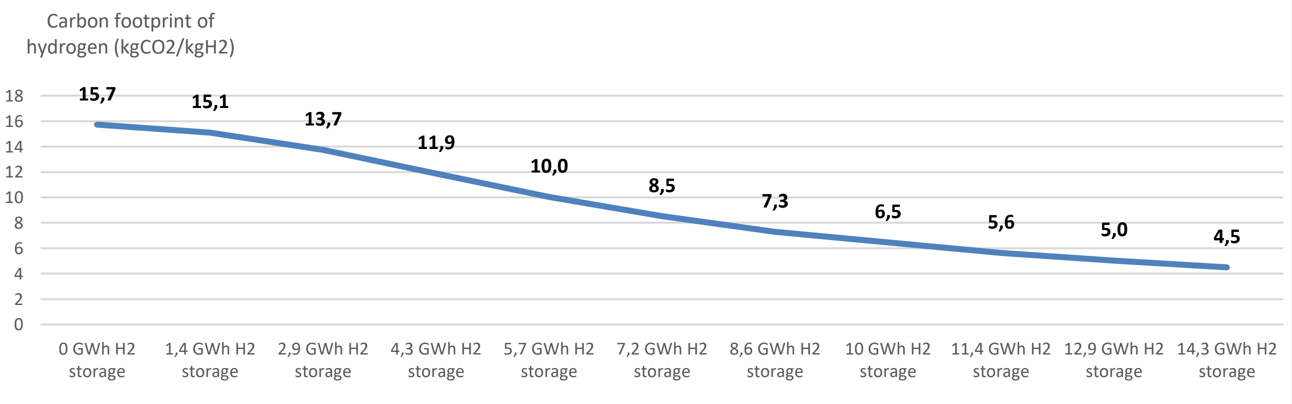
Sensitivity: Northern Europe country with an offshore wind/solar dedicated RES mix

System value	By allowing for a better use of RES resources and for a reduction of grid withdrawals, H2 storage **reduces the hydrogen costs** by circa 15%*.	
Arbitrage value	By enabling a better use of the cheapest hydrogen sources, the deployment of hydrogen storage technologies results in up to 50% more renewable H2 in the H2 mix.	

*storage investment cost are not included

Sensitivity for use case #1 – Results (2/2)

Sensitivity: Northern Europe country with an offshore wind/solar dedicated RES mix

Kick-start value	In order to exploit at best the dedicated renewables and the cheap prices of power market, H2 storage is key to meet criteria related to **additionality** and to facilitate the emergence of a hydrogen ecosystem.	
Environmental value	By promoting the use of decarbonised electricity for renewable hydrogen production, H2 storage **reduces the average carbon emissions of hydrogen** by more than **70%.**	

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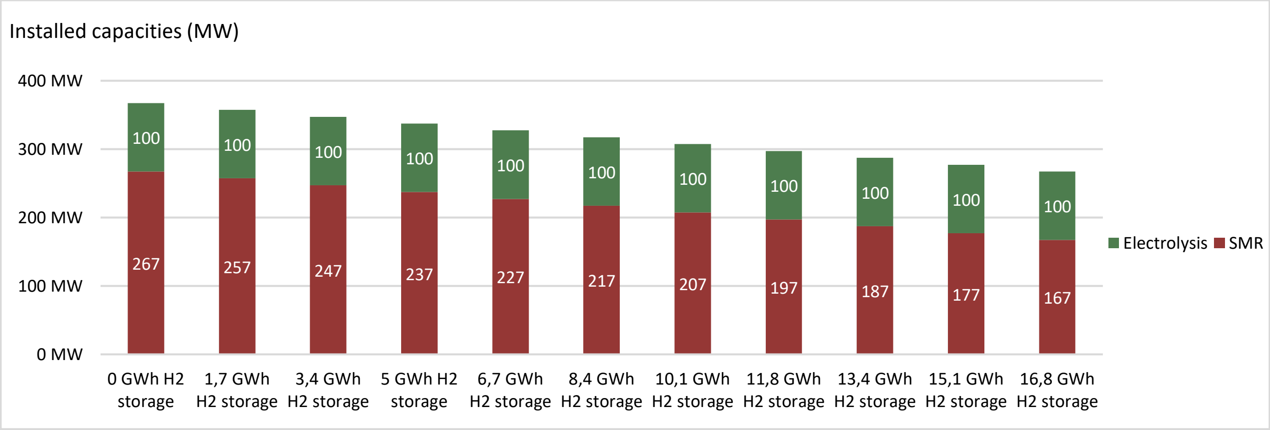
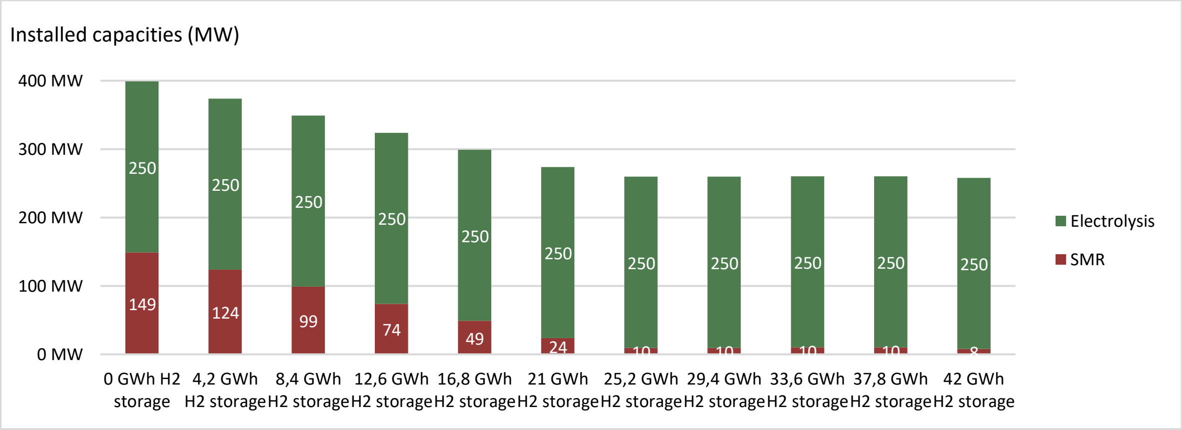
Sensitivity for use case #2 – Results (X/X)

Insurance value	By securing hydrogen supply, at a low cost, hydrogen storage **decreases the capacity needs of a back-up hydrogen supplier** (here SMR+CCS). The back-up capacity decreases with the size of the grid connection capacity.

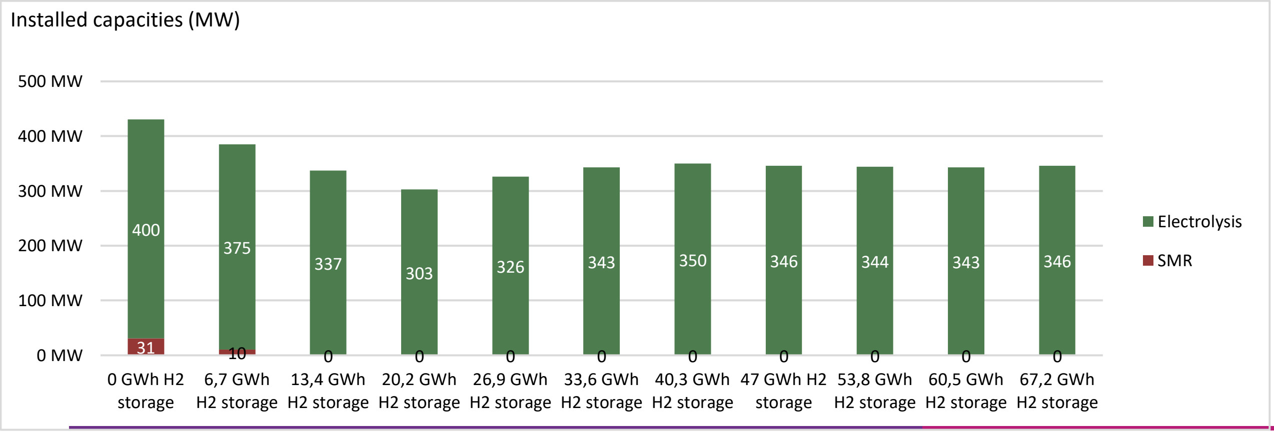
100 MW grid connection



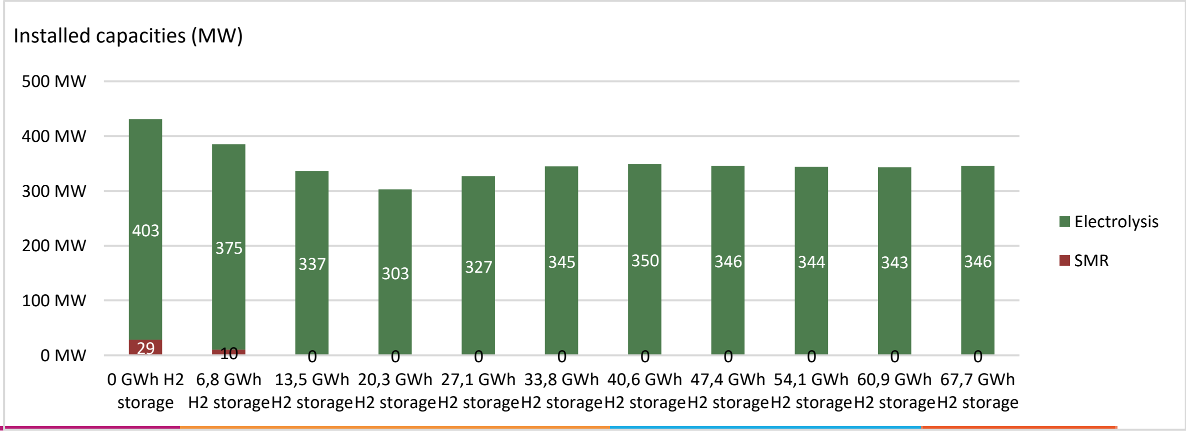
250 MW grid connection



400 MW grid connection



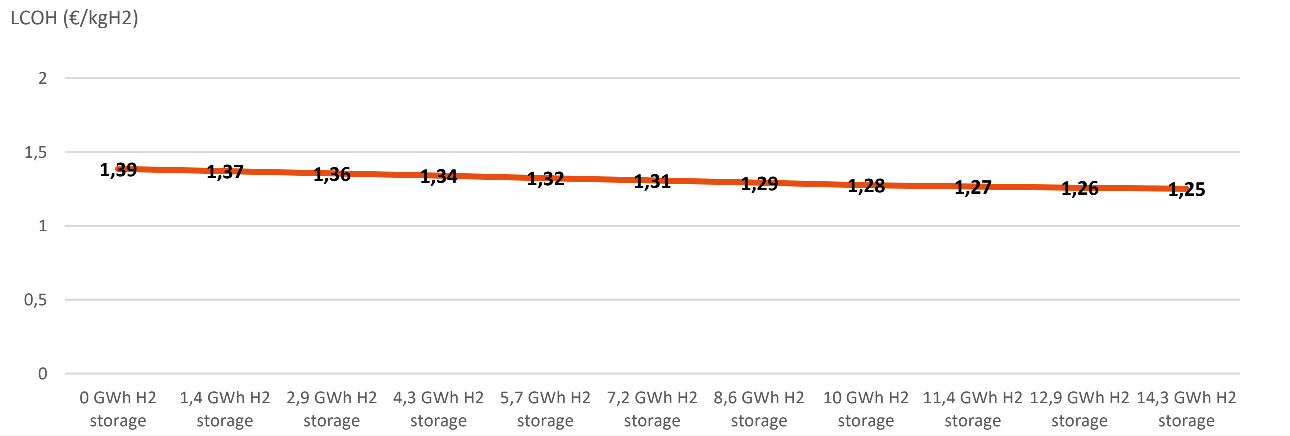
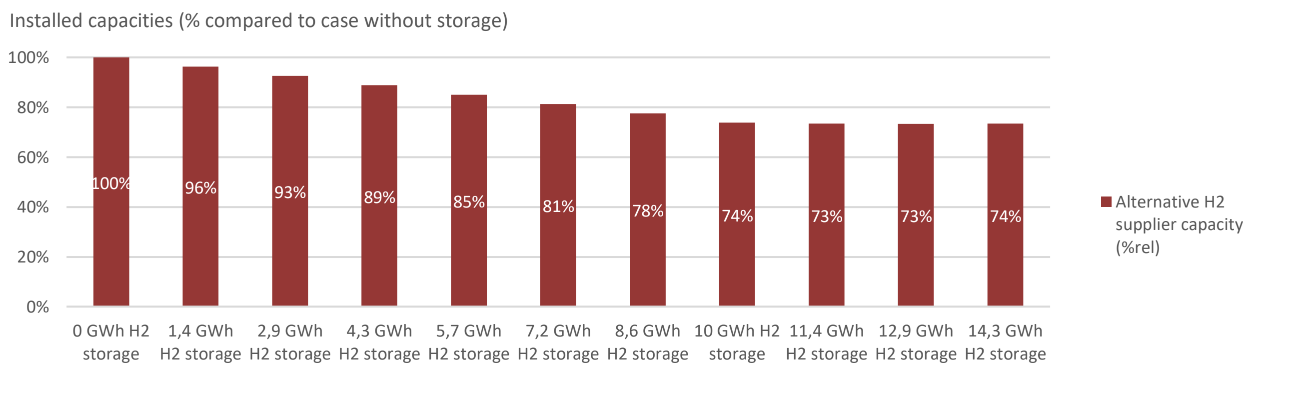
450 MW grid connection



Contents - Appendix

Sensitivity for use case #3 – Results (1/2)

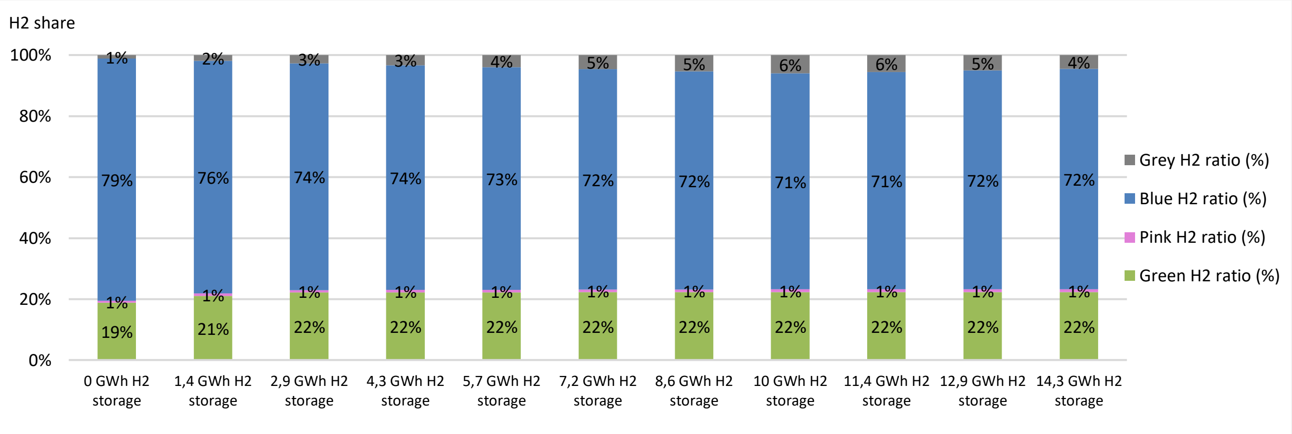
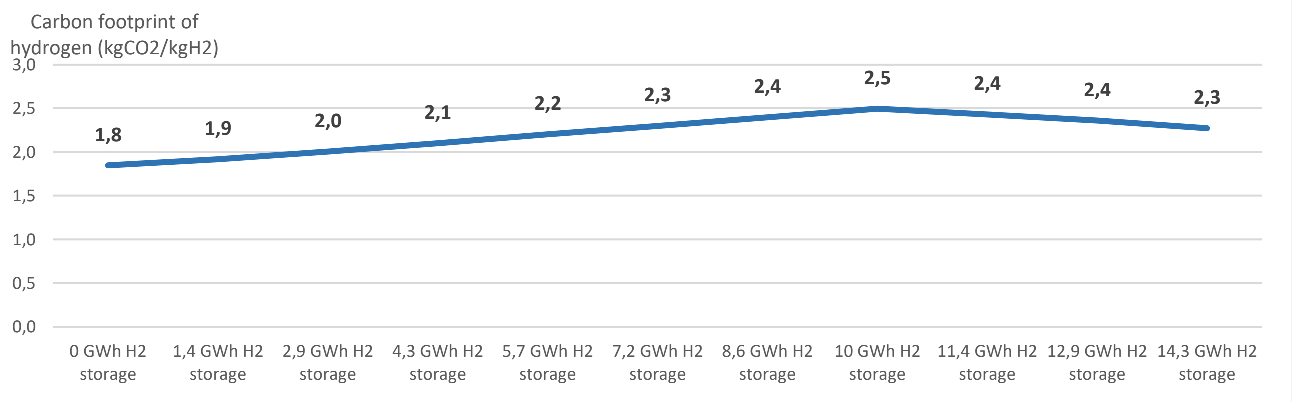
Sensitivity: Northern Europe country

System value	H2 storage allows to decrease investment in SMR+CCS by purchasing more electricity from the grid. This trade-off has a positive system impact as it **reduces LCOH by up to 9,6%***.	
Insurance value	By securing hydrogen supply, at a low cost, hydrogen storage **decreases the capacity needs of a back-up hydrogen supplier** (here SMR+CCS) by up to **26%.**	

*storage investment cost are not included

Sensitivity for use case #3 – Results (2/2)

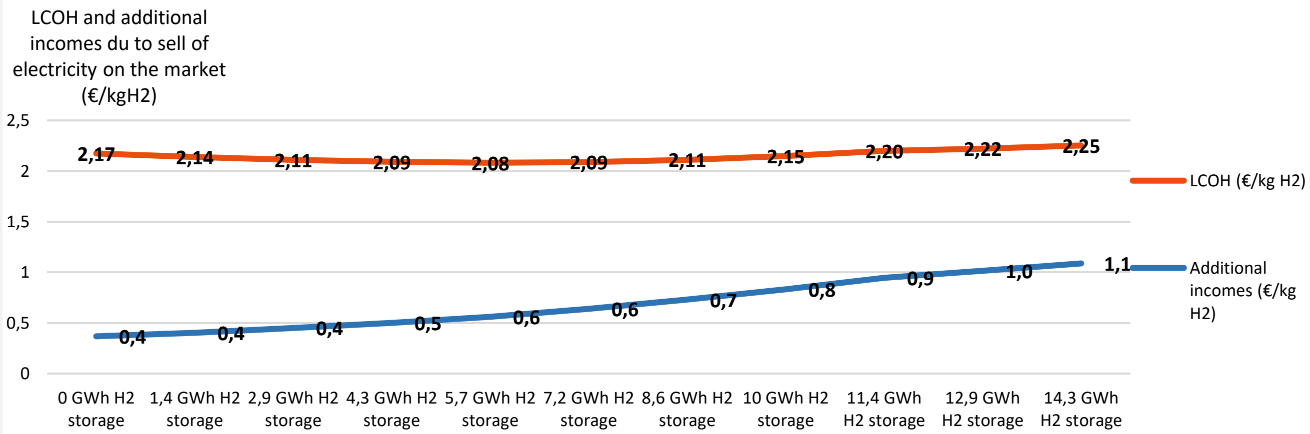
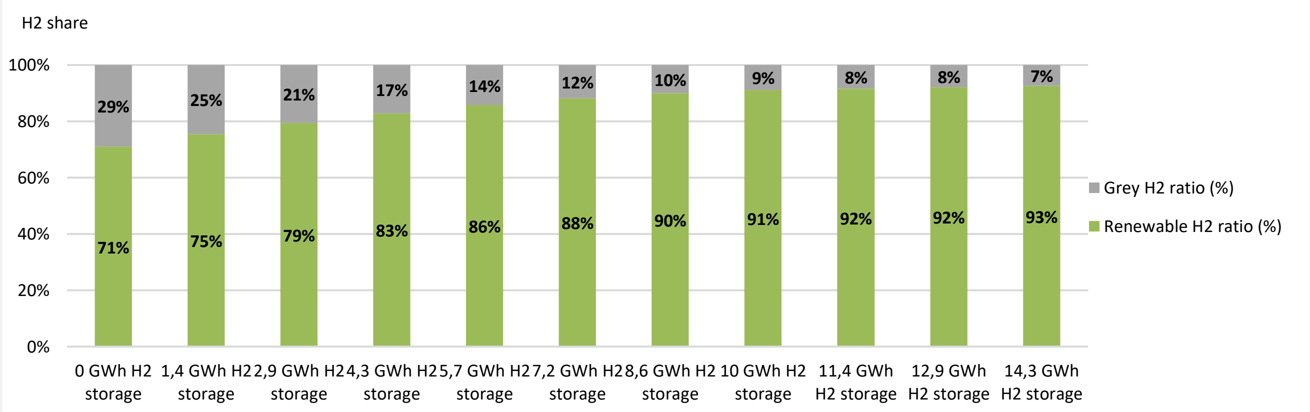
Sensitivity: Northern Europe country

Arbitrage value	In order to exploit at best the cheap prices of power market, H2 storage allows to **increase the renewable electrolytic hydrogen production by up to 3%** (green/pink H2). Electrolytic hydrogen production is also slightly increased since it is more economical to consume electricity during additional high-price hours (carbon intensive) than to invest in SMR + CCS.	
Environmental value	Increasing the storage size has **limited impacts on CO2 emissions** since it is more economical to consume electricity during additional high-price hours (carbon intensive) than to invest in SMR + CCS. However, the overall carbon intensity remains low, as the alternative H2 supply is not carbon intensive (SMR+CCS).	

Contents - Appendix

Sensitivity for use case #4 – Results (1/4)

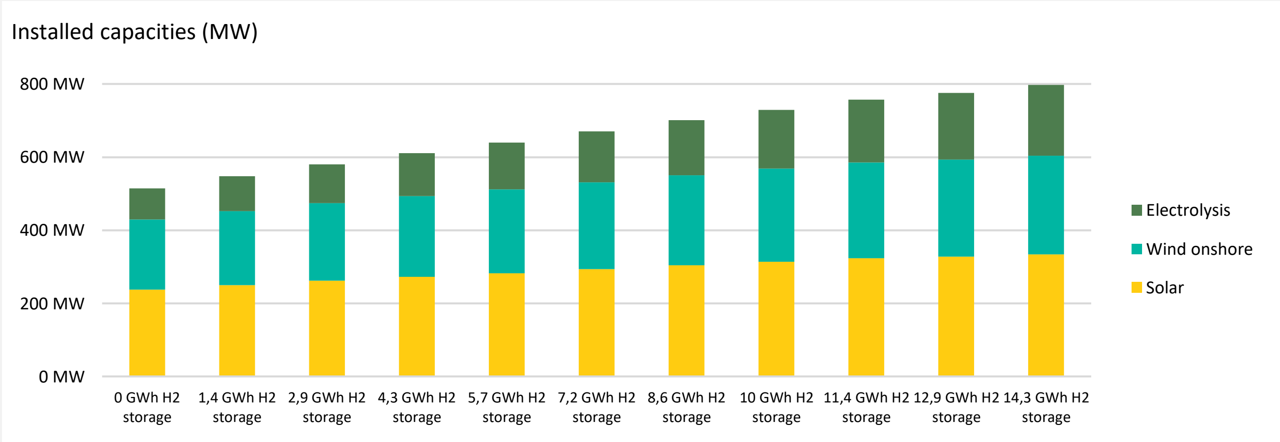
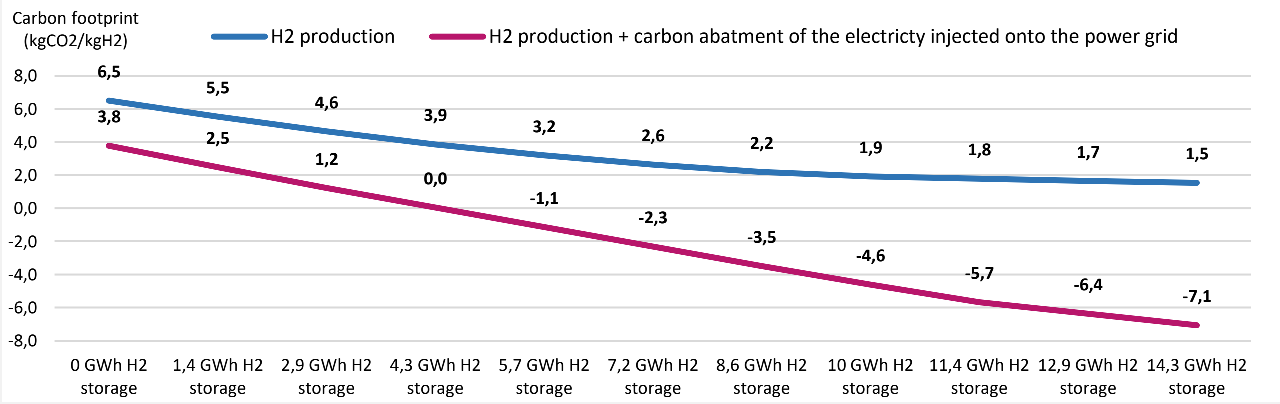
Sensitivity: **50/50%** share of solar and wind in the dedicated renewable generation mix

System value	By reducing the cost of the electricity being withdrawn from the grid, H2 storage **reduces the hydrogen costs**. The amount of electricity sold to the market increases with storage. Curtailment decreases.	
Arbitrage value	By making **a better use of the cheapest hydrogen sources,** hydrogen storage increases the penetration of renewable hydrogen suppliers (up to 20%). Hydrogen storage also ables a least-cost arbitrage between withdrawal and injection of electricity from/onto the grid.	

*storage investment cost are not included

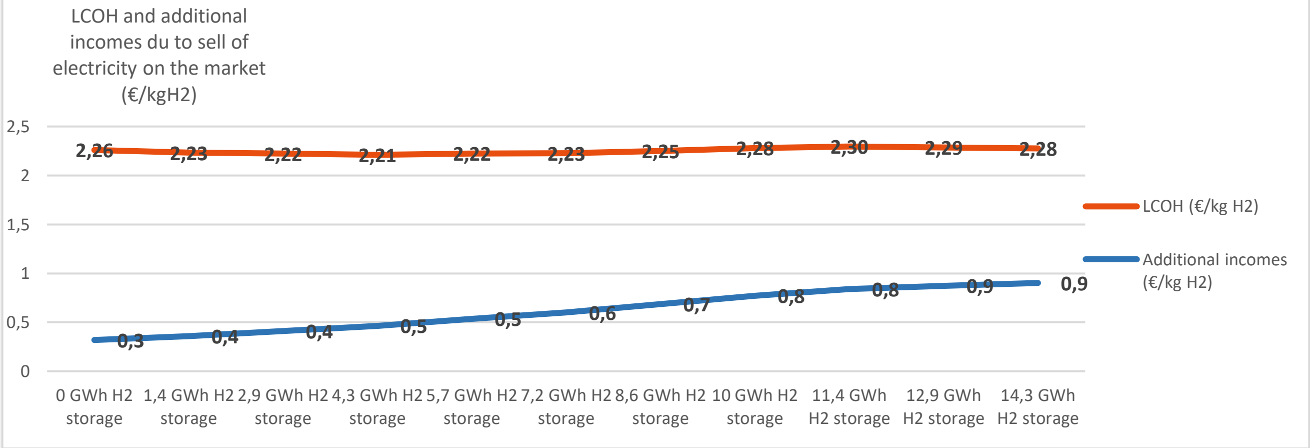
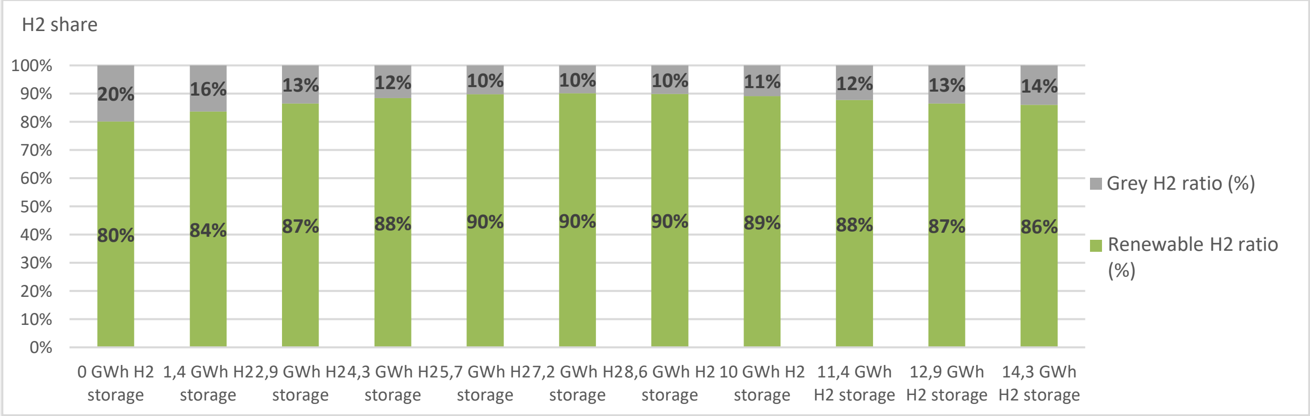
Sensitivity for use case #4 – Results (2/4)

Sensitivity: **50/50%** share of solar and wind in the dedicated renewable generation mix

Kick-start value	The electrolysis capacity and renewable generation capacity increase when hydrogen storage increases. The load factor of electrolysers drops as a consequence: storage allows for a system-level optimisation of electrolysis and renewable electricity production	
Environmental value	By increasing the power injection from the on-site renewables onto the grid, **hydrogen storage contributes to GHG abatement** in the power system.	

Sensitivity for use case #4 – Results (3/4)

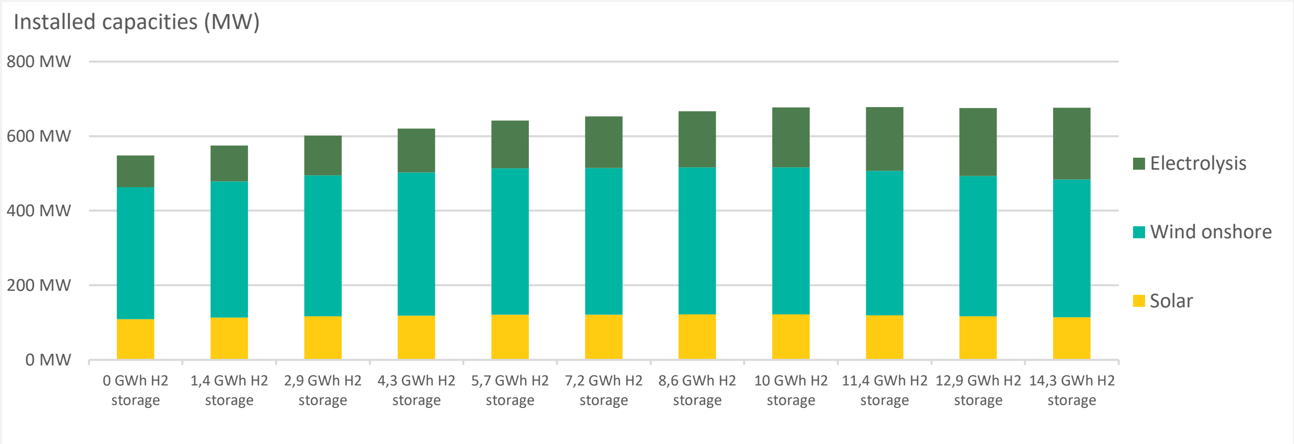
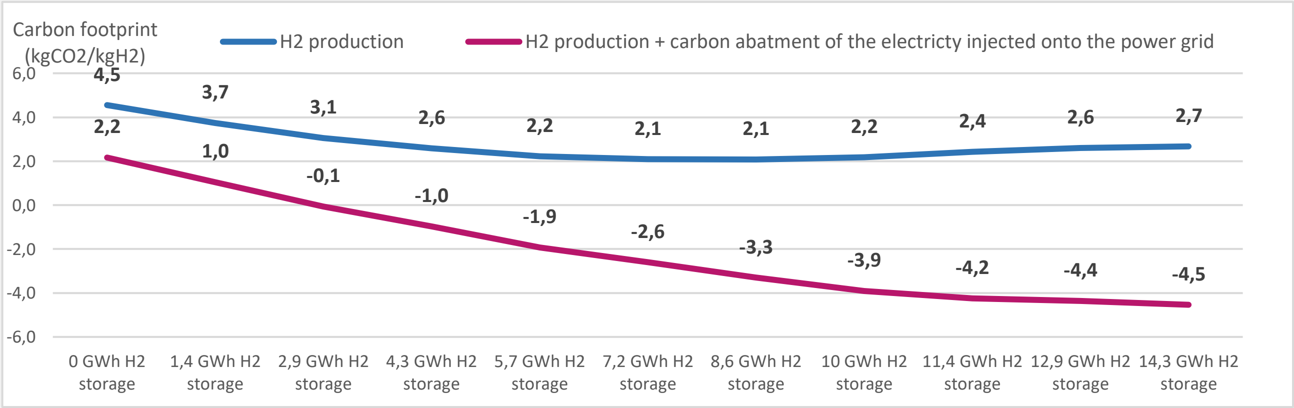
Sensitivity: **20/80%** share of solar and wind in the dedicated renewable generation mix

System value	By reducing the cost of the electricity being withdrawn from the grid, H2 storage **reduces the hydrogen costs** by up to 22%*. The amount of electricity sold to the market increases with storage, providing additional incomes to the use case including storage.	
Arbitrage value	By making **a better use of the cheapest hydrogen sources,** hydrogen storage increases the penetration of renewable hydrogen suppliers (up to 10%). Hydrogen storage also ables a least-cost arbitrage between withdrawal and injection of electricity from/onto the grid.	

*storage investment cost are not included

Sensitivity for use case #4 – Results (4/4)

Sensitivity: **20/80%** share of solar and wind in the dedicated renewable generation mix

Kick-start value	The electrolysis capacity and renewable generation capacity increase when hydrogen storage increases. The load factor of electrolysers drops as a consequence: storage allows for a system-level optimisation of electrolysis and renewable electricity production	
Environmental value	By increasing the power injection from the on-site renewables onto the grid, **hydrogen storage contributes to GHG abatement** in the power system.	

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