# Role of Hydrogen for large Scale Energy Storage

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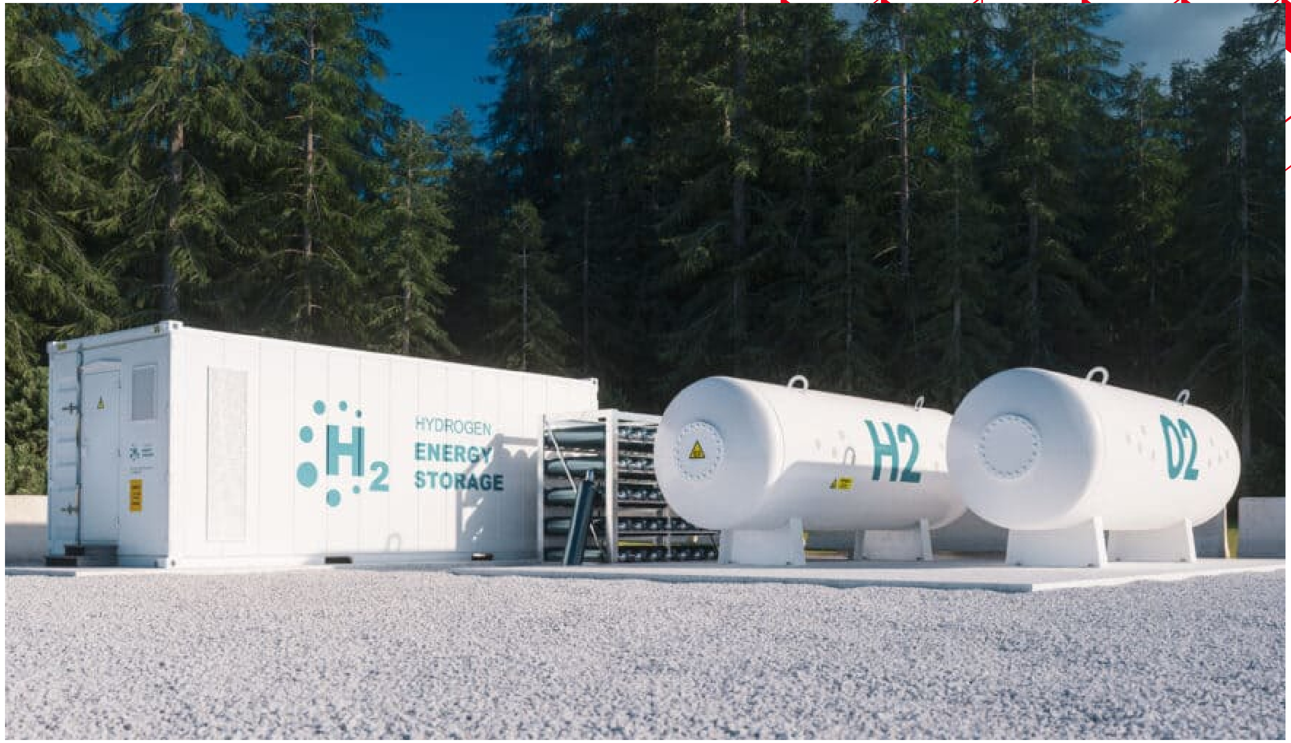
# OUTLINE

1. Introduction
2. Energy storage options
3. Hydrogen as an energy storage mean
4. Technology bricks involved
5. Opportunities and challenges
6. Conclusion



# 1. Introduction

# Hydrogen usages

Usages in 2030 and beyond

## Usage in 2024

### “Industrial” $H_2$

- World ≈ 100 Mt/yr
- Europe ≈ 8.2 Mt/yr

- **Chemistry (ammonia)**
- **Oil Refining**
- **Iron & steel**

### “Industrial” and “energy” $H_2$

Achieving deep decarbonization of >80% of $CO_2$ emissions requires hydrogen

**Ultra-low-carbon $H_2$ as feedstock, e.g, chemistry**

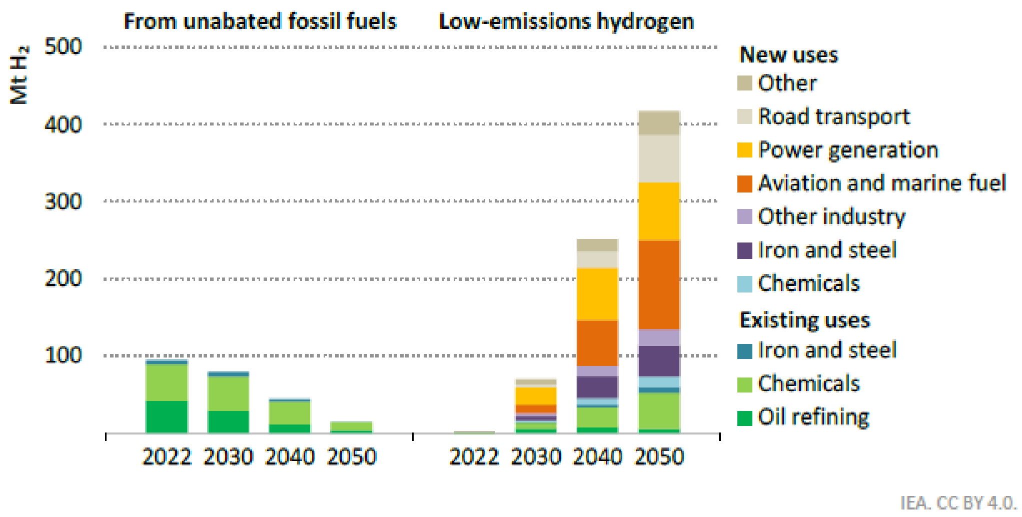
**Decarbonization of industrial process :**

**- directly: e.g. steel (direct reduction of iron)**

**- indirectly: high-grade heat**

**Store variable renewable electricity and bring stability and flexibility to the electricity grid**

**Fuel cells/synfuels for heavy transport and long distances**




*Use of low-emissions hydrogen rises significantly to 70 Mt by 2030 and extends to new applications such as in aviation and shipping*

*Source : IEA, NetZero Roadmap (2023)*

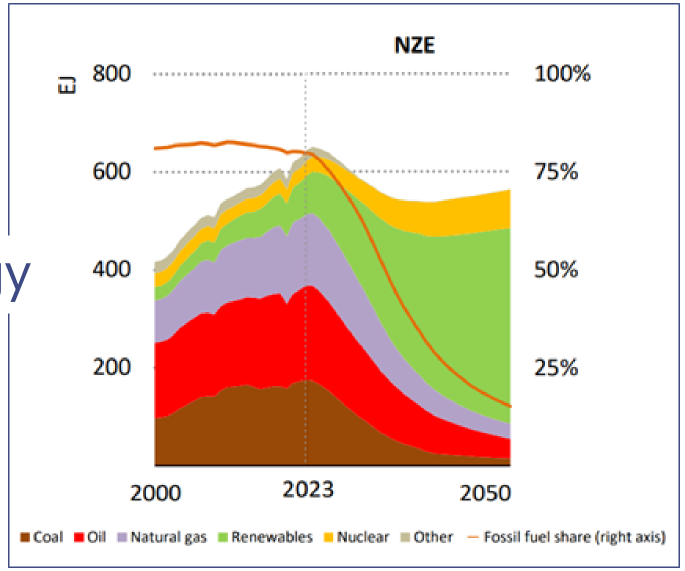
### $H_2$ Needs x4.5 until 2050

- **Needs to:**
  - **Produce hydrogen**
  - **Storage and transport it**
  - **Before using it**

# Evolution of energy demand

- **Overall energy demand**
  - **We should be at a tipping point for NZE scenario…** less energy consumed, with a decay of fossil fuel share

Energy



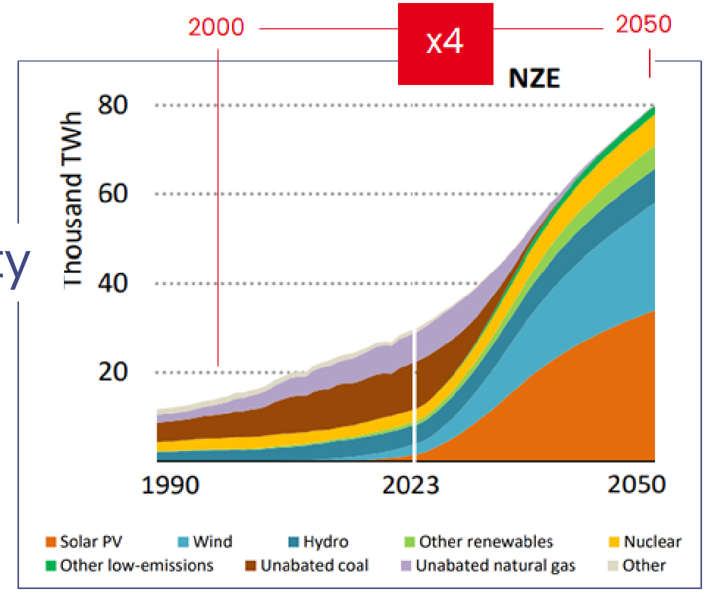

  - **Reality:** Global energy demand **grew by 2.2% in 2024**, a notably faster rate than the annual average of 1.3% seen between 2013 and 2023

*Source: IEA*

- **Electricity consumption:**
  - **NZE scenario:** expected x4 between 2000 and 2050

    Total share of RES: ~30% in 2023, ~90% in 2050

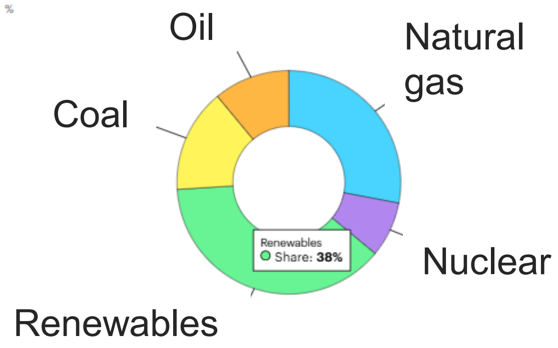
Electricity




  - **Reality:** Electricity demand grew more rapidly than overall energy demand, increasing by **4.3% in 2024**

    **RES = + 38%** in 2024

Share of energy demand growth by source



# Variability of RES

- RES are VRE (variable renewable energies)
  - Output: not constant
  - Varies over time due to environmental conditions beyond direct control

| Feature | Solar PV | Wind Power |
|---|---|---|
| **Daily Pattern** | Clear diurnal peak around midday | Higher at night, lower during the day |
| **Seasonal Pattern** | Higher in summer, lower in winter | Higher in spring, lower in summer |
| **Inter-Annual Variability** | Moderate, influenced by weather conditions | High, influenced by wind patterns |
| **Geographic Impact** | Sunlight relatively consistent across broad geographic regions | Varies significantly by region |

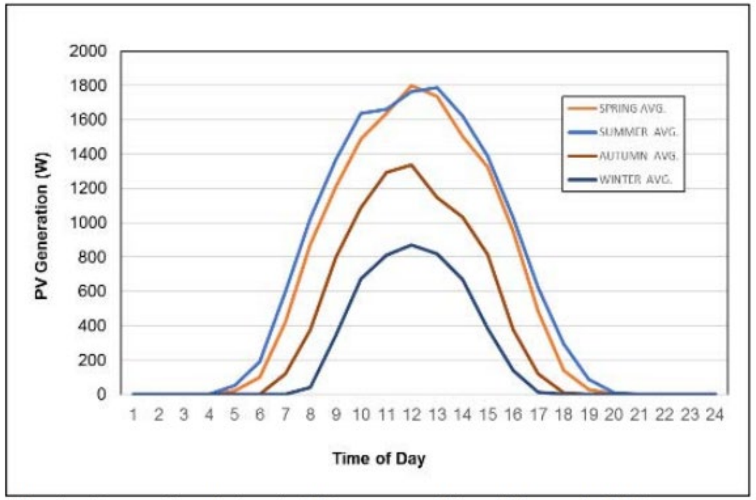
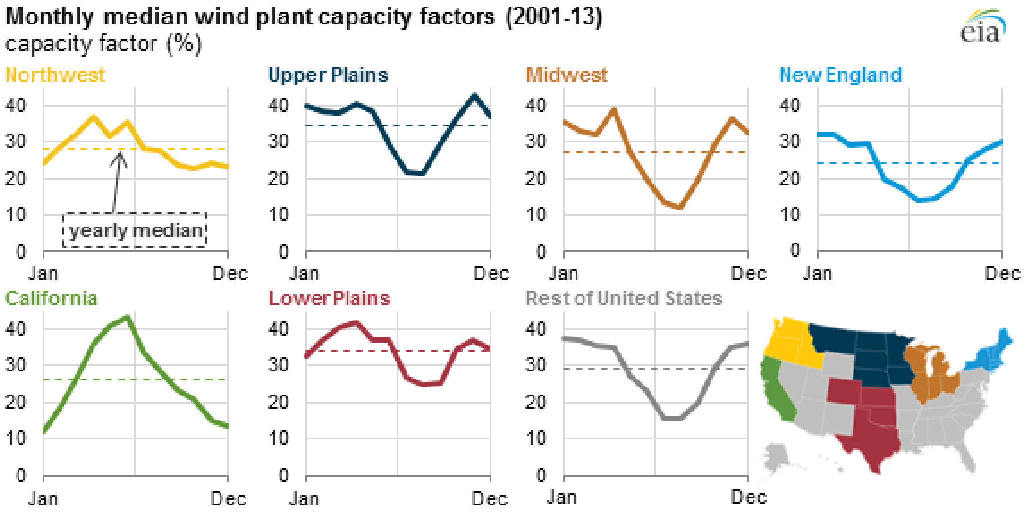


Fig. 1. Seasonal variation in PV output profiles of the typical PV system.

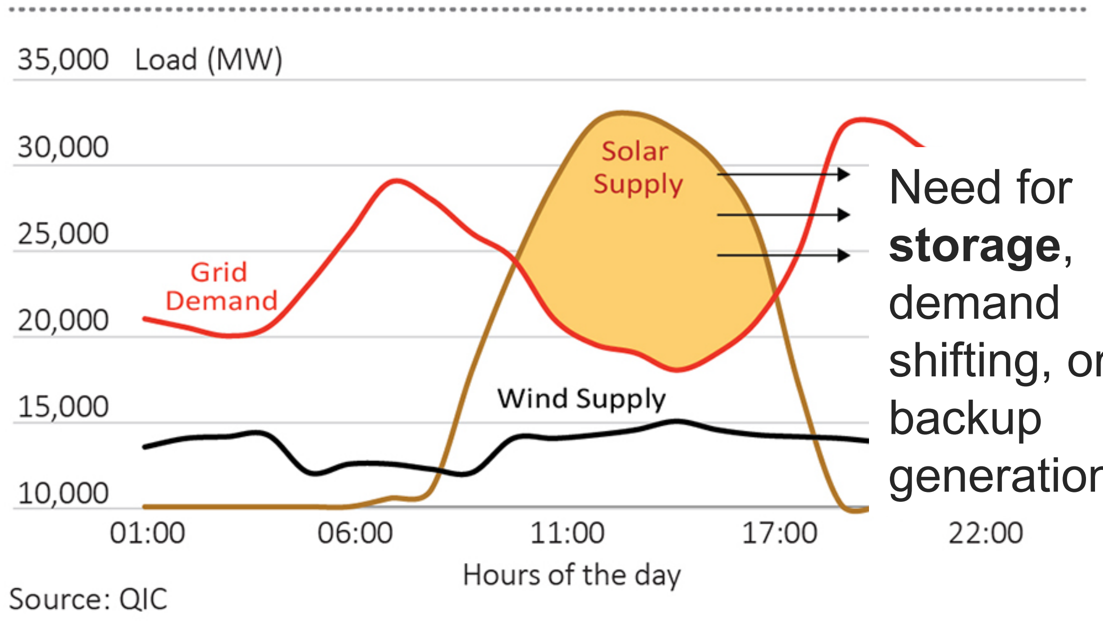
*Source M. Allison, 2018*




**Source:** U.S. Energy Information Administration, Forms EIA-860 and EIA-923
**Note:** Data include facilities with a net summer capacity of 1 MW and above only.

# Mismatch between electricity production and demand

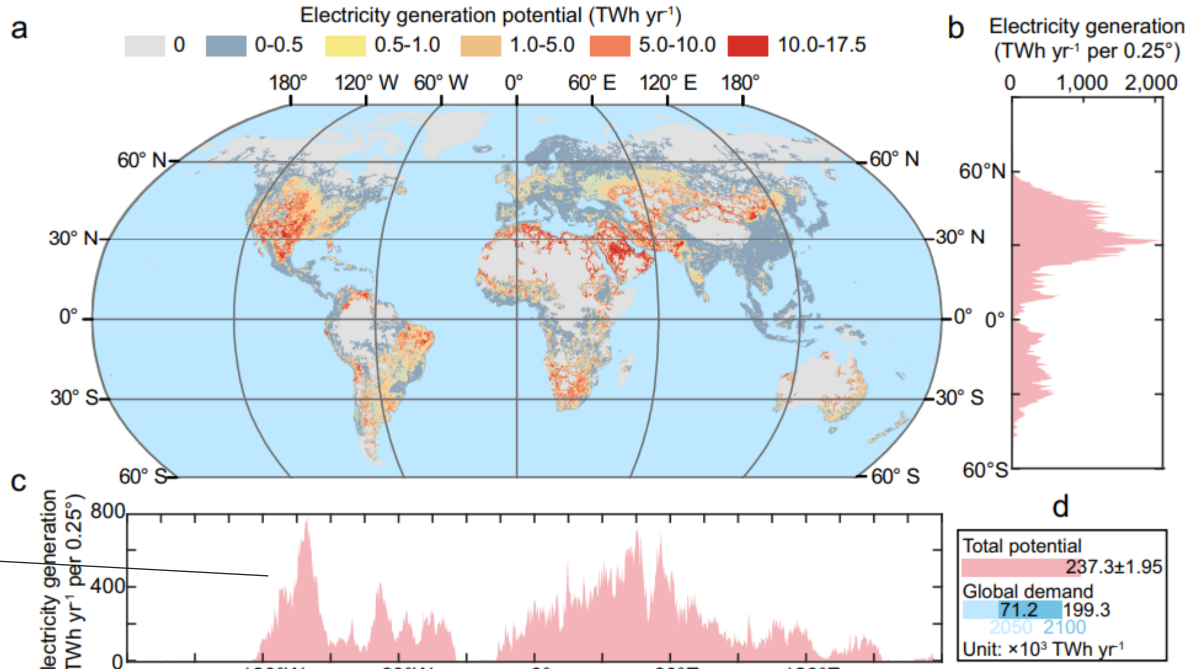
- **Temporal mismatch**
  - **Daily Mismatch:** Peaks around midday, but demand often peaks in the evening
  - **Seasonal Mismatch:**
    - electricity demand peaks in winter (heating) or summer (cooling) → rarely a perfect match with PV
    - Wind: complements solar seasonality (e.g., in EU, wind stronger in winter, solar in summer).




Need for **storage**, demand shifting, or backup generation

- **Geographical mismatch**
  - Solar: Highest in South/near equator regions, but demand higher elsewhere (e.g., Northern EU).
  - Wind: Strongest in coastal/offshore/plains regions, but demand centers may be far inland.

Need for grid **Interconnections, transport**, or flexible demand




*Source: Jiang, Nature Comm, 2025*

# 2. Energy storage options

# Large scale energy storage options

- **Several energy storage options exist**
  - **Different types:** mechanical, chemical, electrical, thermal, electrochemical
  - **With variable features** in terms of power, energy capacity and duration
  - **Complementarity** can be searched to find the optimum

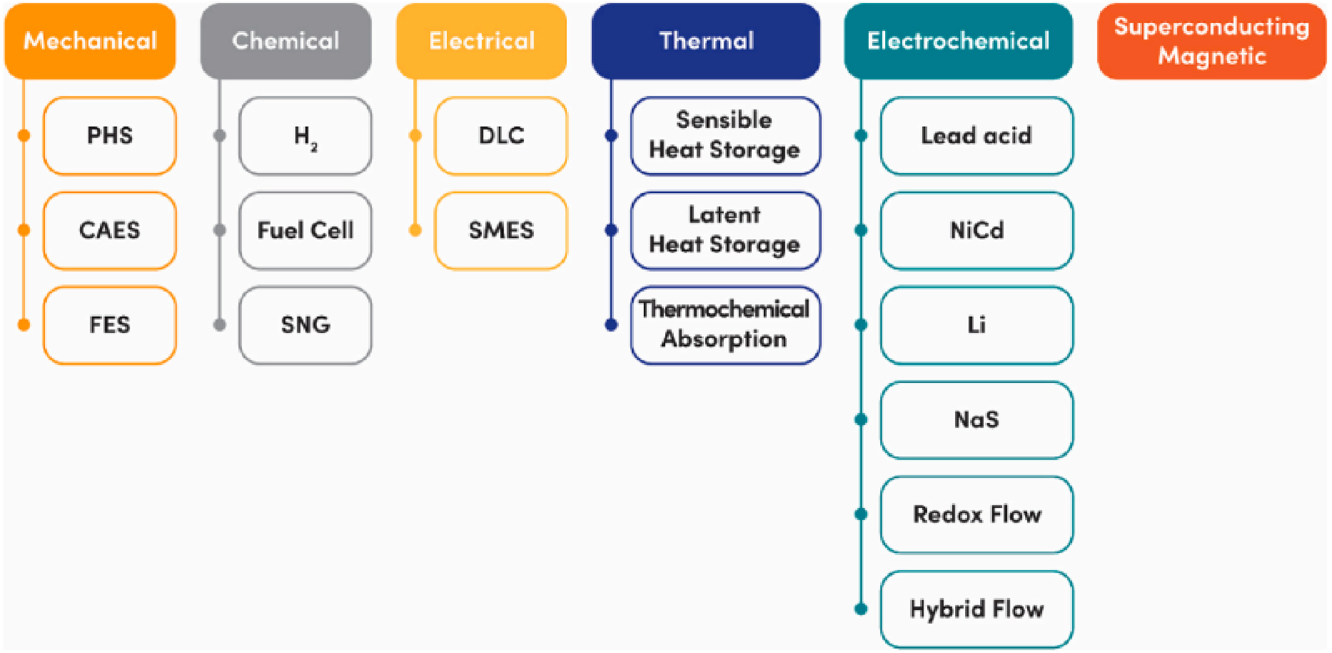
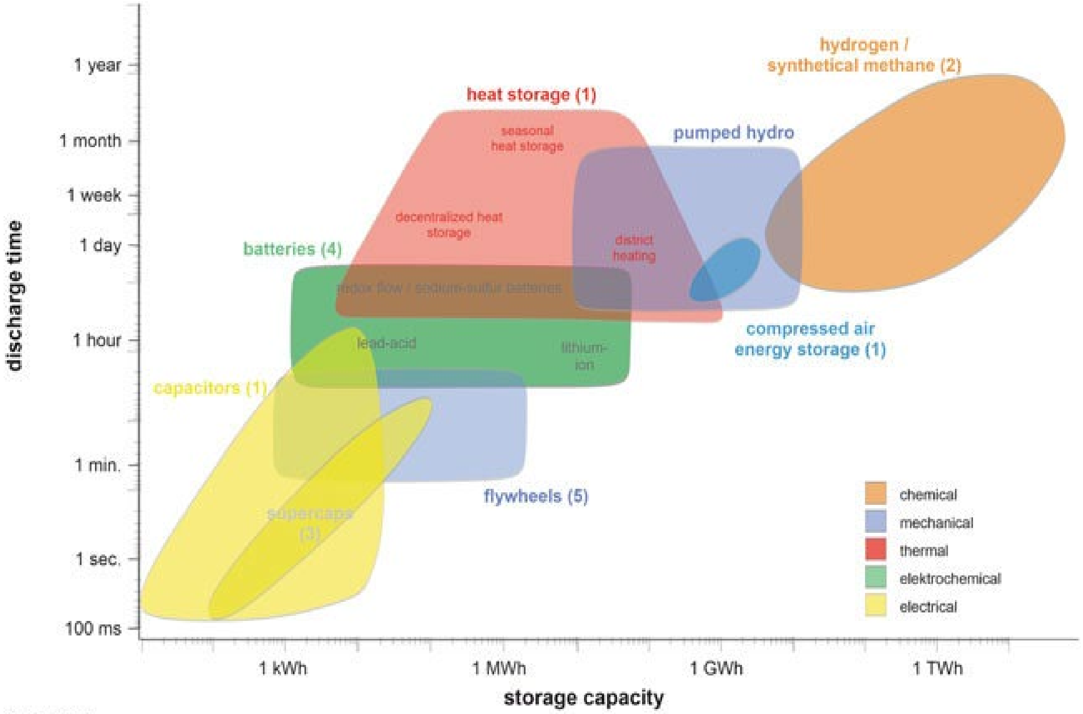



**Fig. 1.** Energy Storage Systems typology by storage method.

*Source: Khamikov, IJHE 2024*




Data sources:
(1) Own data, Fraunhofer UMSICHT
(2) Moore, Jason; Shabani, Bahman: A Critical Study of Stationary Energy Storage Polices in Australia in an International Context The Role of Hydrogen and Battery Technologies; School of Engineering, RMIT University, 2015
(3) Sterner, M.; Stadler, I.: Energiespeicher - Bedarf, Technologien, Integration; Springer, 2017
(4) Eigene Daten, Fraunhofer UMSICHT + Wang, Zhiwen et al.: A review of marine renewable energy storage; International Journal of Energy Research, Volume 43, Issue:12; DOI: (10.1002/er.4444)
(5) Bos, Martin: Storage of renewable electricity in methanol; ISBN: 978-90-365-4791-8; DOI: 10.3990/1.9789036547918
(6) Doetsch, Chr.,: Energiespeichertechnologien- & Anwendungen, Teil b – „Technologien". [Video] ORCA.nrw. ORCA OER: Energiespeicher_#01b.mp4, 00:07:50-00:09:32 (CC BY-SA 4.0 International), 5.6.2023

*Source: Schischke, E., et al. (2024) https://doi.org/10.1007/978-3-031-48359-2_4*

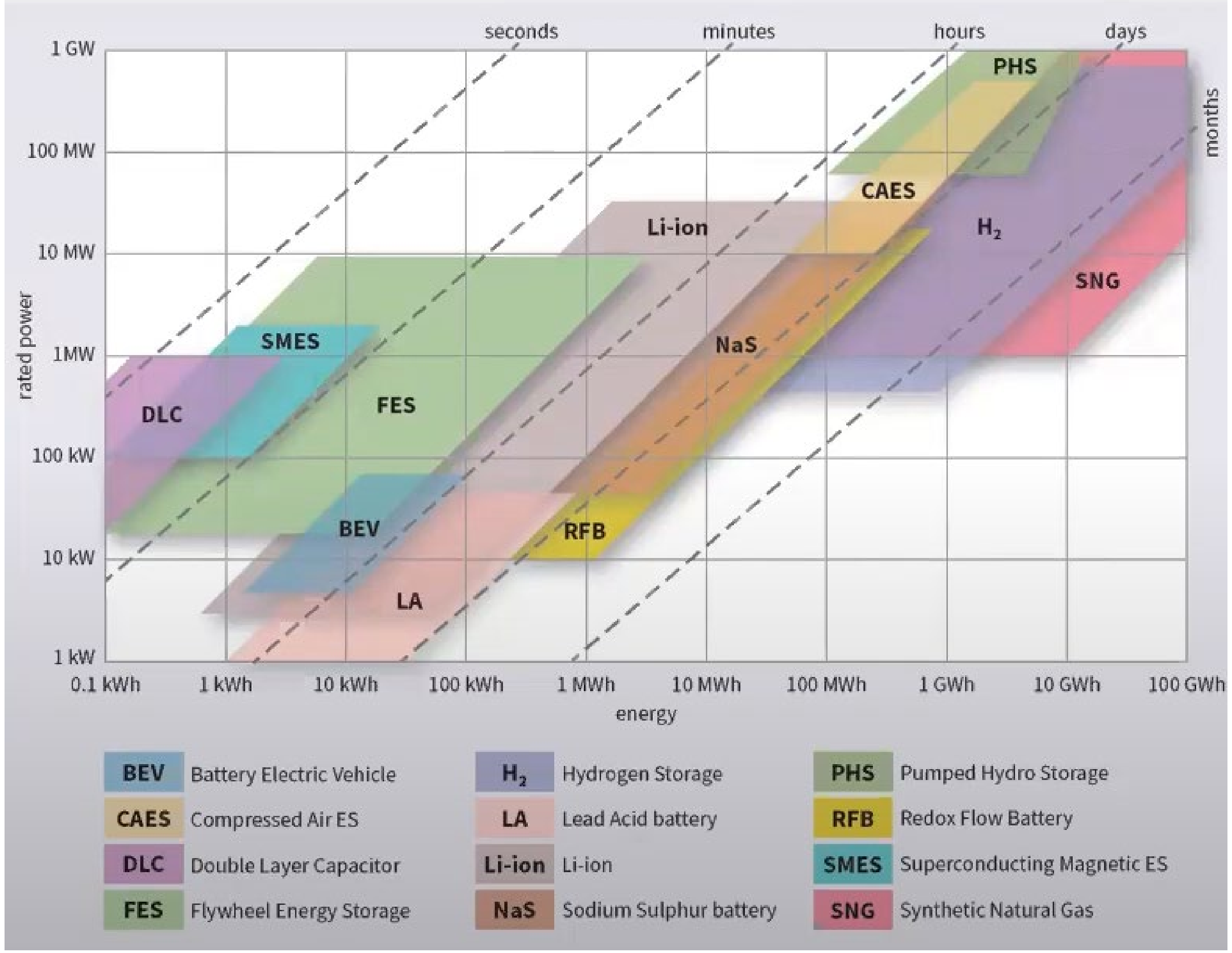
# 3. Hydrogen as an Energy storage mean

# Hydrogen as an energy storage mean

- **Benefit:**
  - large energy/power
  - long time

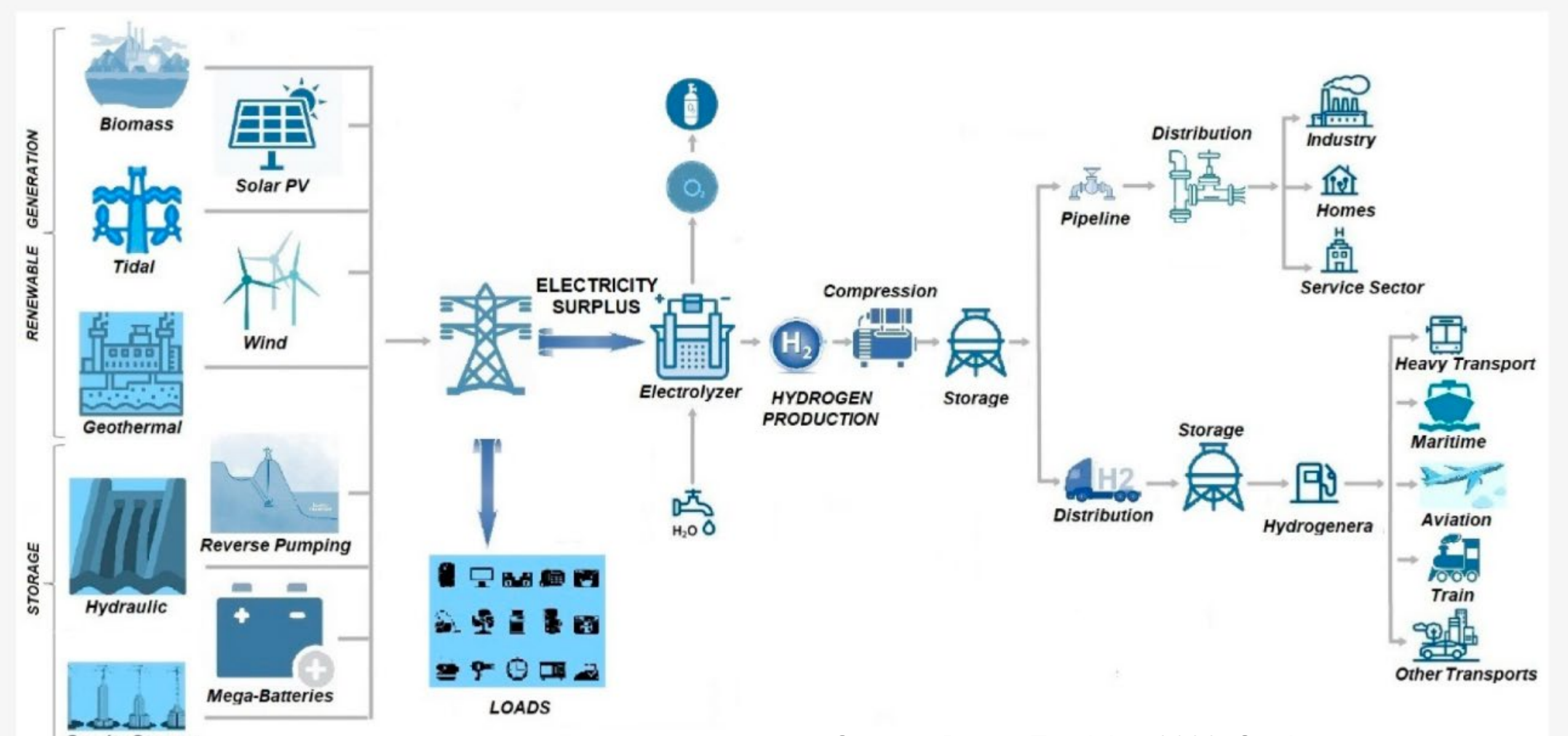
- **Power-to-X**
  - X = hydrogen, synthetic natural gas (SNG), or even fuel

Presented at a double logarithmic scale



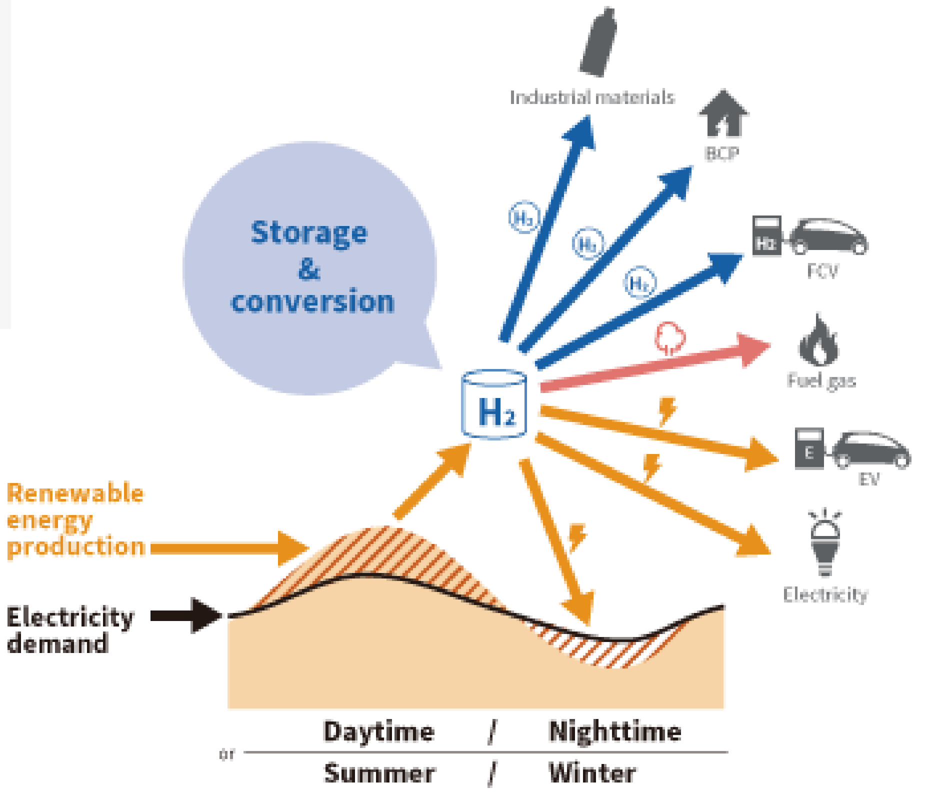

*Source: Wijk, TUDelft, 2023*

# How does Power-to-X work?




Source: Berna-Escriche, 2023, Spain

Source: Toshiba, Japan

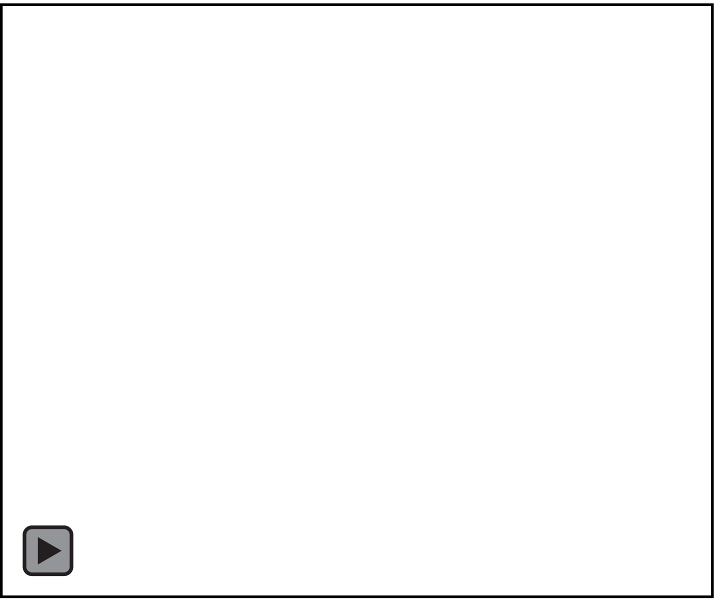



- **Use of surplus electricity**
- **Grid connected** (but can work in direction connection too)
- **Hydrogen production by electrolysis of water**
- **Hydrogen storage and transport**
- **End uses**

# 4. Technology bricks involved

# Electrolyser for $H_2$ production

*Exemple of alkaline electrolysis*



- **Several technologies**
- **No unique solution**

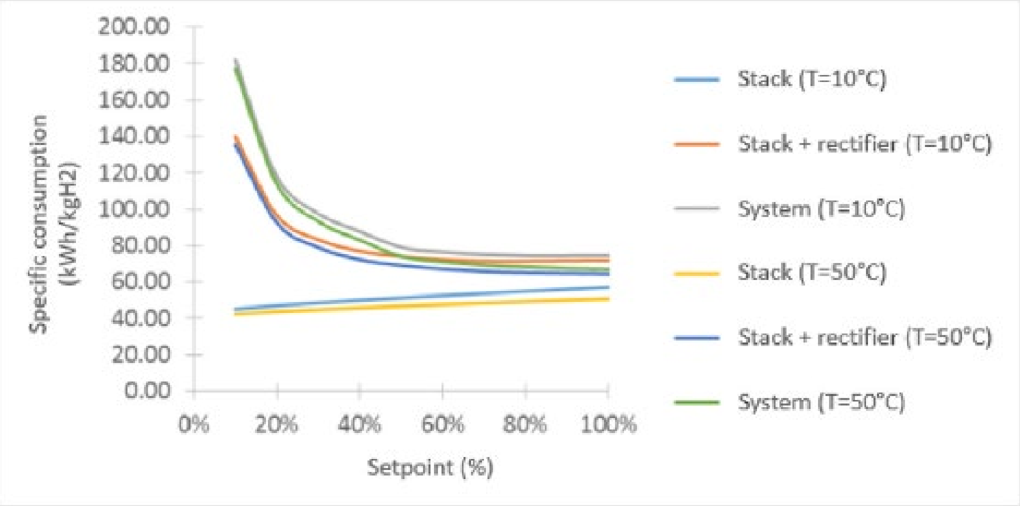
| | Alkaline (AEL) | PEMEL | AEMEL | SOEL |
|---|---|---|---|---|
| **Operating temperature** | (ambient–80–90°C) | 50–90 °C | Room–80 °C | 500–850 °C |
| **Electrolyte / membrane** | Liquid alkaline (KOH/NaOH) | Solid acidic polymer | Solid alkaline polymer | Solid ceramic oxide conductor |
| **Dynamic response / ramping** | Slower to respond | Fast response, excellent load following | Promising fast response | Slow cold startup, dynamic response tbc at large scale |
| **Capital cost (relative)** | Lowest CAPEX, mature tech | Higher CAPEX, compact footprint | Potentially low cost | High CAPEX, complex system |
| **Electrical efficiency (LHV)** | 60-70 | 60-70 | 60-70 | > 84 |
| **Durability / lifetime** | Long operating track record, decades possible | Competitive lifetimes | Durability challenges, needs improvement | Durability issues, |
| **Use cases / best fit** | Large-scale industrial $H_2$ (bulk production) | Renewables integration, mobility refuelling | Emerging: cost-sensitive projects, dynamic operation | Industrial with high-temp heat |
| **Main strengths** | Low CAPEX, proven tech, scalable | Fast dynamics, high purity, compact | Non-precious catalysts, good dynamics | Highest efficiency |
| **Main weaknesses** | Slower dynamics, limited HP | Higher CAPEX, sensitive to impurities, degradation risk | Immature technology, durability issues | High CAPEX, complexity, durability risk |

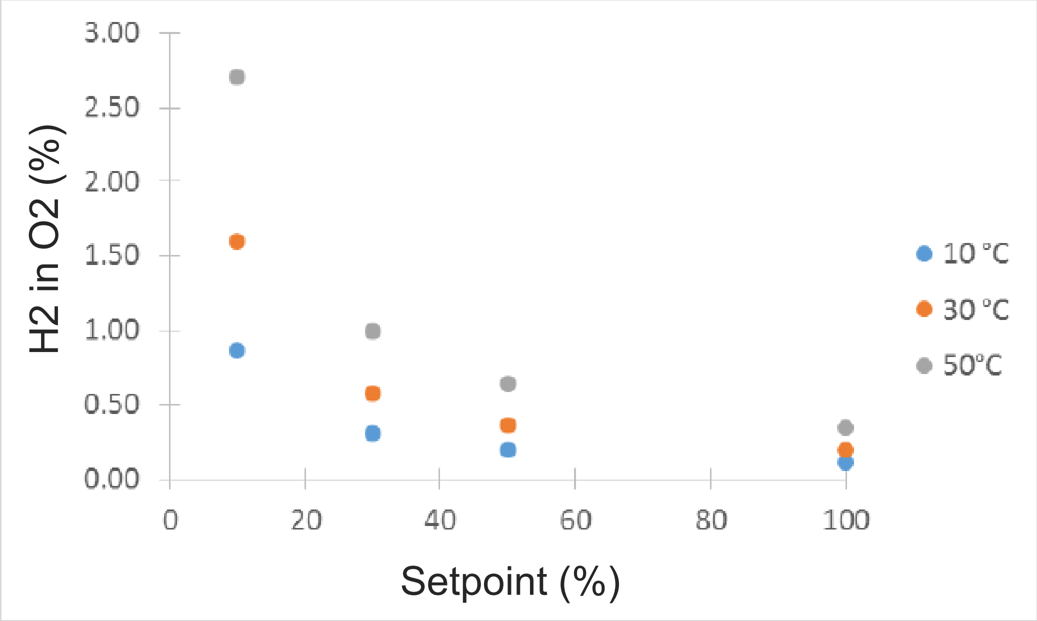
# Electrolyser for $H_2$ production

- **Need to operate dynamically for VRE coupling**

- **Impact on :**
  - **Efficiency:** efficiency curve depends on load
  - **Water and heat management**: Fluctuations complicate thermal control and water feed systems
  - **Lifetime:** material degradation
  - **$H_2$ purity**
  - **even safety**

- **➔ Advanced control strategies, system design (buffer tanks, hybridization), and robust materials = essential to mitigate these impacts**



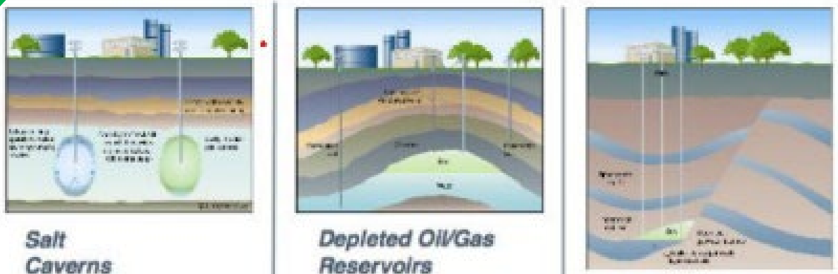




*Source: Olivier PhD thesis, 2016*

# Hydrogen storage

- Several technologies
- No unique solution

**Underground storage**



*Salt Caverns*

- Salt caverns are solution mined cavities within either salt domes or bedded salts that do not match reservoir volume capacity.

*Depleted Oil/Gas Reservoirs*

- Depleted reservoirs are proven gas reservoirs that are easy to develop and operate due to existing infrastructure.

*Aquifers*

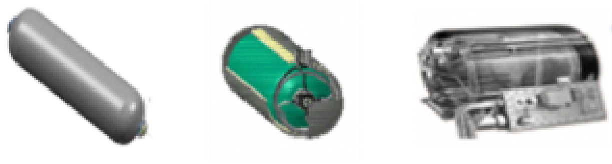
- Aquifers are similar in geology to depleted reservoirs, but have not been proven to trap gas and must be developed.

Maturity scale

**How is hydrogen stored?**

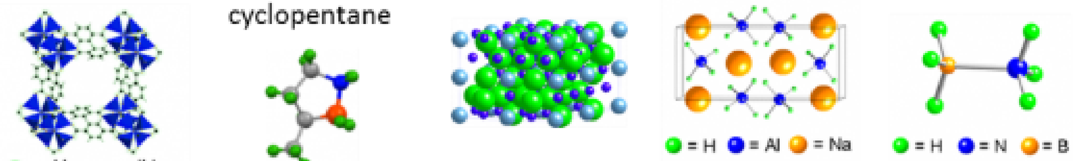
**Physical-based**

- Compressed Gas
- Cold/Cryo Compressed
- Liquid $H_2$



**Material-based**

- Adsorbent — Ex. MOF-5
- Liquid organic — Ex. BN-methyl cyclopentane
- Interstitial hydride — Ex. $LaNi_5H_6$
- Complex hydride — Ex. $NaAlH_4$
- Chemical hydrogen — Ex. $NH_3BH_3$ NH3




LOHC
(liquid organic hydrogen carriers)

# Hydrogen storage

- **Selection of $H_2$ storage technology**
  - The storage technology needs to be selected as a function of the application and of the location

| | Gaseous state | | | | Liquid state | | | Solid state |
|---|---|---|---|---|---|---|---|---|
| | Salt caverns | Depleted gas fields | Rock caverns | Pressurized containers | Liquid hydrogen | Ammonia | LOHCs | Metal hydrides |
| Main usage (volume and cycling) | Large volumes, months-weeks | Large volumes, seasonal | Medium volumes, months-weeks | Small volumes, daily | Small - medium volumes, days-weeks | Large volumes, months-weeks | Large volumes, months-weeks | Small volumes, days-weeks |
| Benchmark LCOS ($/kg)[1] | $0.23 | $1.90 | $0.71 | $0.19 | $4.57 | $2.83 | $4.50 | Not evaluated |
| Possible future LCOS[1] | $0.11 | $1.07 | $0.23 | $0.17 | $0.95 | $0.87 | $1.86 | Not evaluated |
| Geographical availability | Limited | Limited | Limited | Not limited | Not limited | Not limited | Not limited | Not limited |

*Source: BloombergNEF. Note: [1] Benchmark levelized cost of storage (LCOS) at the highest reasonable cycling rate (see detailed research for details). LOHC – liquid organic hydrogen carrier.*

Extra cost due to state transformation needed: consumes energy and requires installations

# Hydrogen storage

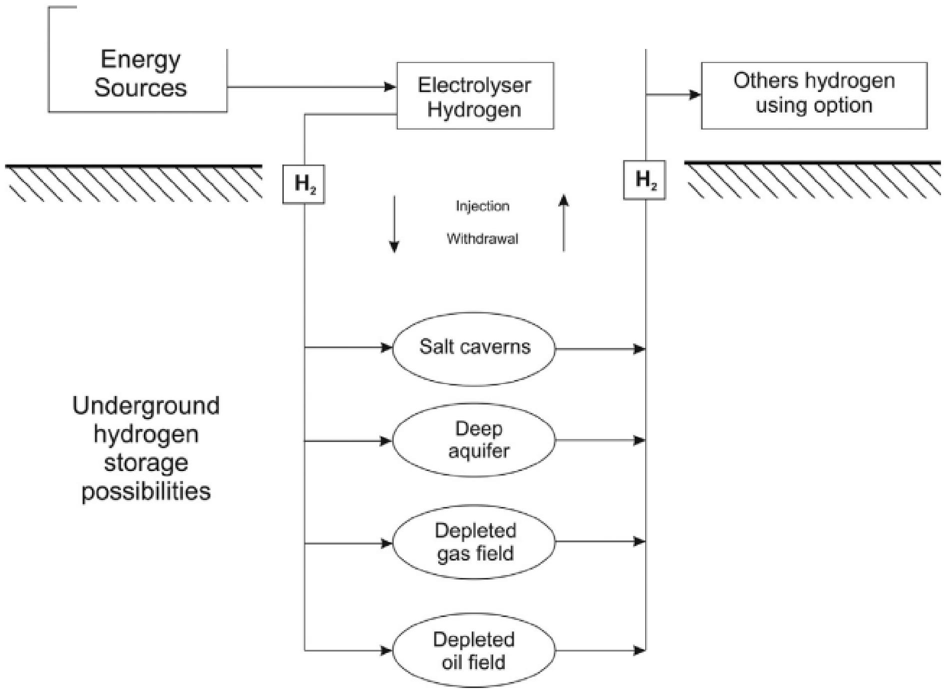
- Comparison above ground / underground storage

- For large scale energy storage, underground storage looks relevant

| | Above-Ground Storage | Underground Storage |
|---|---|---|
| **Typical forms** | Compressed $H_2$ vessels, cryogenic $LH_2$ tanks, LOHC tanks, solid hydrides | Salt caverns, depleted gas fields, aquifers |
| **Capacity (scale)** | kWh → few MWh per site; limited by tank size | GWh → TWh scale; seasonal/long-duration |
| **Footprint** | Large surface land footprint if scaled up | Minimal surface footprint |
| **Capital cost (relative)** | High cost per kg (tanks & cryogenics expensive) | Low cost per kg at scale (esp. salt caverns) |
| **Losses / efficiency** | Boil-off ($LH_2$), conversion losses (LOHC), hydride charging penalty | Low leakage in salt caverns; porous rock higher risk |
| **Response time** | Fast withdrawal/delivery | Slower injection/withdrawal; not suited for fast cycling |
| **Safety** | Easy monitoring but high-pressure/cryogenic safety risks | Safer containment underground; geology-dependent leakage risk |
| **Technology maturity** | Mature for compressed & cryogenic; LOHC/hydrides still developing | Salt caverns proven; porous rock in early demo |
| **Best applications** | Distributed storage, refuelling, backup power, export hubs | Seasonal storage, grid balancing, industrial hydrogen hubs |

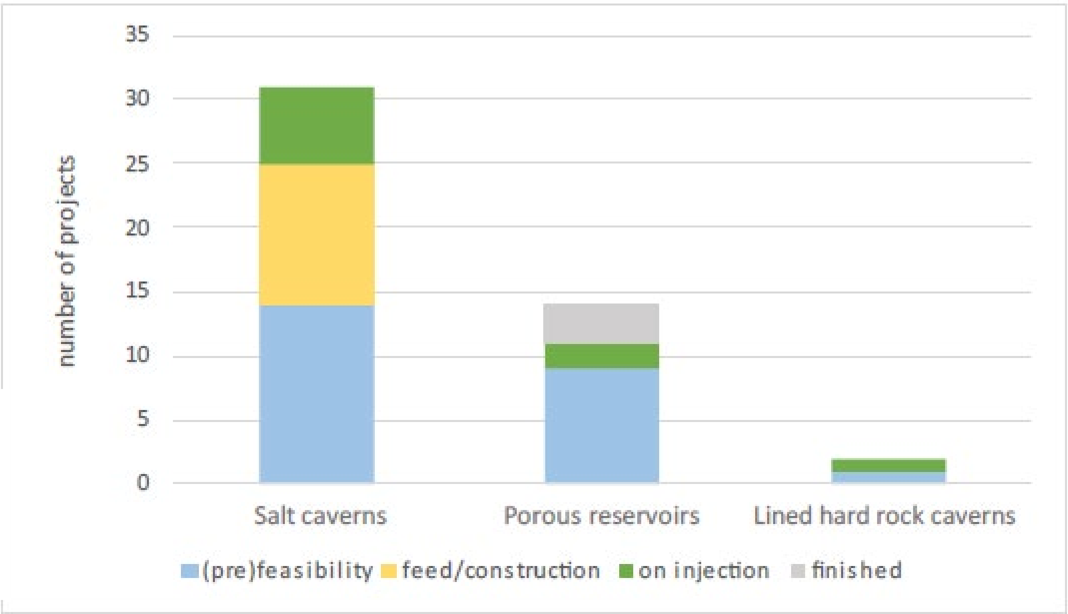
# Hydrogen storage

- Focus on underground storage




| Storage Option | Capacity | Strengths | Challenges |
|---|---|---|---|
| Salt Caverns | Very large (TWh) | Low cost, excellent containment | Geological limitations, site preparation |
| Depleted Gas Fields | Large | Existing infrastructure | Gas mixing, leakage, purity |
| Aquifers – porous rock media | Large (site-specific) | Vast potential | Uncertain geology, leakage risks |

- Several projects worldwide at different levels of achievements



# Hydrogen storage

- Example of HYPSTER project

**Contributing to the energy transition and the hydrogen market development through the deployment of large-scale hydrogen storage in salt caverns**

–

The HyPSTER project has demonstrated the technico-economic feasibility of large-scale hydrogen storage in salt caverns.


$H_2$ — **1st demonstrator**
First demonstrator of green hydrogen underground storage

15,5 M€ — **Total budget**
5 million euros granted by the Clean Hydrogen Partnership, CHP

1 MW — **Electrolyser**

400 kg/day — **Production of 400 kg of hydrogen per day**
(the equivalent of the consumption of 16 hydrogen buses).

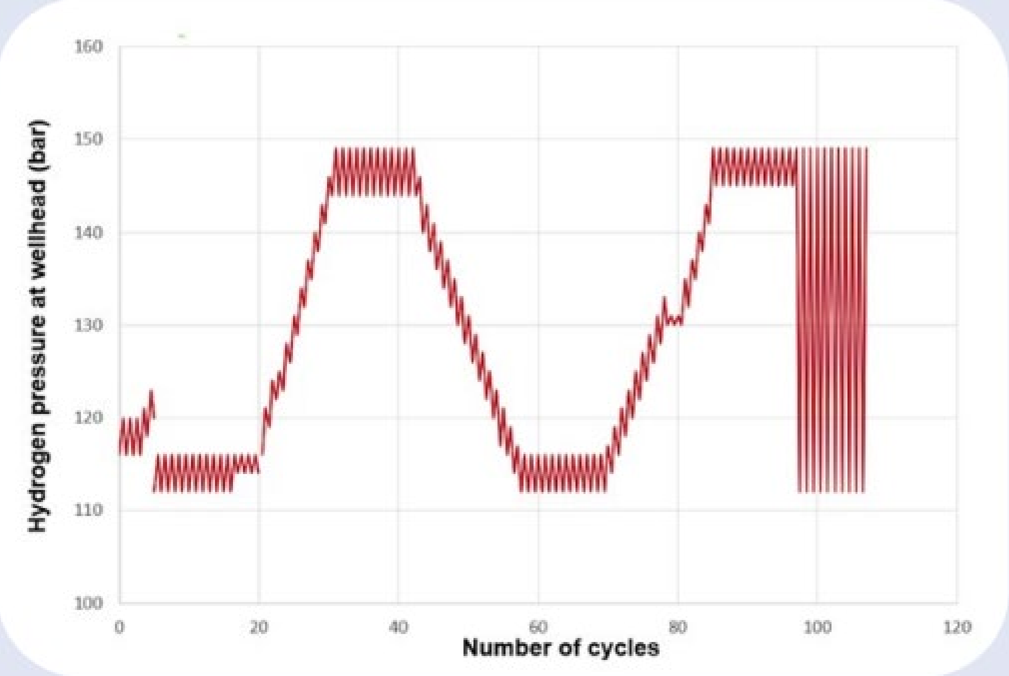
2.6 tons — **Of green hydrogen stored**
during the demonstrator phase

# Hydrogen storage

- **Example of HYPSTER project**

## Cyclic testing in salt cavern

Cyclic tests validated the ability to commercially operate hydrogen storage in salt caverns.




100 cycles have been successfully carried out to study of the cavern and hydrogen response to different cycle profiles (slow/fast; low/high pressure variations), reflecting the variety of cycles which would be encountered in commercial operations.

# Hydrogen storage

- **Example of HYPSTER project**

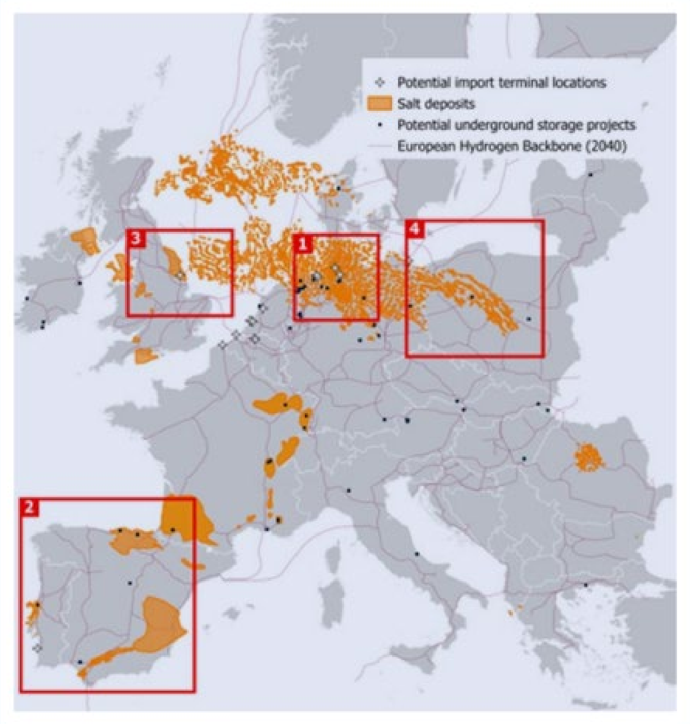
## Roadmap toward replication

**4 key regions have been identified where salt caverns will benefit from infrastructures and hydrogen flows.**

Techno-economic assessment and replication in the EU

- **~0.5€/kg**: average cost of $H_2$ storage
- **From €40m to €140m**: CAPEX required to build a salt cavern
- **Up to 2000** : number of salt caverns could be needed in the EU by 2050 (estimation 2022 by HyUSPRe project).

Europe, a high potential area:



# Hydrogen transport

- **Selection of $H_2$ transport technology**
  - The transport option needs to be selected as a function of the application, the distance and the location

Legend (costs): <0.1 USD/kg | 0.1–1 USD/kg | 1–2 USD/kg | >2 USD/kg

| | | Costs | | | | |
|---|---|---|---|---|---|---|
| | | Distribution | | Transmission | | |
| | | 0–50 km | 51–100 km | 101–500 km | >1,000 km | >5,000 km |
| Pipelines[1] | Retrofitted | City grid | Regional distribution pipelines | Onshore transmission pipelines | Onshore/Subsea transmission pipelines | N/A |
| | New | City grid | Regional distribution pipelines | Onshore transmission pipelines | Onshore/Subsea transmission pipelines | N/A |
| Shipping | $LH_2$ | N/A | N/A | N/A | $LH_2$ ship | $LH_2$ ship |
| | $NH_3$[2] | N/A | N/A | N/A | $NH_3$ ship | $NH_3$ ship |
| Trucking | LOHC[2] | N/A | N/A | N/A | LOHC ship | LOHC ship |
| | $LH_2$ trucking | Distribution truck $LH_2$ | Distribution truck $LH_2$ | Distribution truck $LH_2$ | N/A | N/A |
| | Gaseous trucking | Distribution truck $CH_2$[3] | Distribution truck $CH_2$[3] | Distribution truck $CH_2$[3] | N/A | N/A |

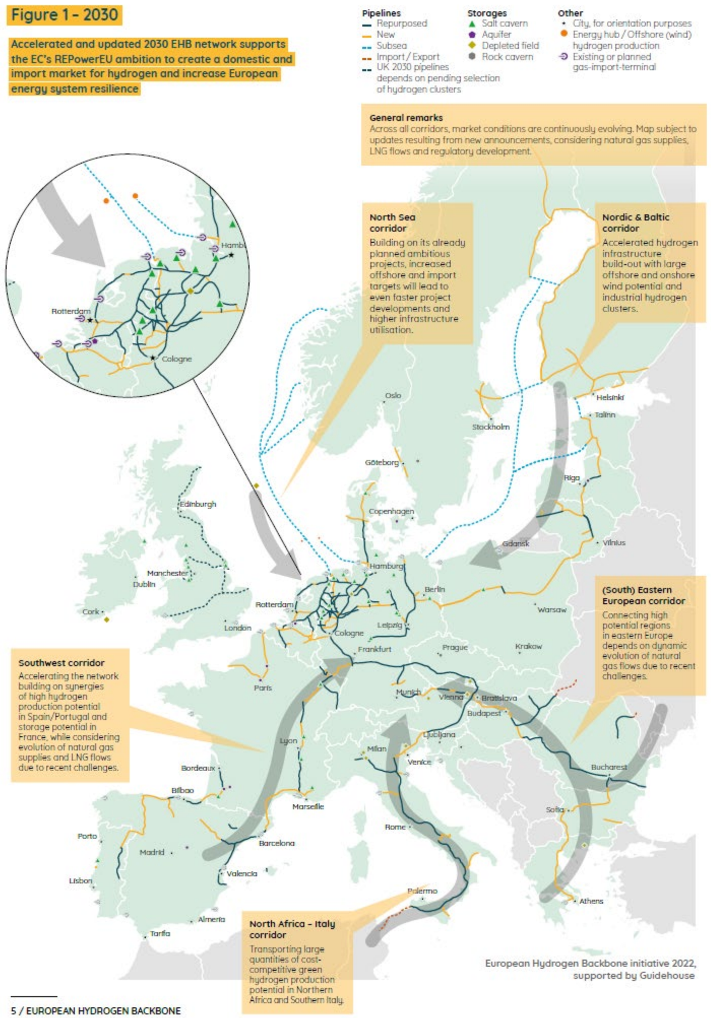
1. Assuming high utilization
2. Including reconversion to $H_2$; LOHC cost dependent on benefits for last mile distribution and storage
3. Compressed gaseous hydrogen

- **Hydrogen pipelines are cheaper than electricity transmission lines**
  - **Can transport 10 times the energy at one-eighth the cost associated with electricity transmission line**

*Source: Hydrogen Insights Report, Hydrogen Council, 2021*

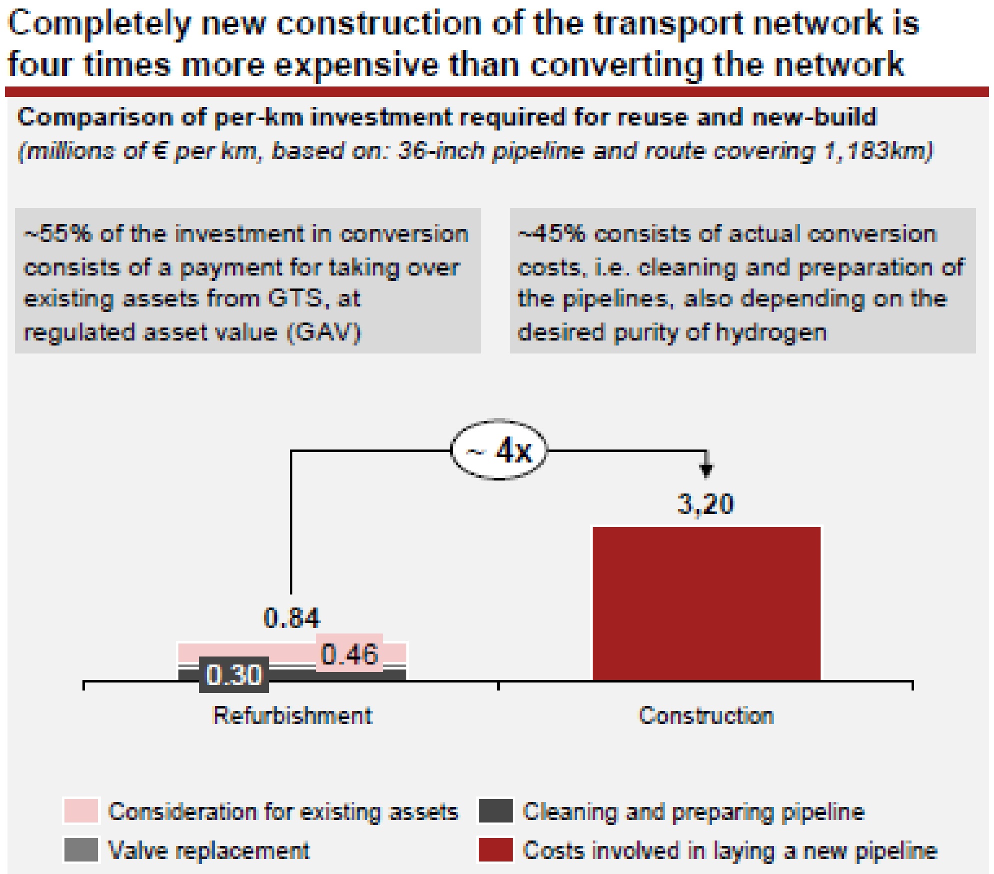
# Hydrogen transport

- European Hydrogen Backbone plan for 2040: 53000 km
  - 69% retrofitted
  - 31%: new




Source: EHB

- Retrofitting of transport network more cost efficient
  - Investment 4X expensive with new pipes
  - Cost to transport 1kg $H_2$ over 1000 km with 900 mm pipe
    - ~ 0,11 € with retrofitted pipe
    - ~ 0,30 € with new pipe




Source: Hyway

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# 5. Opportunities and challenges for H2 energy storage mean

# Opportunities

- **Massive Energy Storage Potential**
  - $H_2$ can store energy over long durations, from hours to months: ideal for seasonal storage.
  - Potential for TWh-scale storage, especially in underground formations like salt caverns.
- **Decoupling Energy Supply and Demand**
  - Enables storage of surplus renewable energy (wind, solar) when generation exceeds demand.
  - Acts as a buffer for intermittent renewables, enhancing grid stability.
- **Sector Coupling**
  - Hydrogen is a flexible energy carrier that can be used across sectors:
    - Electricity (fuel cells/turbines); Industry (steel, chemicals); Transport (trucks, shipping, aviation); Heating
  - Supports deep decarbonization.
- **Long-Distance Transport & Export**
  - $H_2$ (or hydrogen carriers like ammonia, LOHC) can be transported globally, enabling energy export/import.
  - Opens new markets for renewable energy-rich regions.
- **Strategic Energy Security**
  - Large-scale hydrogen storage provides energy security against supply disruptions.
  - Allows countries to store energy for months or seasons.
- **Integration with Existing Infrastructure**
  - Possible use of existing natural gas pipelines (blending hydrogen) and gas storage formations.
  - Potential to repurpose infrastructure from oil & gas industries.

# Challenges

- **Energy Efficiency**
  - Depends on storage method (compressed gas, liquid hydrogen, underground storage, LOHC).
  - Electrolysis → storage → electricity round trip efficiency: ~30–50% < batteries (~80–90%).
- **High Costs**
  - Electrolysers, compression, liquefaction, storage&transport infrastructure: capital intensive.
  - Hydrogen storage costs per MWh are higher than pumped hydro and batteries at present.
- **Material and Technical Challenges**
  - Hydrogen embrittlement, leakage potential issues.
  - Purity requirements for some applications demand advanced purification.
  - Need to operate technologies flexibly: impact of efficiency/lifetime/safety to be further checked
- **Geographic Limitations**
  - Not all regions have suitable formations for underground $H_2$ storage.
- **Infrastructure Gaps**
  - Few existing hydrogen storage sites; pipeline networks for hydrogen are limited.
  - Need for standardisation, safety protocols, and regulation.
- **Safety Concerns**
  - $H_2$: highly flammable + wide explosive range: Robust safety systems and public acceptance needed.
- **Market and Regulatory Uncertainty**
  - Lack of a mature global hydrogen market.
  - Policy, regulation, and carbon pricing influence economic viability.
  - Long lead times for developing storage projects.

# 6. Conclusion

# Conclusion

- **Due to the increasing share of VRE in the energy mix**
  - ➔ storage need
  - At large scale, over long duration, and sometimes with transport from one area to another
- **Several storage options exist**
  - $H_2$ can be one of them because it presents several assets
  - Potentially in combination with other ones
  - Needs to be selected in terms of relevancy for the specific use case
- **For $H_2$ as a large scale energy storage mean**
  - Coupling of several technology bricks: electrolyser – storage – transport to end-use
  - Several technologies exist for each brick
  - Need to be selected in terms of relevancy for the specific use case
- **Still some concrete actions needed to increase the use of $H_2$ as an energy storage mean**
  - Technical
  - Economical
  - Regulatory


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# Thank you for your attention