Artelys | OPTIMIZATION SOLUTIONS

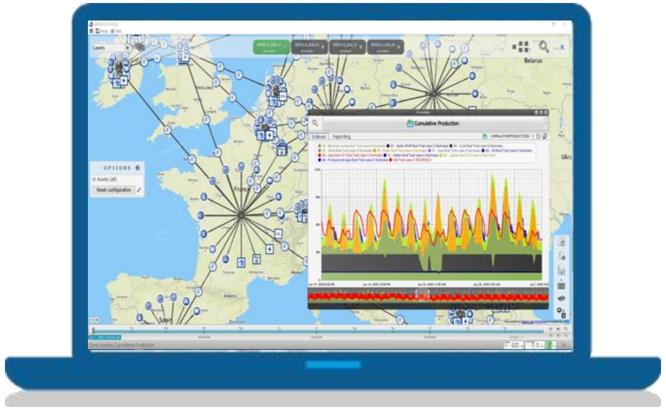
Gas Infrastructure Europe

Showcasing the pathways and values of underground hydrogen storages

Presentation of the final report

October 2022

Artelys



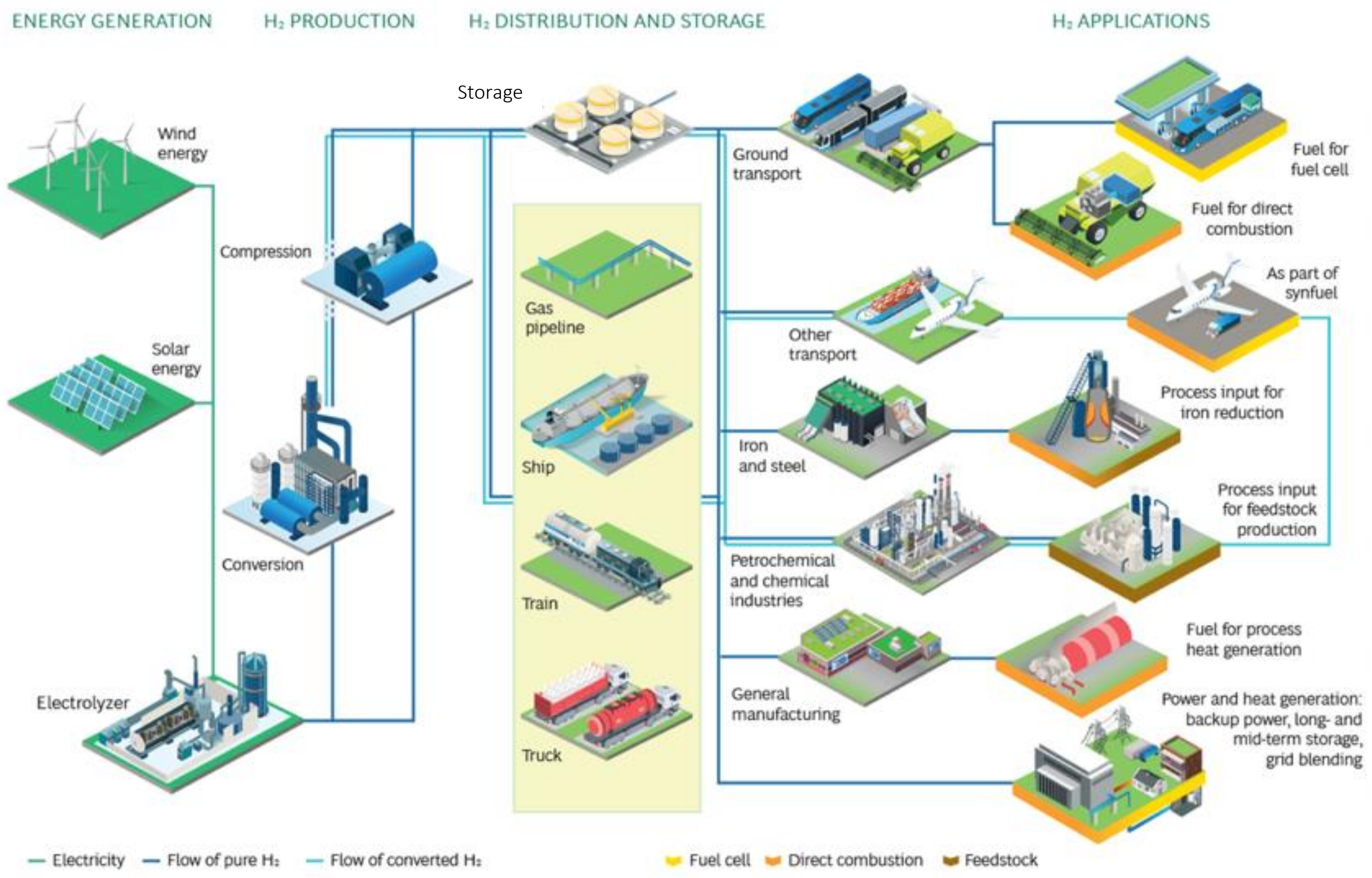
Artelys Crystal SuperGrid

- Artelys is an **independent** software edition and consulting company specialised in decision support, modelling and optimisation
- Founded in **2000** by its current President, Arnaud Renaud
- More than **300 customers** in **40 countries**
- Around **100 members of staff** in Paris, Nantes, Lyon, Brussels, Madrid, Montréal, and Chicago
- Artelys is active in **multiple areas**: energy, resource planning, logistics, transport and mobility
- In the energy sector, we work for clients all along the value chain (utilities, associations, TSOs, DSOs, SSOs, NRAs, ministries, agencies, EC, etc.)

Contents

Hydrogen will be part of 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.

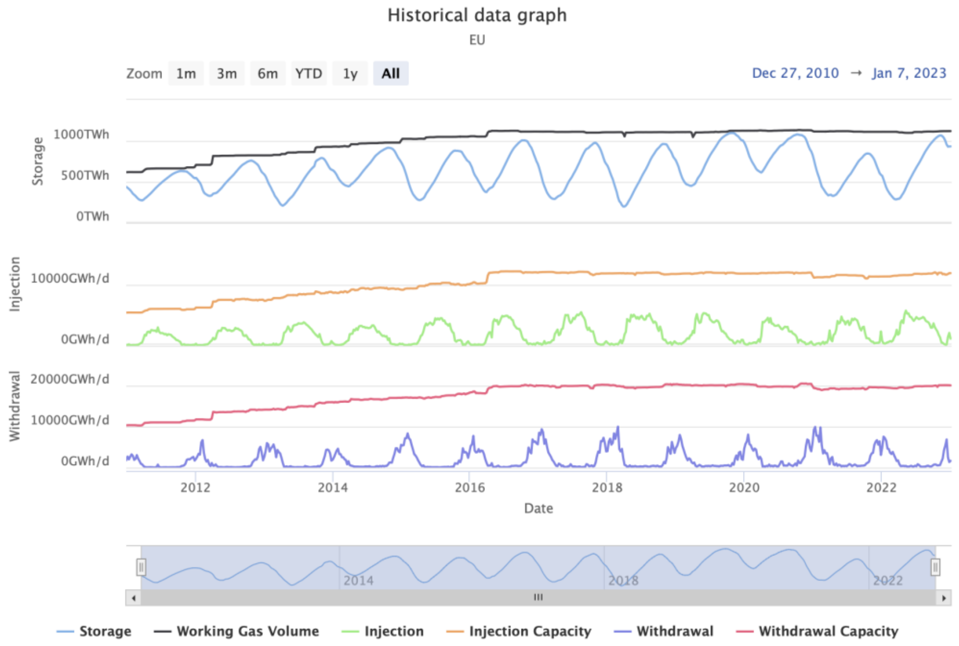


Source: BCG analysis

Key question: what role for hydrogen storage?

- To answer that question, let's look at the role of the infrastructure developed for methane. It is at the forefront of the provision of flexibility services to the EU energy system, via, for instance, storage in salt caverns, depleted oil/gas fields, aquifers, lined rock caverns, etc.

	Methane infrastructure	
	Consumption	Production
Drivers of hourly flexibility needs (and below)	Daytime vs night-time activities (residential, tertiary)	Methane production and imports are largely constant over these timescales (except in cases of maintenance)
Drivers of weekly flexibility needs	Weekday vs weekend activities (residential, tertiary)	
Drivers of seasonal flexibility needs (and higher)	Thermo-sensitivity (mostly residential)	



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	Methane infrastructure		Hydrogen infrastructure	
	Consumption	Production	Consumption	Production (for electrolytic H2)
Drivers of hourly flexibility needs (and below)	Daytime vs night-time activities (residential, tertiary)	Methane production and imports are largely constant over these timescales (except in cases of maintenance)	Daytime vs night-time 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)	Thermo-sensitivity (mostly residential)		Thermo-sensitivity (mostly residential)	RES production variability (hydro, wind and solar PV), network congestions

Additional drivers of flexibility needs, specific to electrolytic hydrogen

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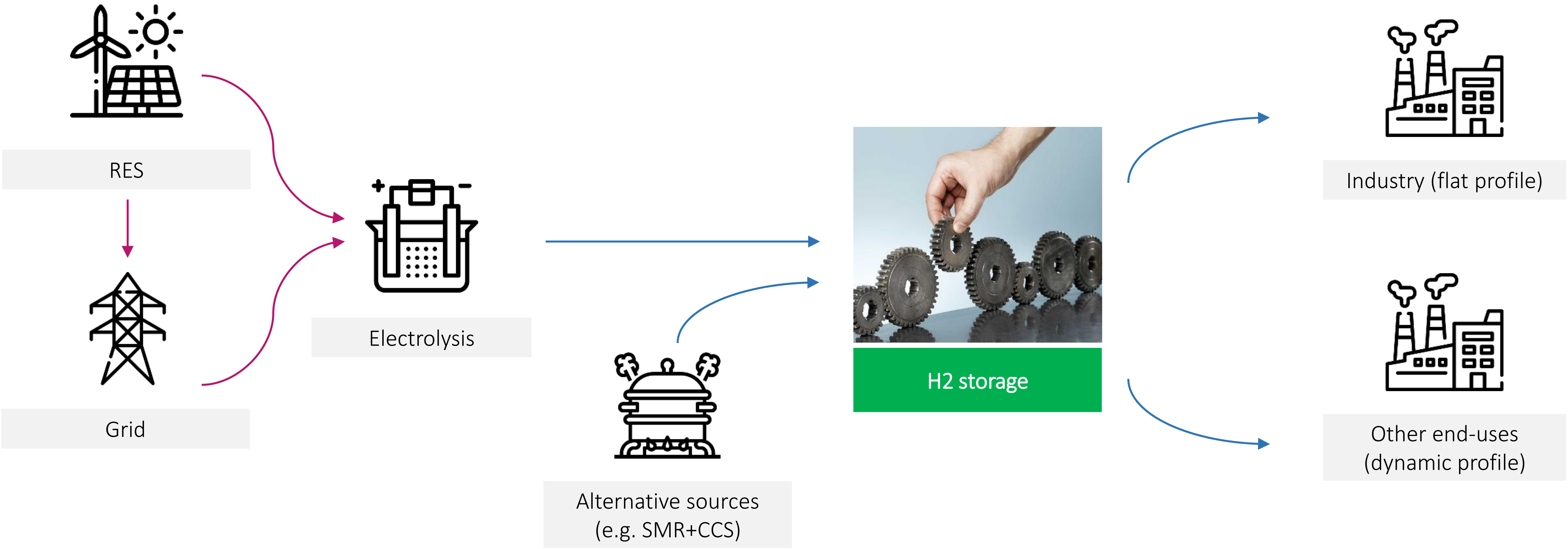
Additional drivers of flexibility needs, specific to electrolytic hydrogen

- 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.

Objectives of the study

- **Objective 1** - Identify and characterise the values of underground hydrogen storage, recognising cross-sectoral interactions
- **Objective 2** - Illustrate these values on a selection of territorial use-cases



Contents

How to identify the values of hydrogen storage?

- Hydrogen storage provides different services to the energy system. In this study, we have aimed at identifying the values of storage by asking the following question:

> "What are the impacts of having access to hydrogen storage compared to a situation without hydrogen storage, or with a regulatory regime hampering the provision of flexibility?"

How to identify the values of hydrogen storage?

- Hydrogen storage provides different services to the energy system. In this study, we have aimed at identifying the values of storage by asking the following question:

"What are the impacts of having access to hydrogen storage compared to a situation without hydrogen storage, or with a regulatory regime hampering the provision of flexibility?"

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

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.

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.

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.

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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.

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Kick-start value (Specific to H2)	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.

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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.

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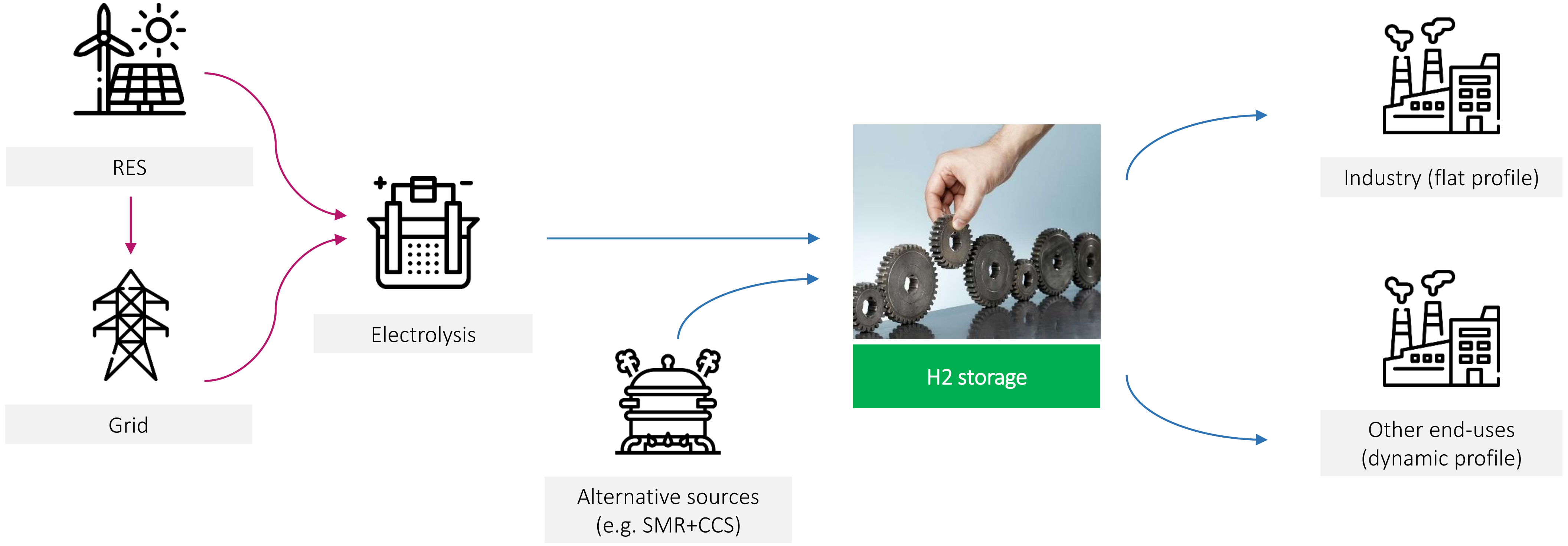
Contents

Quantification of values in selected use-cases

- Four territorial use-cases representing different virtual 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.



List of selected territorial use-cases

#1	On-site green hydrogen production for an 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
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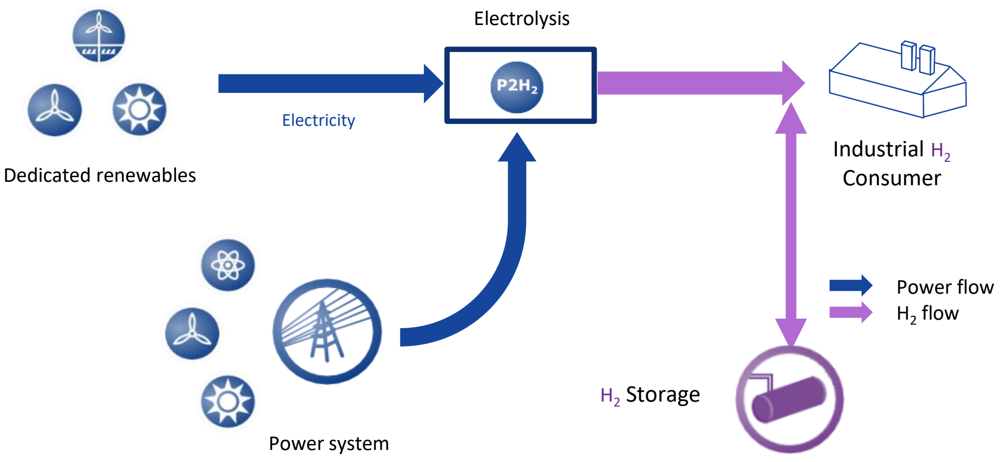
Use-case #1 – Overview

On-site green hydrogen production for industrial consumer

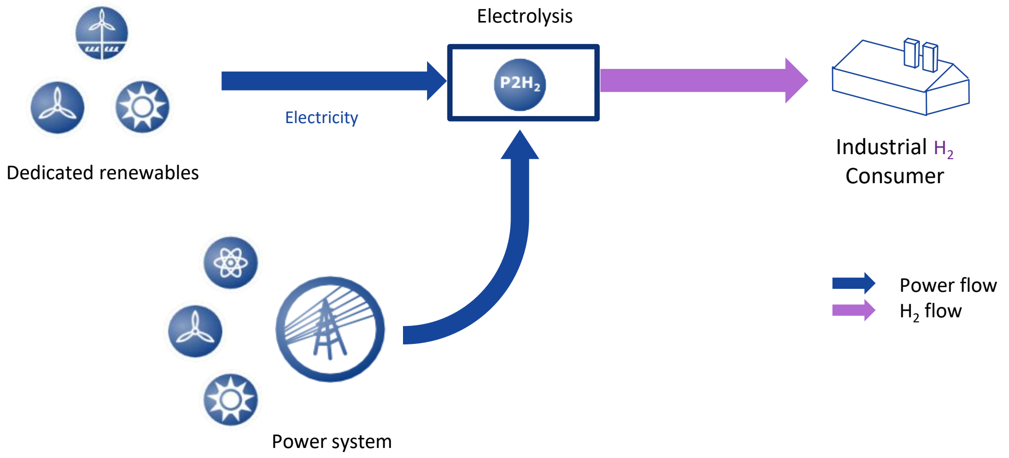


We have analysed the impacts of gradually adding hydrogen storage into the use-cases on (a) investments (RES, electrolysers, etc.) and (b) hourly operations.

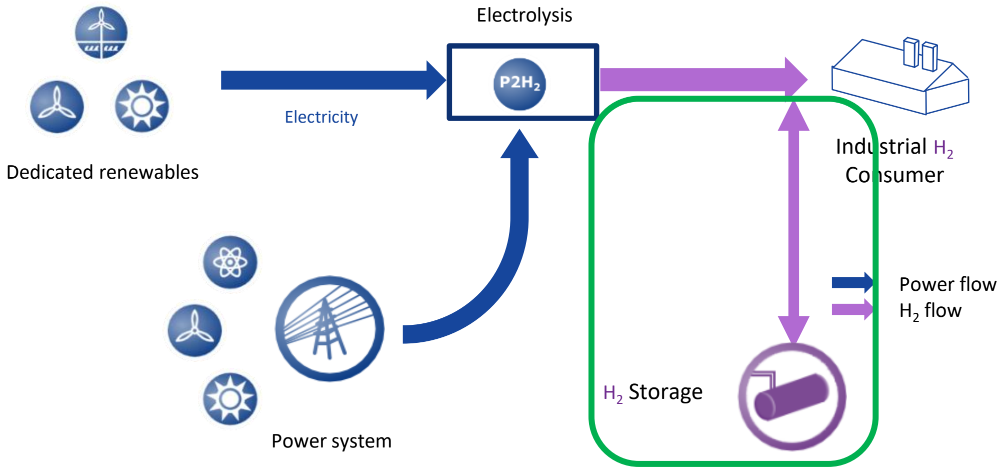
Territorial use case #1 – Effects of hydrogen storage

On-site green hydrogen production for industrial consumer

Configuration 1 – Without access to hydrogen storage



Configuration 2 – With access to hydrogen storage



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.

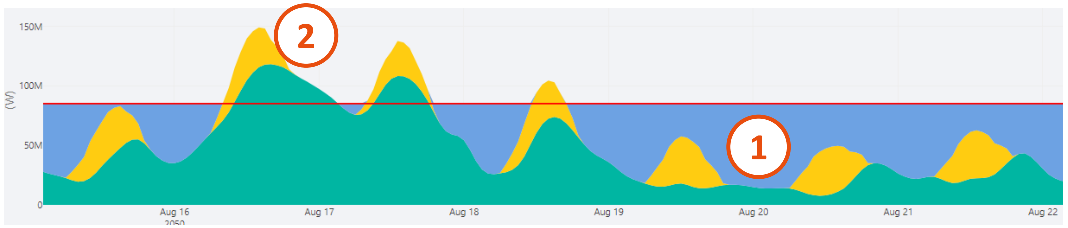
A system with UHS (right): better use of RES and better capture of low electricity prices

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

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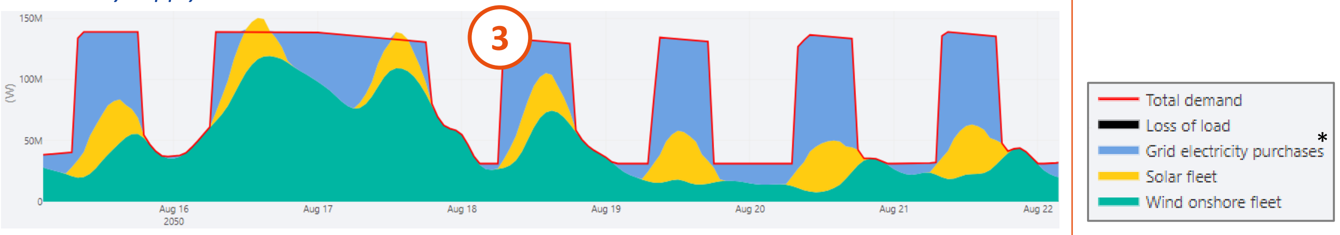

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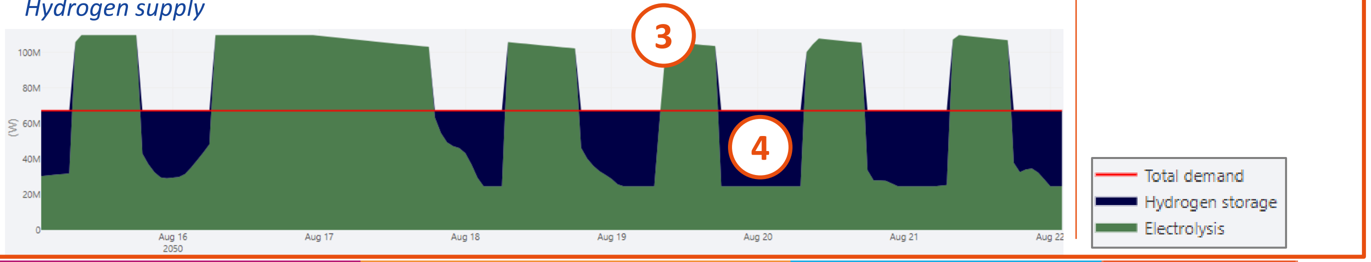

*The purchase of electricity from the grid (in blue on the charts) can be either renewable or fossil. The introduction of storage reduces the carbon footprint of the electricity being withdrawn.

Territorial use case #1 – Effects of hydrogen storage

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

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

Total demand
Loss of load
Grid electricity purchases*
Solar fleet
Wind onshore fleet

Hydrogen supply

Total demand
Hydrogen storage
Electrolysis

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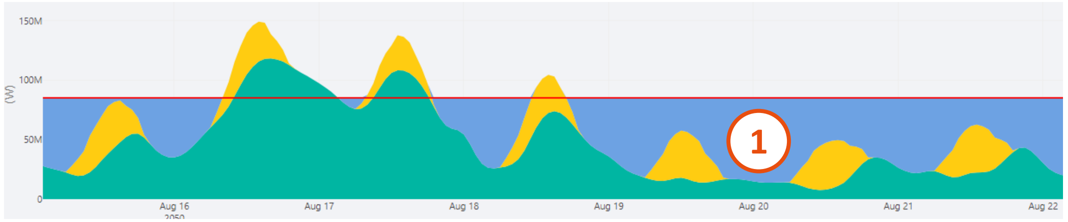

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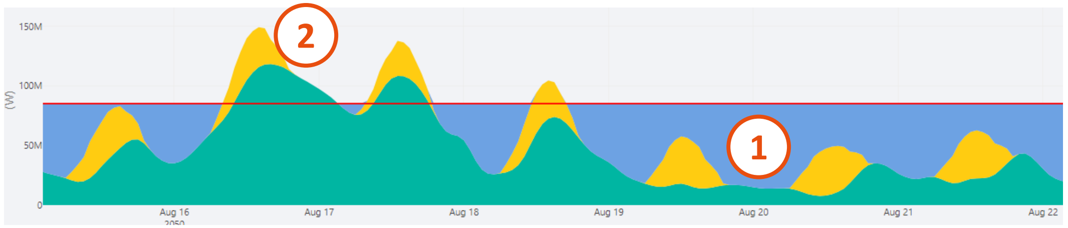

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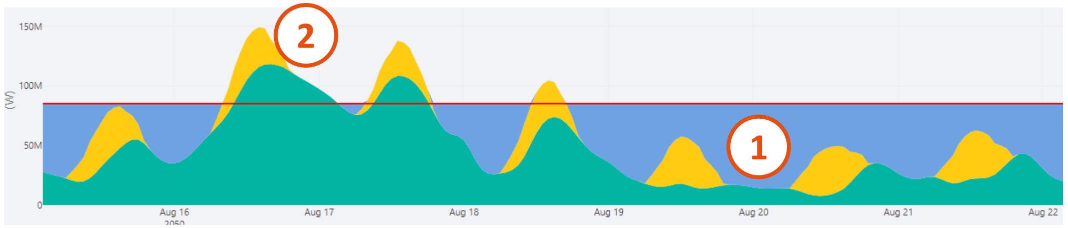

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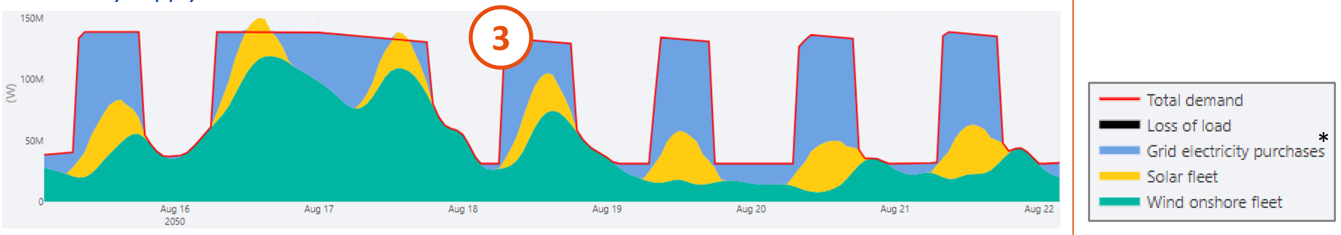

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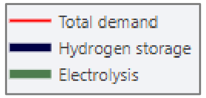

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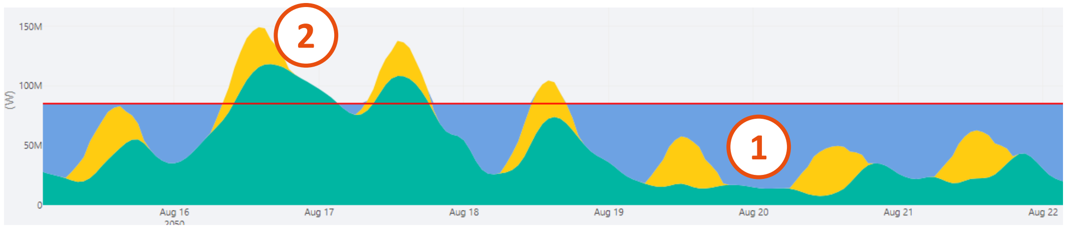

Hydrogen supply

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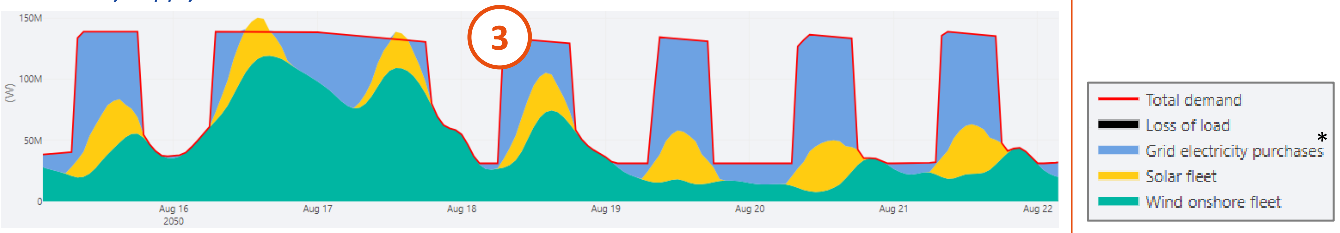

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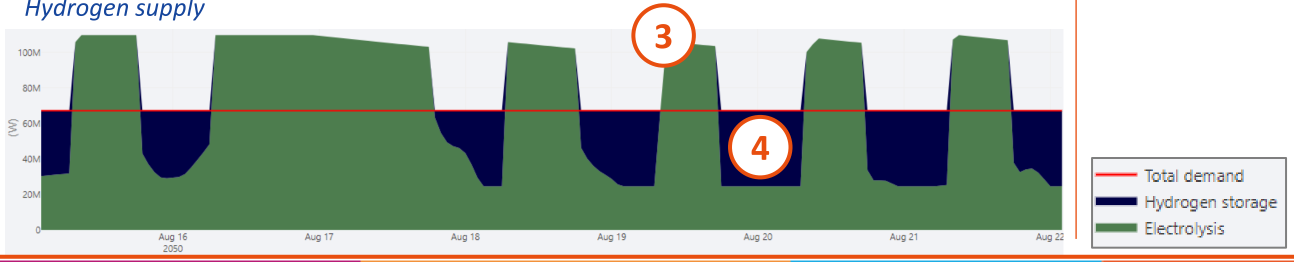

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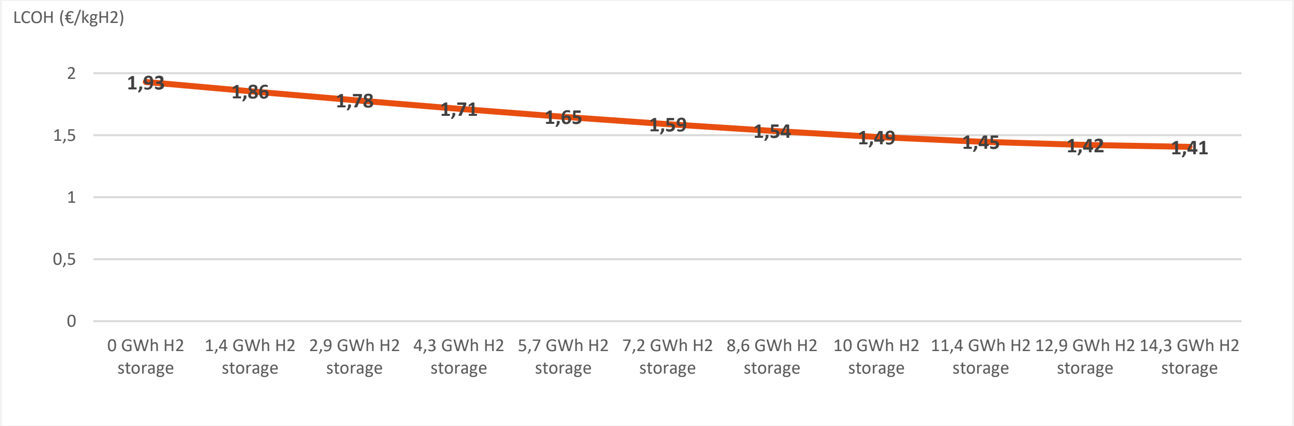
Territorial use case #1 – Results (1/2)

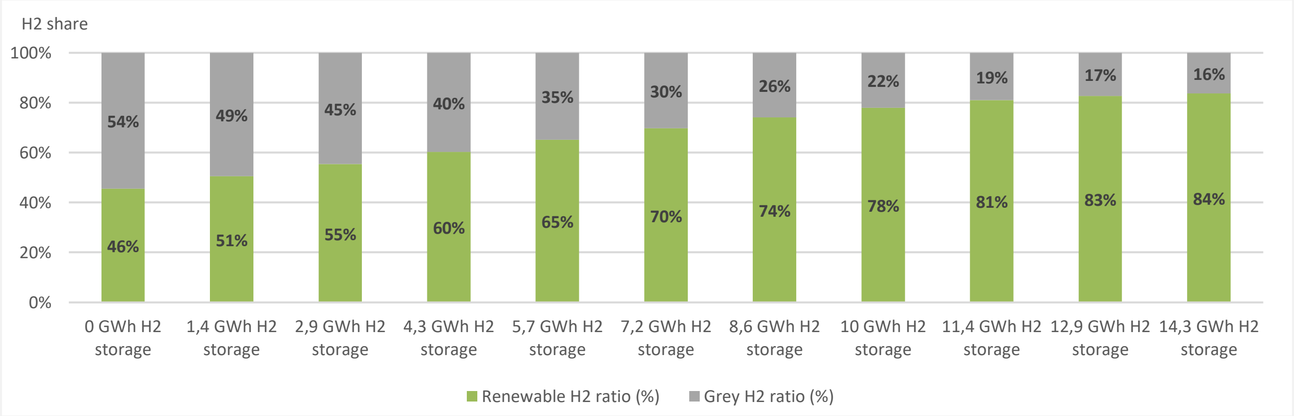
System value

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%*.



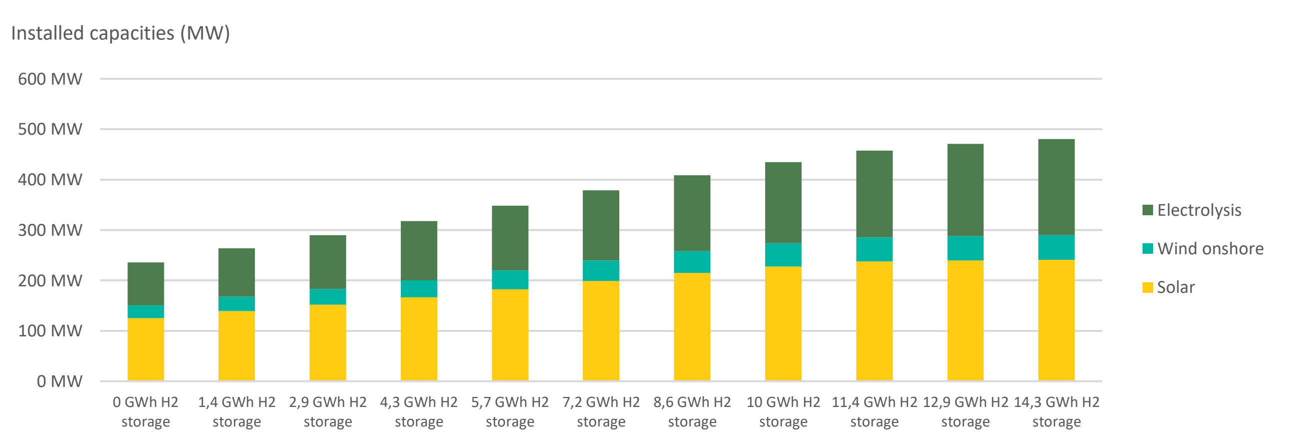
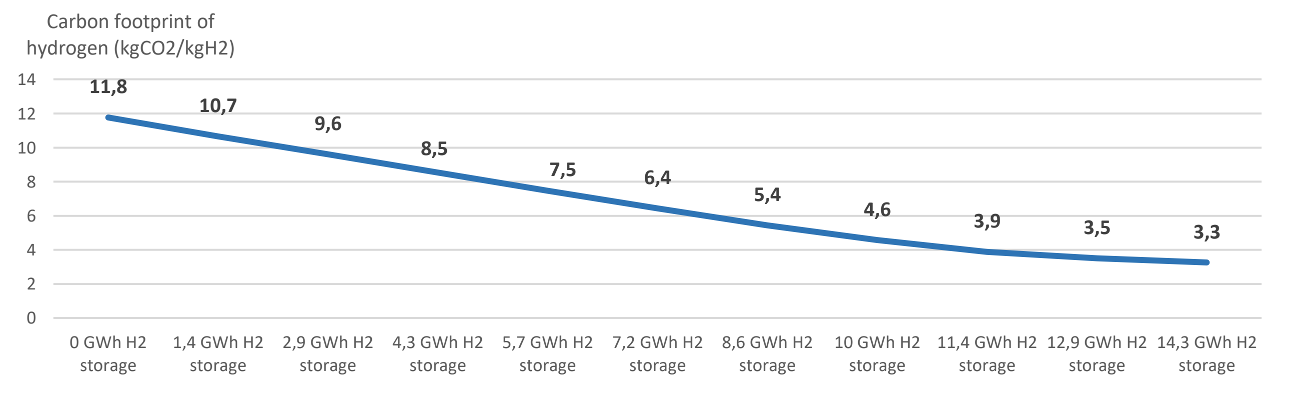
Arbitrage value

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%**.	

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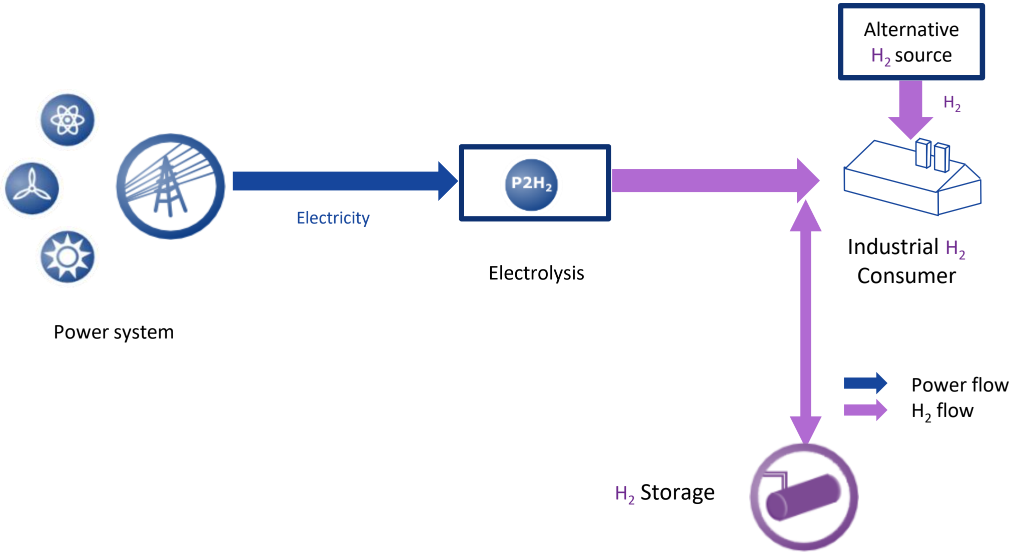
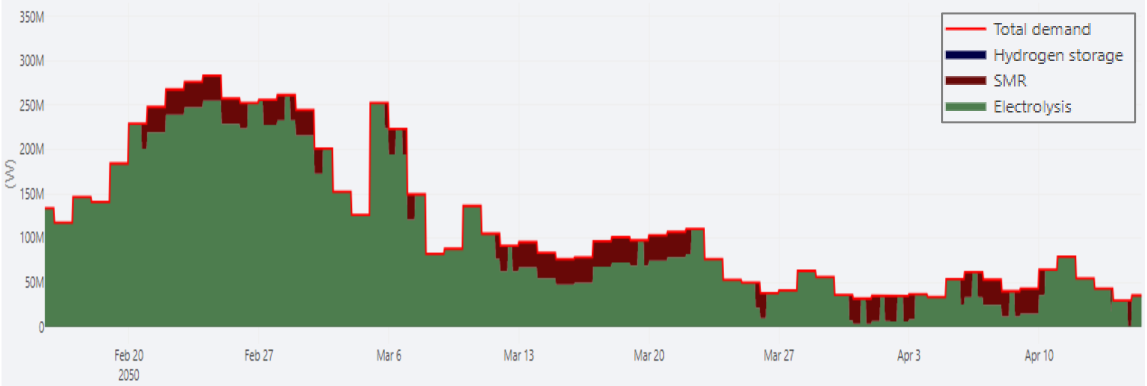
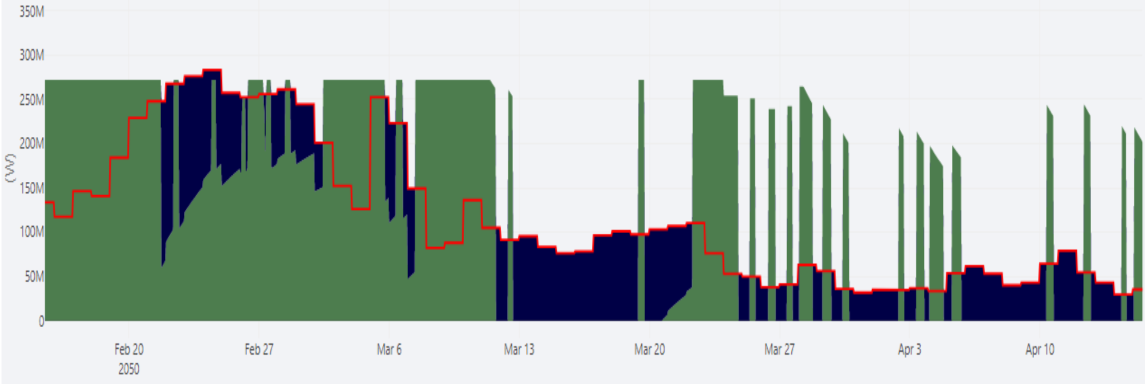
Use-case #2 – Overview

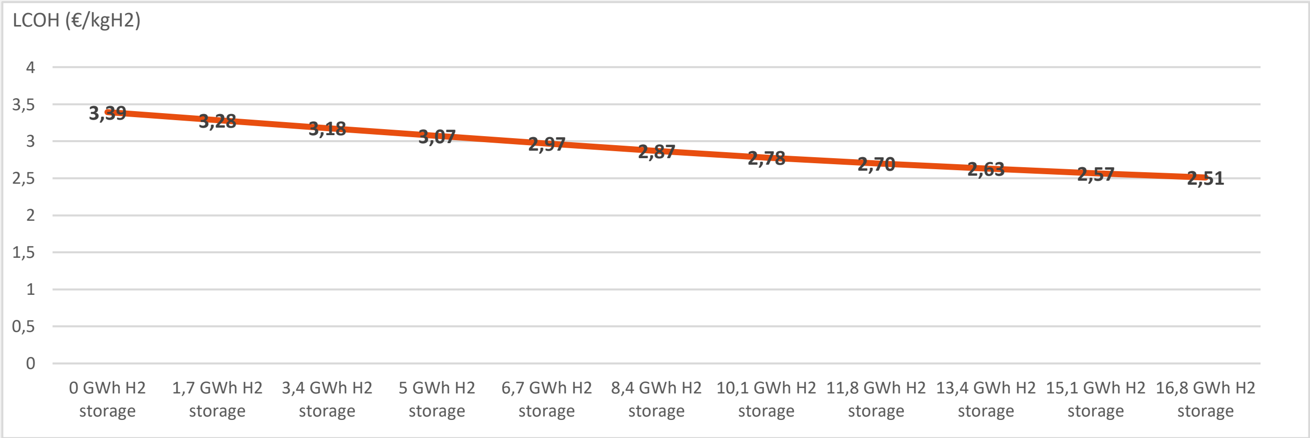
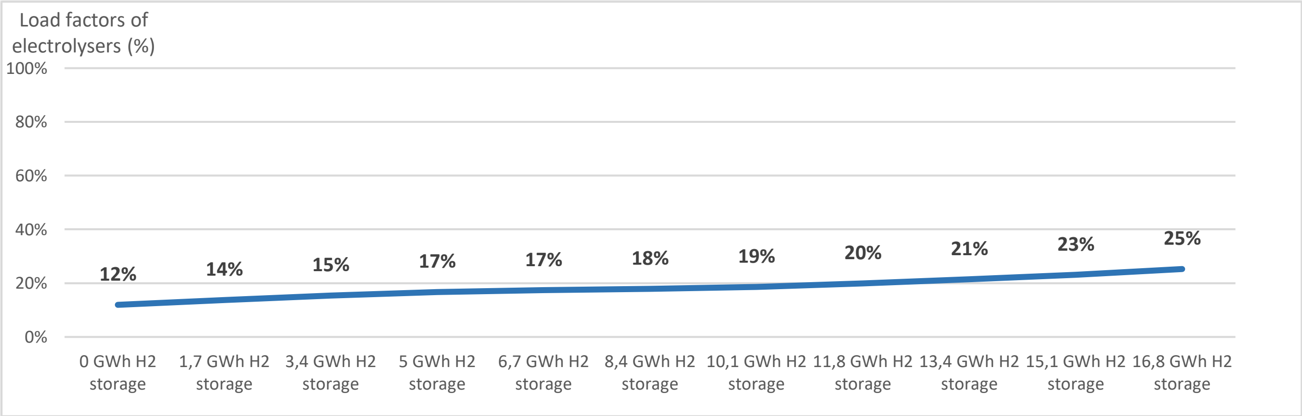
Hydrogen production from grid-connected electrolysis for thermosensitive consumer (heating) backed-up by an alternative supply option





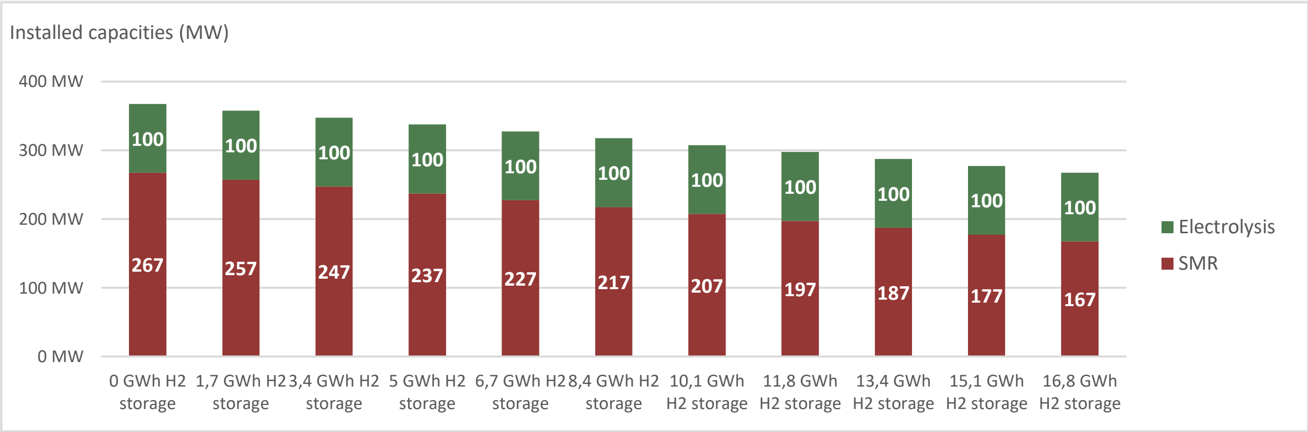
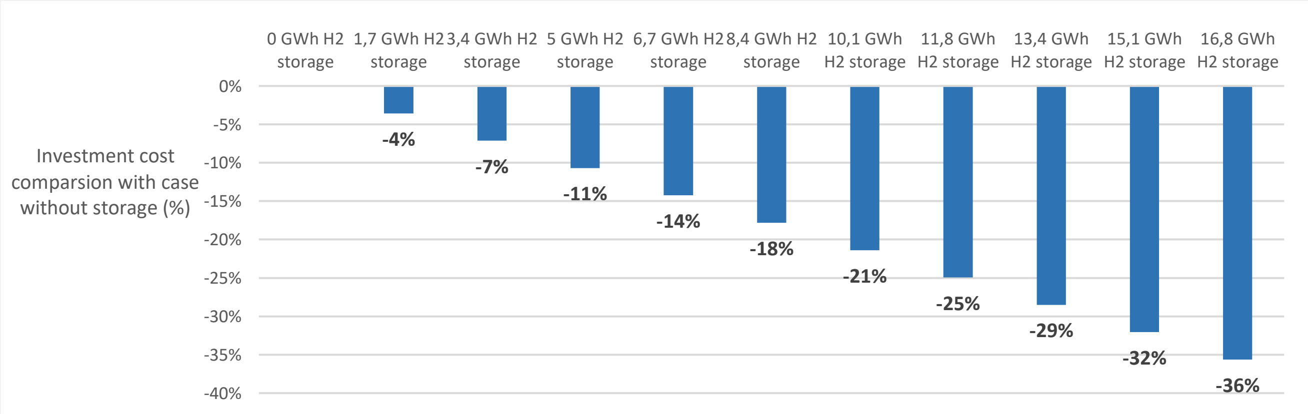


Territorial use case #2 – Results (1/2)

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

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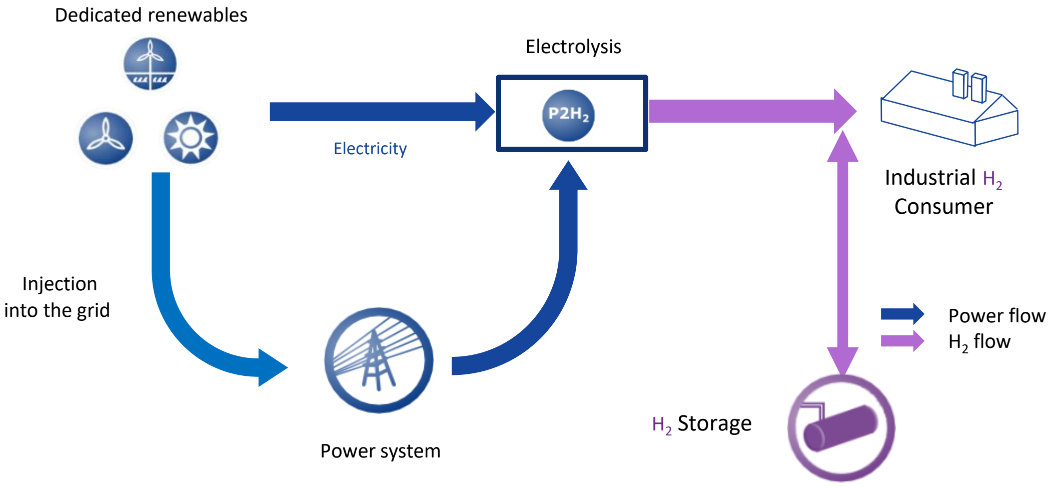
Use-case #4 – Overview

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



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.

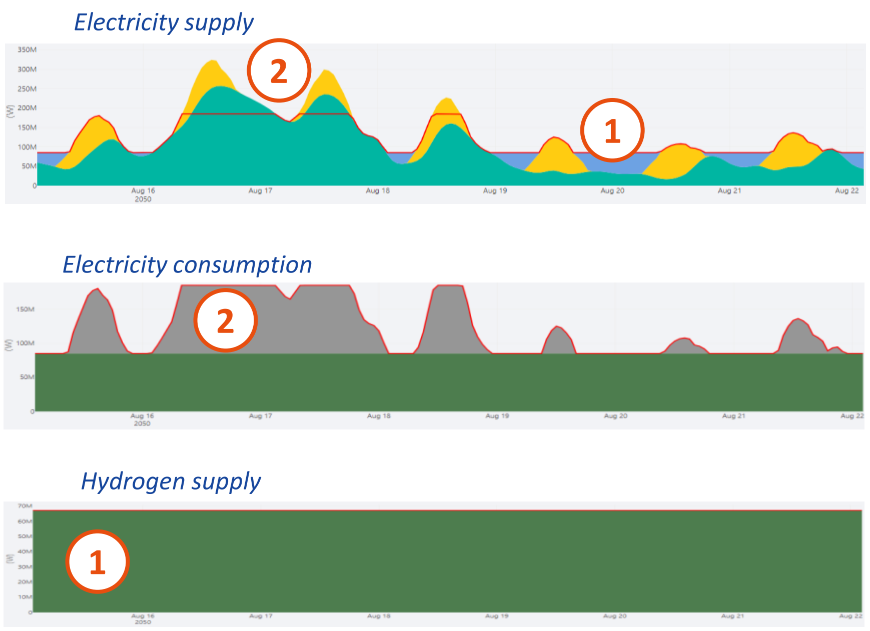
A system with UHS (right charts) : more flexibility enables a more profitable managment of dedicated RES and electricity market

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

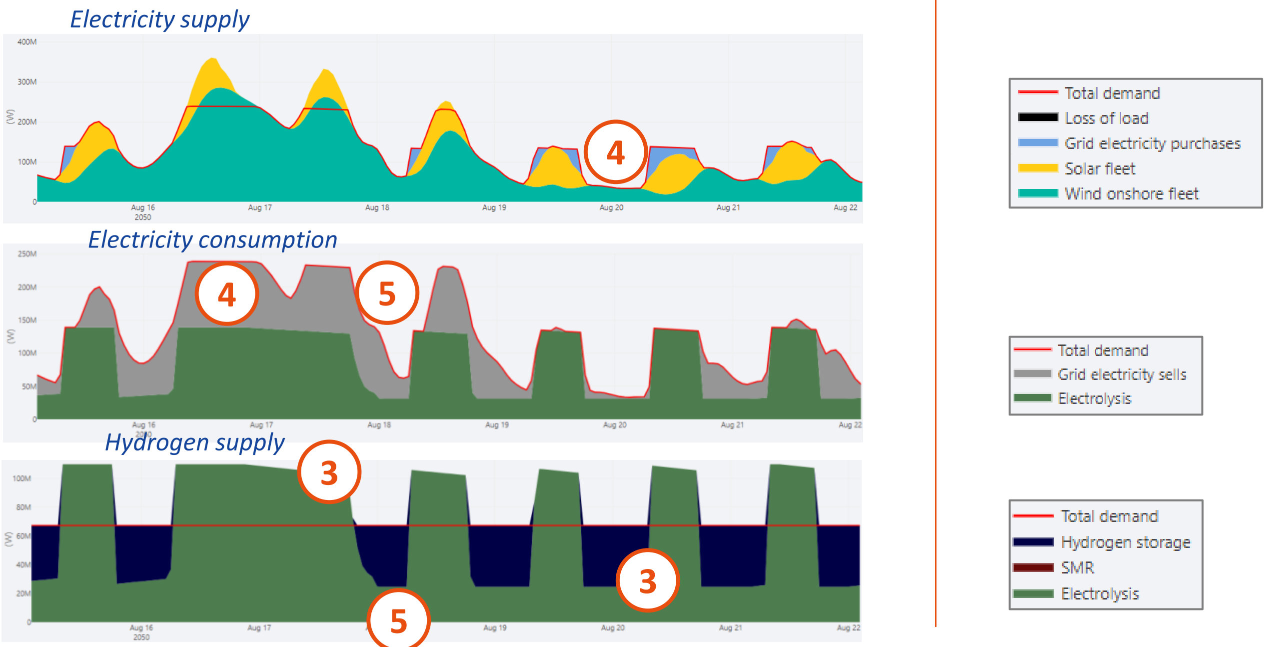
4. Electricity withdrawal from the grid decreases with storage and injections increase. Curtailment is lowered.

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

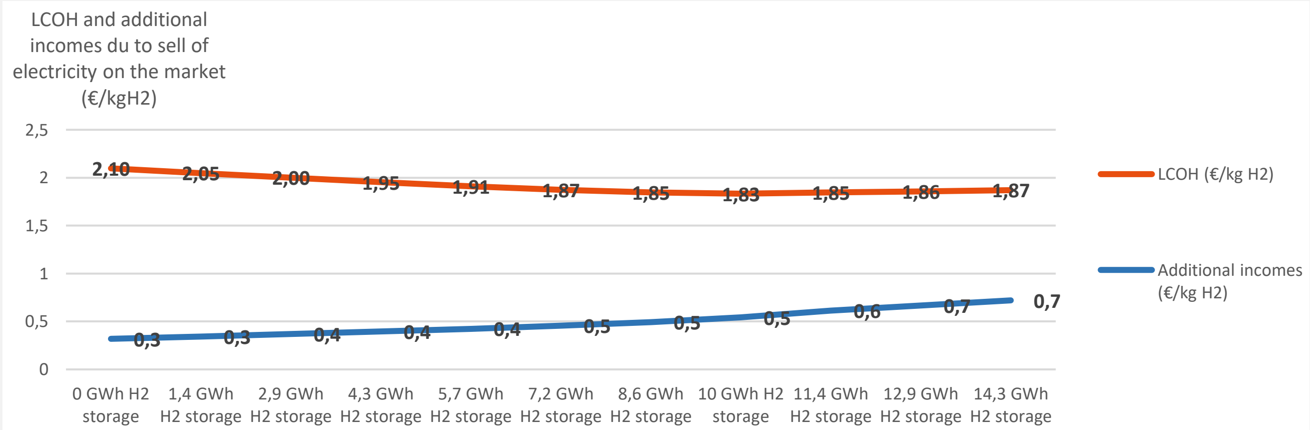


Territorial use case #4 – Results (1/2)

System value

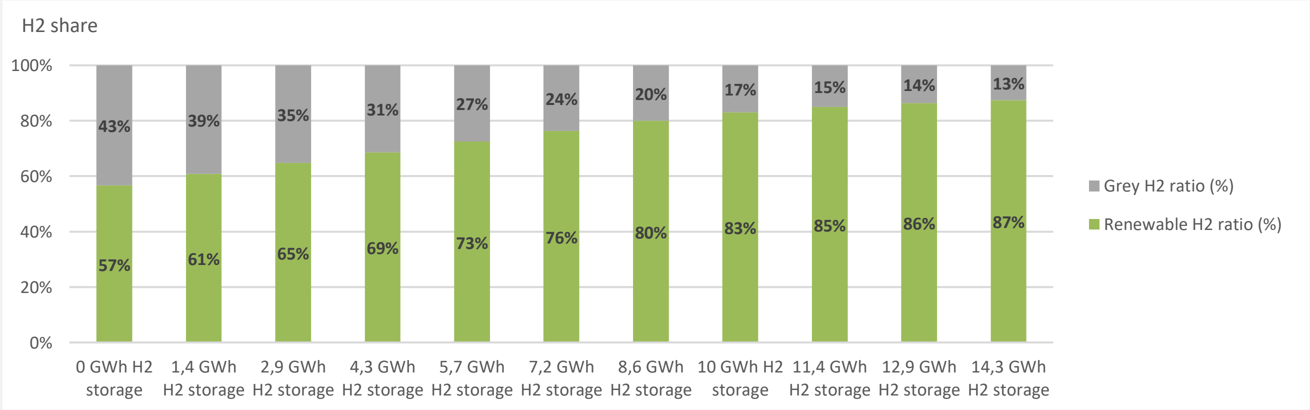
By reducing the cost of the electricity being withdrawn from the grid, H2 storage **reduces the hydrogen costs** by up to 13%*.

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



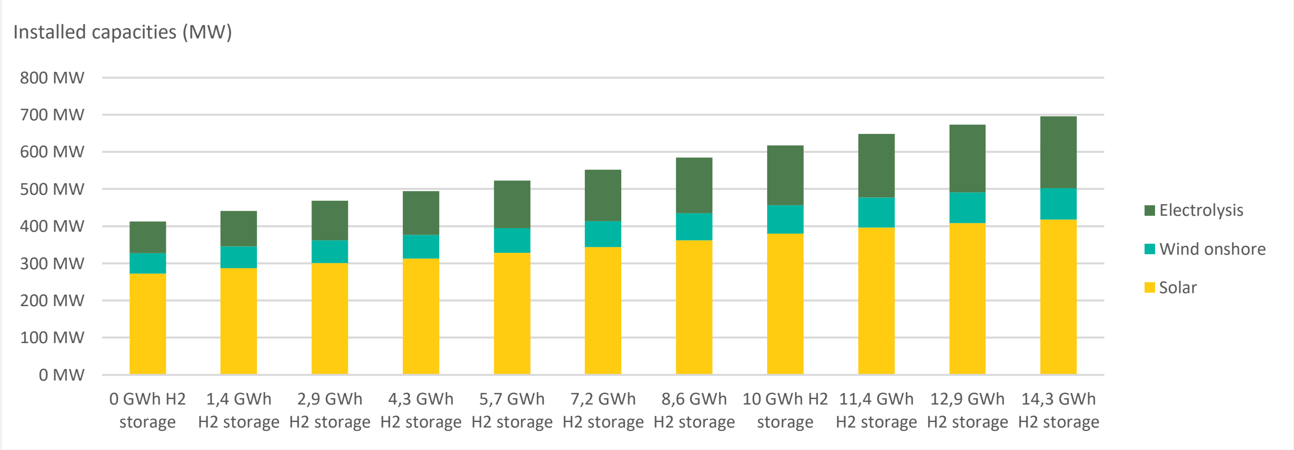
Arbitrage value

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)

<table>
<tr><td>Kick-start value</td><td>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.</td><td>
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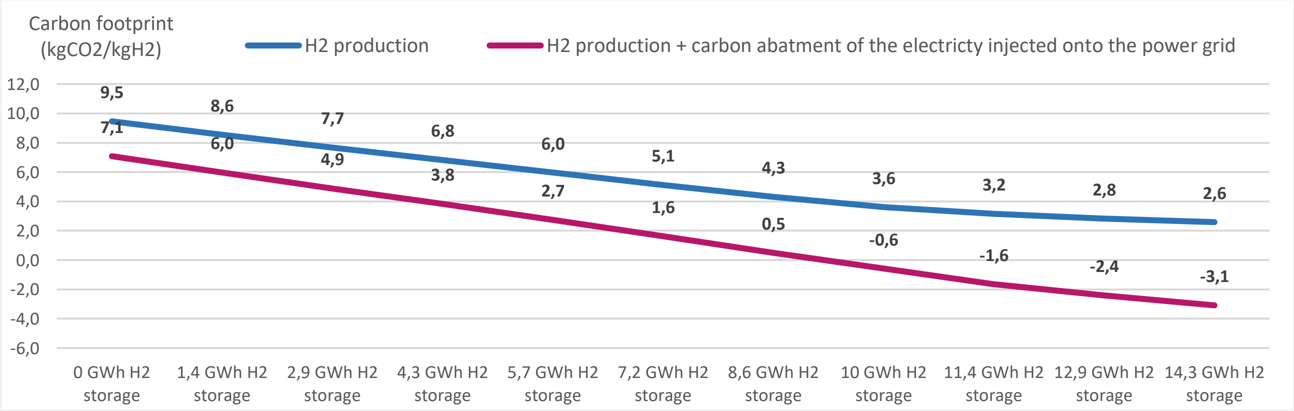
<tr><td>Environmental value</td><td>By increasing the power injection from the on-site renewables onto the grid, hydrogen storage contributes to GHG abatement in the power system.</td><td>
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Contents

Conclusion and outlook

- The report is based on the analysis of the values brought by hydrogen storage assets in a series of use-cases, using a cross-sectoral perspective.

- The key conclusions are that hydrogen storage will be a key enabler of the decarbonisation effort, as it allows to reduce the carbon footprint of electrolytic hydrogen, reduce RES curtailment, increase security of supply and help deliver the transition at a lower cost.

- The hydrogen storage needs in Europe depend on a number of factors, notably:
  - Hydrogen *demand* levels in 2030, 2040, 2050
  - Dynamics of hydrogen *demand* (e.g. notably thermo-sensitivity of end-uses), and the evolution of the dynamics
  - Role of *imports and exports*, form of extra-EU imports (pipeline hydrogen, ammonia, methanol, etc.) and expected dynamics
  - Composition of the *portfolio of electricity generation* technologies
  - Level of *co-location* between electrolysis and hydrogen demand centres
  - Ability to *repurpose* existing gas storage assets to hydrogen
  - Off-grid vs *grid*-connected electrolysis
  - *Regulatory framework*

Thank you for your attention!

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