Road to Clean Energy Transition: Steps on Hydrogen

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Why Hydrogen?

Indicative **applications** of hydrogen: fuel for vehicles, ammonia production for fertilizers, metal refining.

Why are we interested?

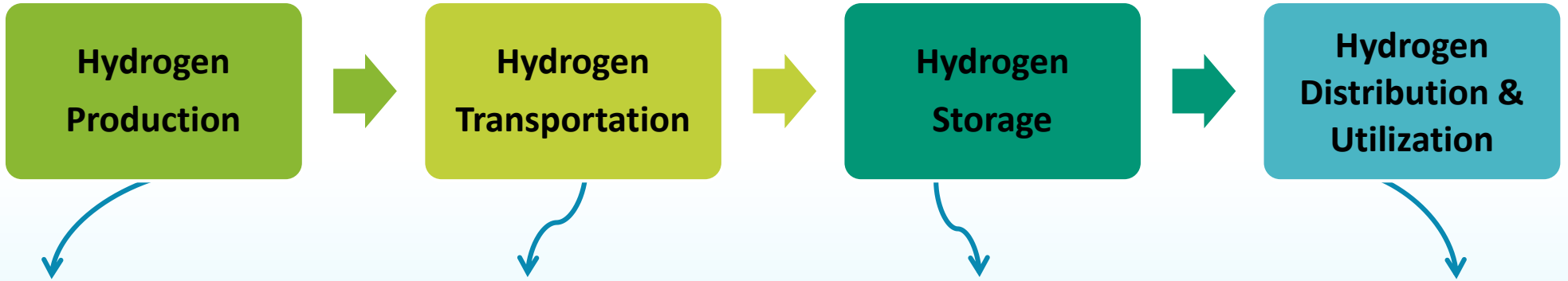
It can be **produced from renewable energy sources** and used as a **clean fuel** for transportation and power generation → is expected to play a **key role in the transition to a low CO_2 economy.**

It can be used for **electricity generation, without harmful by-products**.

Hydrogen value chain

Hydrogen value chain ⇨ describes the whole process from production to end use and consists of **4 stages**.

⇨ Each stage operates **independently**, but constitutes an **integral part** of the chain.



Hydrogen **is not a by-product** of a production process, **as is CO_2**. Thus, it **must be produced** in order to be used later.

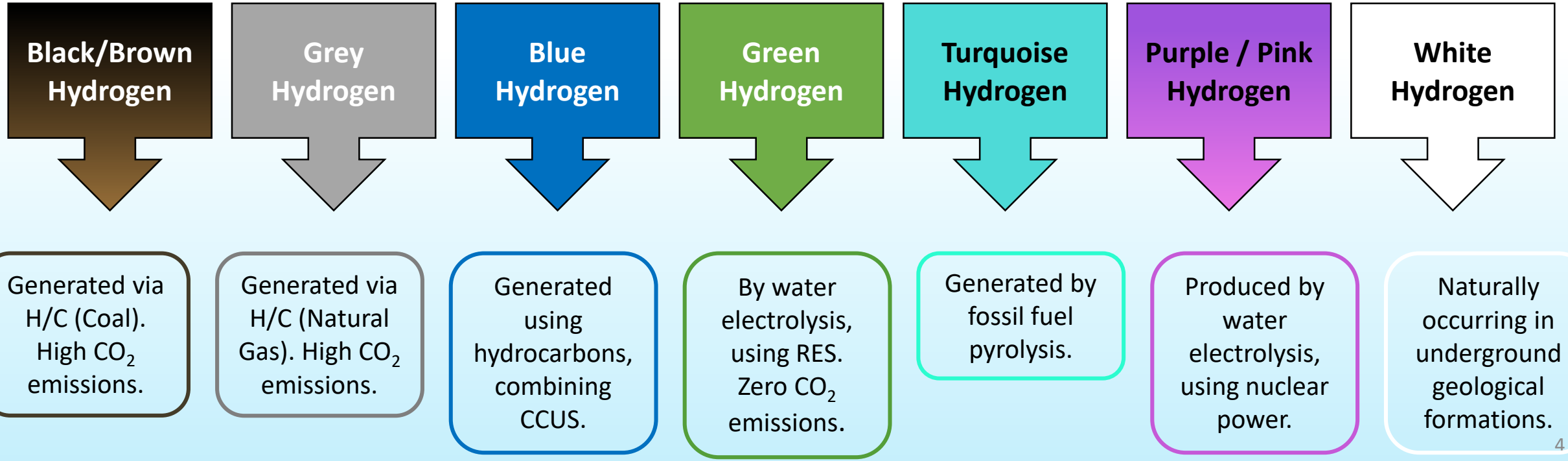
Hydrogen transportation is a process that requires compliance with strict protocols to **ensure safety**.

Hydrogen is stored in order to be **used for satisfying energy needs during periods of high demand**.

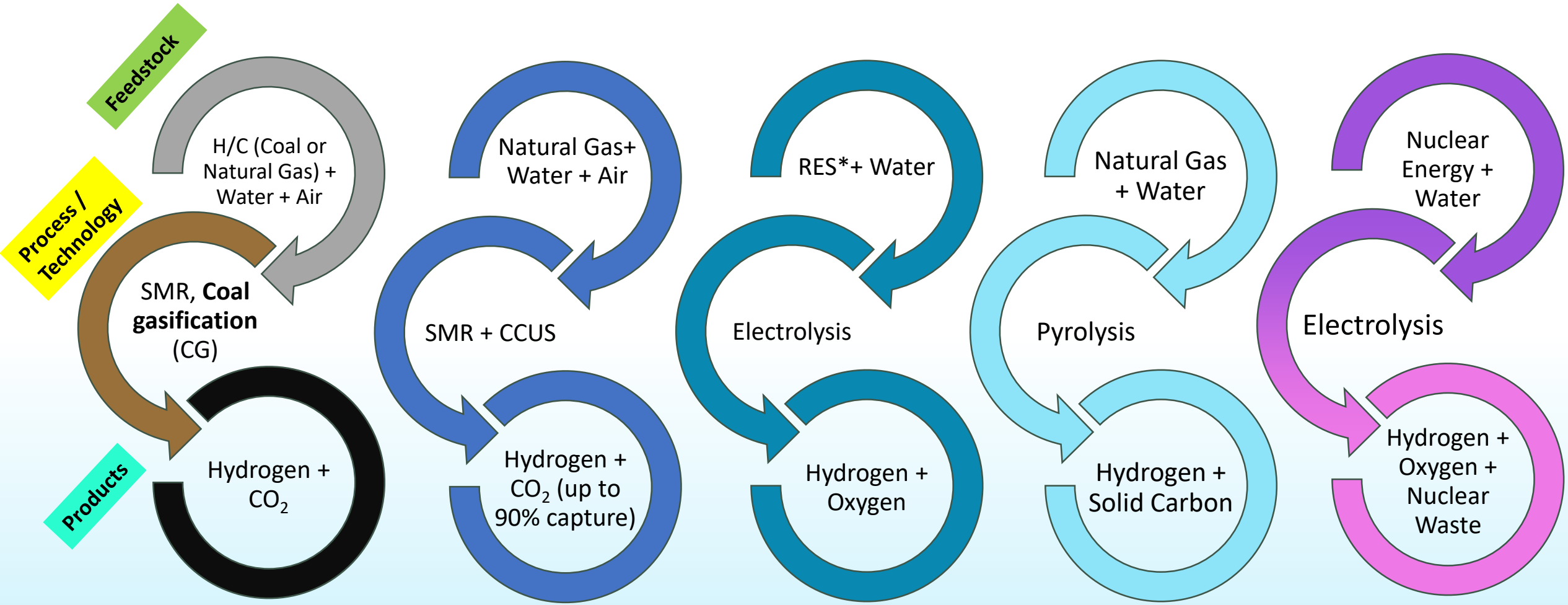
End-users deploy hydrogen to **satisfy demands** mainly related to **transport** and **energy production**.

H_2 value chain - Hydrogen Production

- Hydrogen can be produced by a variety of methods, such as **steam methane reforming**, **electrolysis** and **biomass gasification**.
- Some methods **emit** greenhouse gases **(GHG)** as **by-products**, while in other methods **no gaseous pollutants** are **emitted**.
- The different hydrogen production methods are **colour-coded**:



H_2 value chain - Hydrogen Production Processes



*RES = renewable energy sources

H_2 value chain

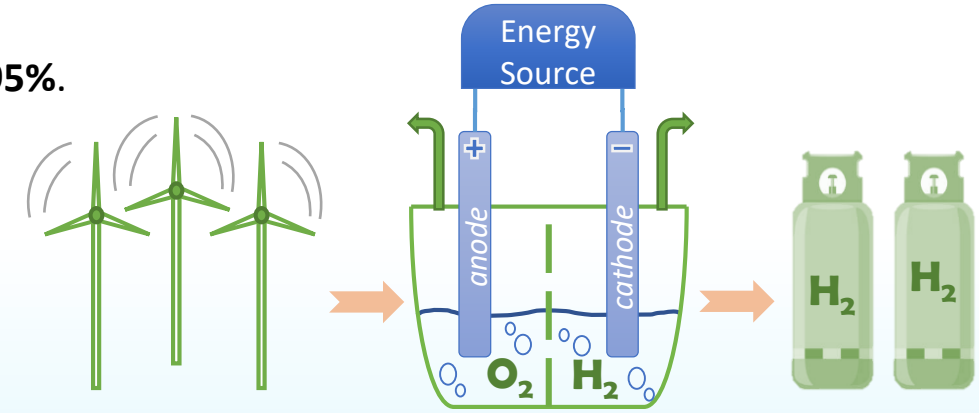
Current focus: Green H_2 Production

Feedstock

- **Water** is used as raw material for the production of green hydrogen.

Process / Technology

- **Electrolysis** using only **renewable energy sources** (RES), mainly solar energy, wind energy.
- **Hydrogen** produced by electrolysis reaches a **purity of > 99.95%**.
- **Three** main **electrolysis methods** have been **developed**:
  - Alkaline water electrolysis (ALK)
  - Polymer electrolyte membrane (PEM)
  - Solid oxide electrolyzer cell (SOEC)



RES *Electrolysis* *Green H_2*

Emissions / By-products

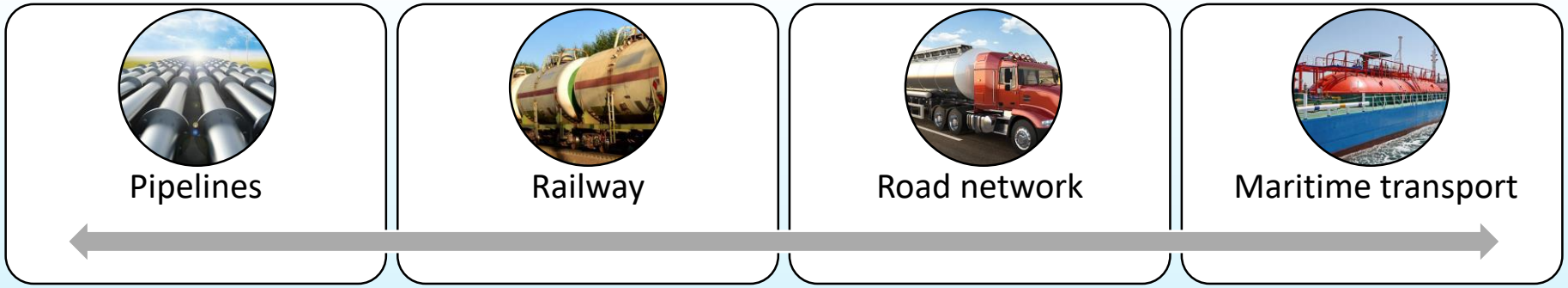
- **No greenhouse gases** (GHG) are emitted. The only by-product is the oxygen released during the electrolysis of water.

H_2 value chain: Hydrogen Transportation

✓ In the hydrogen value chain, **transportation** is identified **at 2 key-points**:

During periods of **low energy demand** → the **generated hydrogen** requires **transportation from** the **production facility to** the underground or aboveground **storage site**.

During periods of **high energy demand** → the **stored hydrogen** should be **transported from the storage** tank or reservoir **to the end users** to fulfil the increased energy needs.



A combination of the available transportation methods can be used

H_2 value chain:

H_2 Transportation Alternative – Gas blending

Except for the **conventional way** of gas transport via pipelines

⇩

H_2 **can also be transported through mixing with natural gas**.

H_2 can be mixed with natural gas and be transported via the existing gas pipeline network ⇨ **gas blending**.

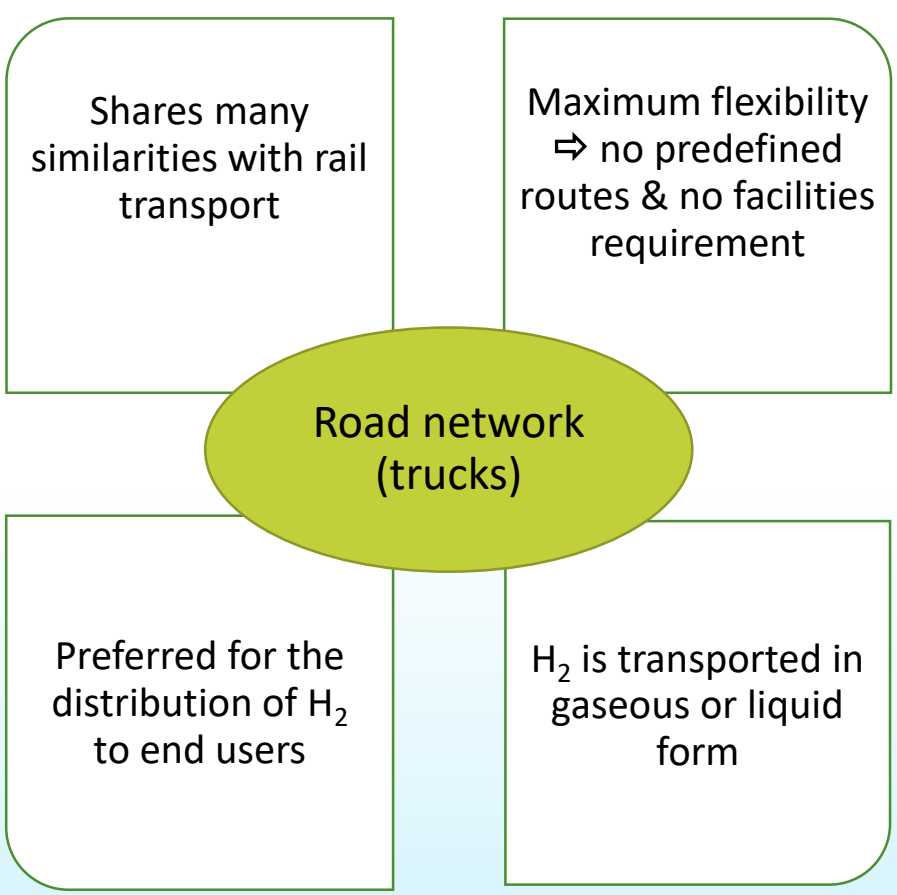
Advantage of this method ⇨ the ability to **use the current network** without significant retrofitting activities.

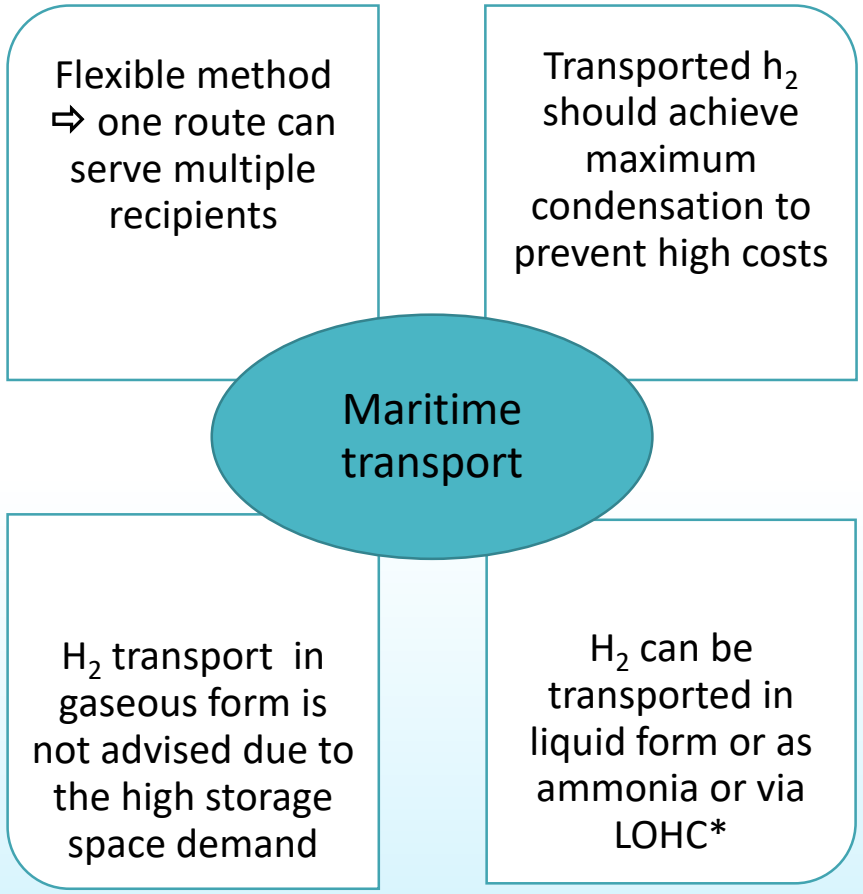
H_2 transport capacity using these systems is **~10%,** with **potential** to reach up to **25-30%** in local transmission networks**.**

Disadvantage of the method ⇨ **H_2 quality degradation** (its purity is reduced through mixing).

H_2 value chain

H_2 Transportation – 2 Preferred Methods





*LOHC: liquid organic H_2 carriers

H_2 value chain: Hydrogen Storage (1)

Two **categories** of H_2 storage:

Aboveground H_2 Storage

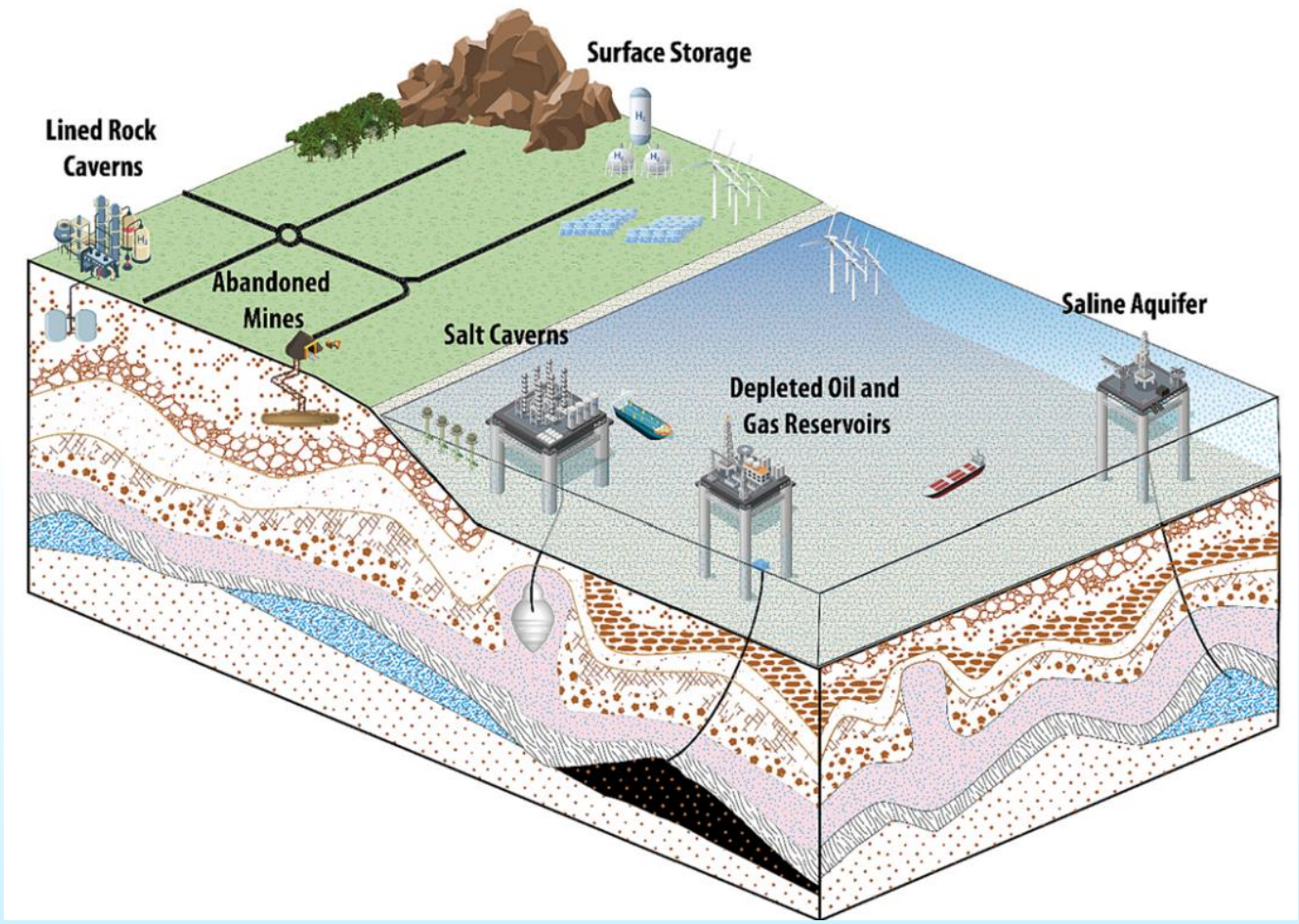
- Storage tanks (method Power-to-Gas (P2G))

Underground H_2 Storage

A. Storage in geological formations:

- Saline aquifers/porous media
- Abandoned rock mines (salt mines, limestone mines, coal mines)
- Depleted H/C (oil & gas) reservoirs
- Salt formations (salt caverns)

B. Storage in Lined or Unlined hard Rock Caverns (LRC)



H_2 value chain: Hydrogen Storage (2)

Underground H_2 storage in Geological Formations:

UHS in Abandoned rock mines

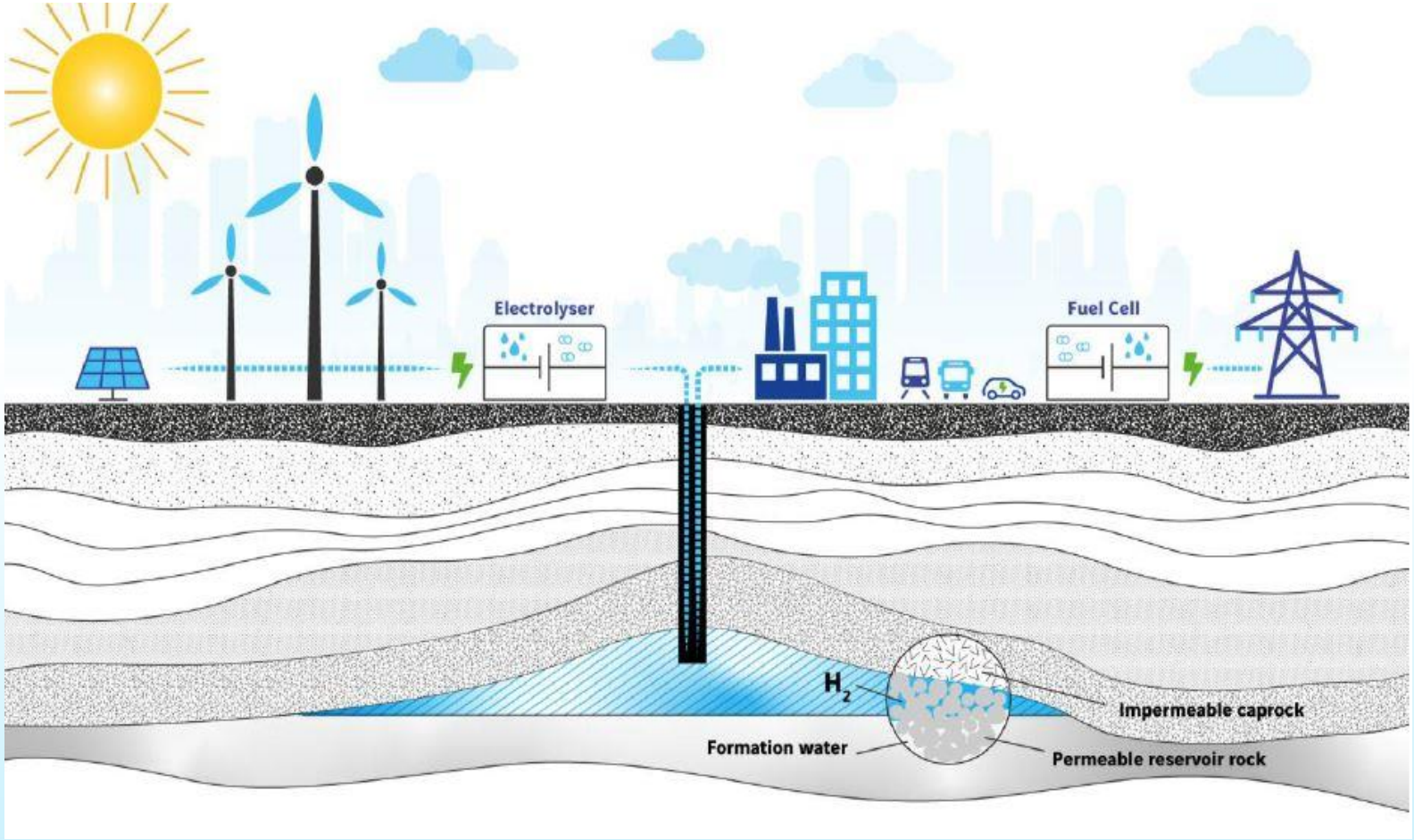
- ✓ **Existing cave** → no drilling is needed.
- ✓ **Possible availability** of **facilities** and **machinery** that can be used after necessary adaptation.

UHS in Saline aquifers/porous media

- ✓ **Experience** due to decades of **storing natural gas in aquifers.**
- ✓ **Requirements:**
  1. **porous formation** capable of retaining H_2
  2. **impermeable formation** to prevent migration

H_2 value chain: Hydrogen Storage (3)

Underground H_2 storage in Porous media/Saline aquifers:

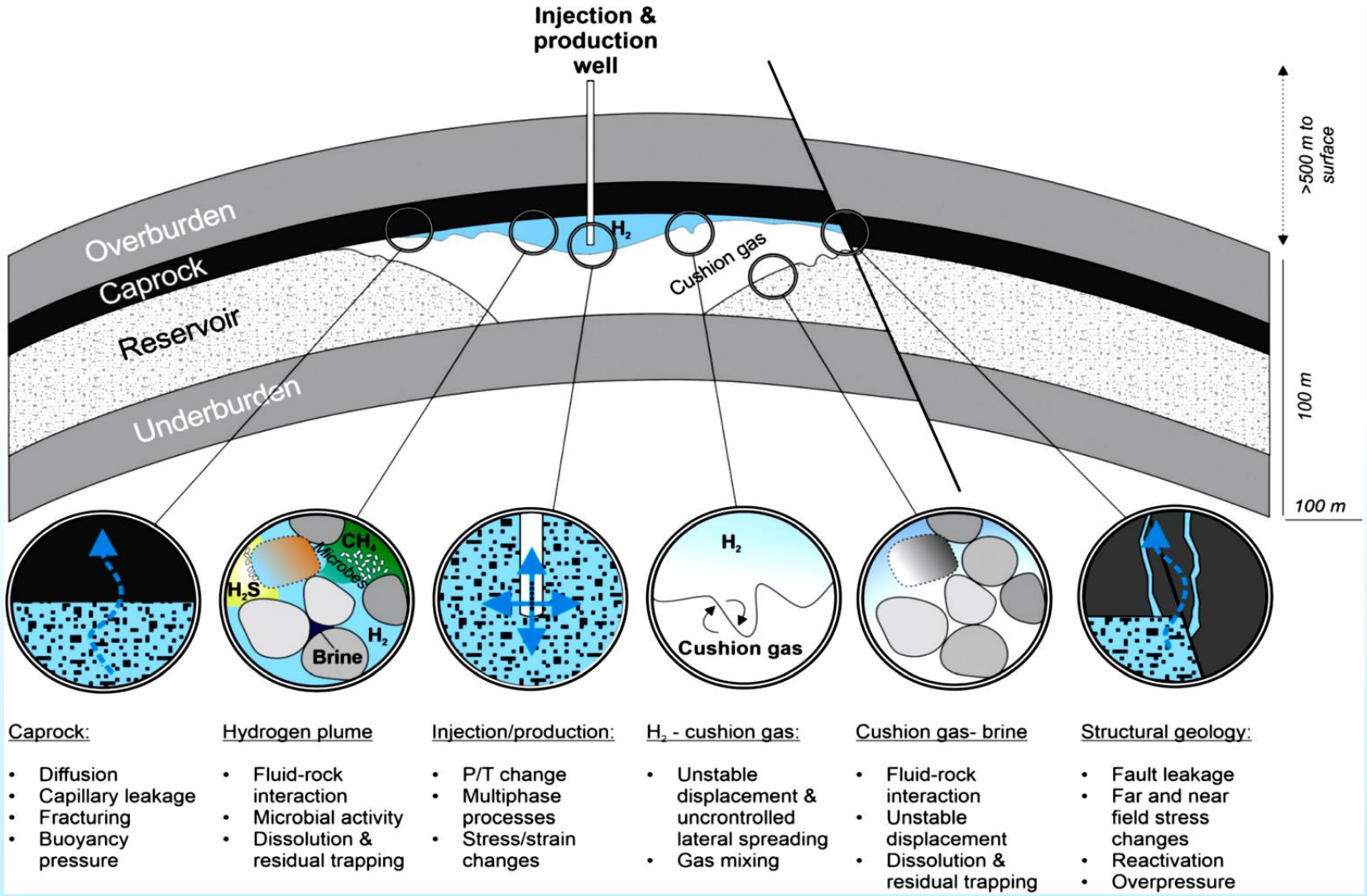


Schematic representation of hydrogen storage in porous rock. The impermeable caprock, forming an anticline that acts as a trap and the underlying porous reservoir rocks are presented.

(Source: Londe, 2021).

H_2 value chain: Hydrogen Storage (4)

Underground H_2 storage in Porous media/Saline aquifers:



Hydrogen storage in porous media highlighting all geological uncertainties.

(source: Heinemann et al., 2020)

H_2 value chain: Hydrogen Storage (5)

UHS in Salt formations (salt caverns)

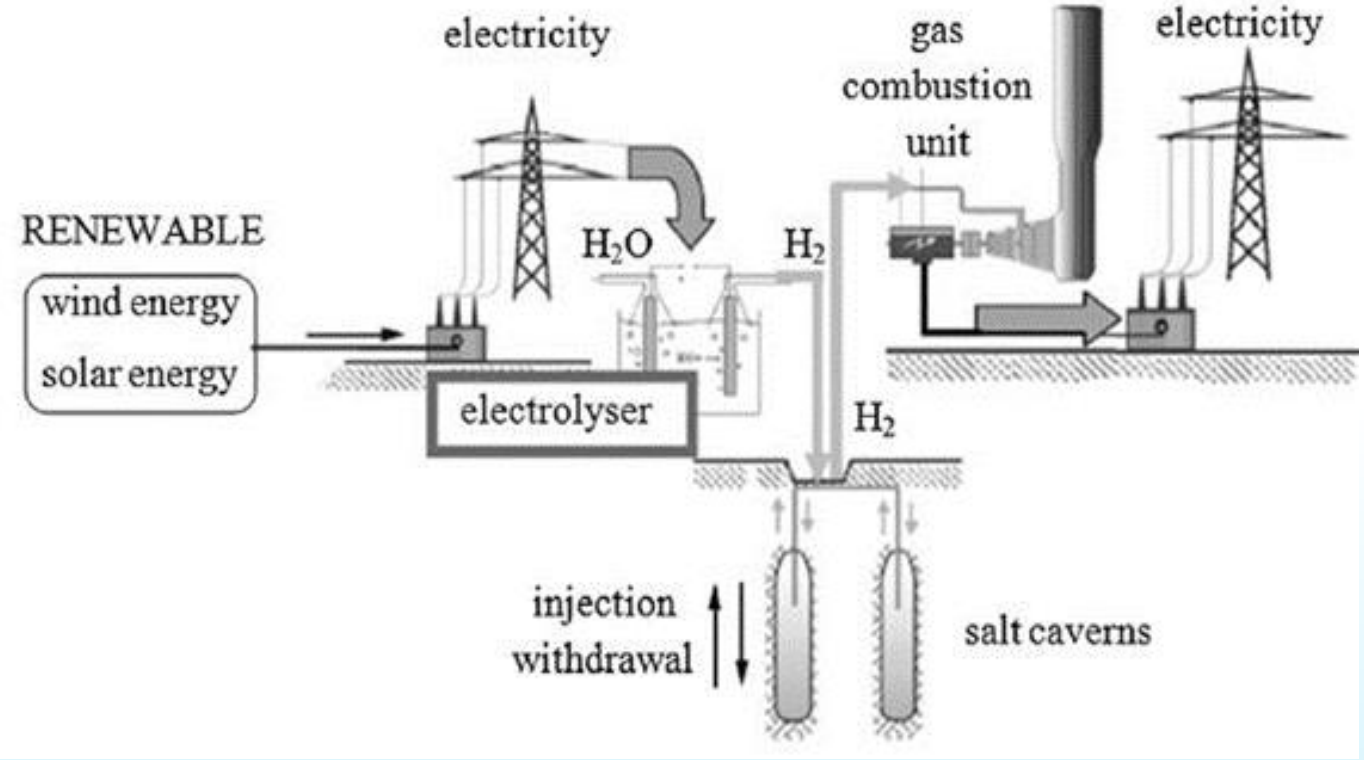
- ✓ **Large capacity and capable pressure conditions.**
- ✓ Relatively inexpensive excavation.
- ✓ **Higher rates of hydrogen storage and extraction → flexibility** to supply energy to the grid when required.

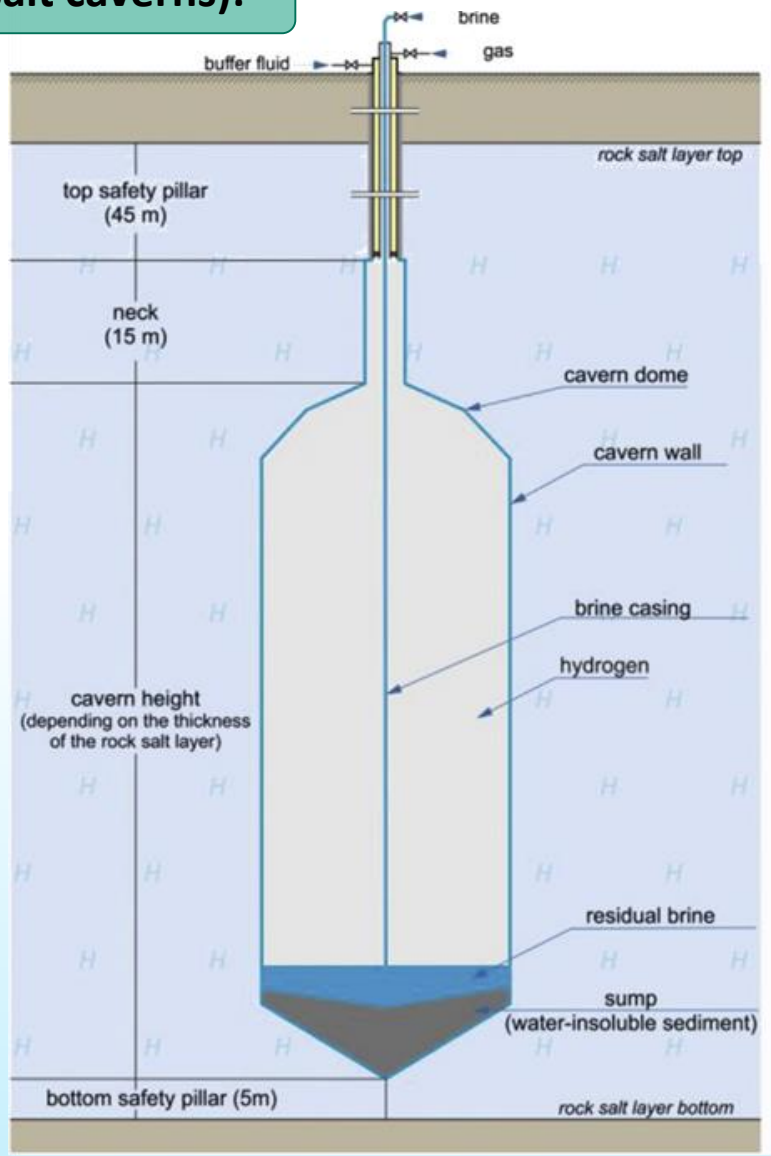
UHS in Depleted oil & gas fields

- ✓ **Optimum conditions** for gas storage.
- ✓ Years of **experience**, advanced **technological resources**, **existing facilities.**
- ✓ **Availability of** a residual gas quantity, which can be used as **cushion gas.**

H_2 value chain: Hydrogen Storage (6)

Underground H_2 storage in Salt formations (salt caverns):





Schematic representation of salt cavern systems for UGS

(Source: Ozarslan A., 2012).

H_2 value chain: Hydrogen Storage (7)

Underground H_2 storage in Salt formations (salt caverns):

Main principles:

A. Utilization of the natural pressure due to the overburdens

B. Large storage volumes & cylindrical shape of the deep geological formations (storage sites).

Construction of a storage salt cavern ➔ achieved by **a leaching process** ➔ using fresh / low salinity water.

Once the leaching is completed ➔ the **gas injection** discharges ➔ **replaces the salt-saturated brine**.

H_2 withdrawal mechanism is based on reducing the pressure of the cavern ➔ a **cushion gas** is used in order to **maintain the stability** of the storage salt cavern ➔ **H_2 delivery**.

H_2 value chain: Hydrogen Storage (8)

Underground H_2 storage in Salt formations (salt caverns):

Suitability of salt formations for UHS is evaluated based on their:

- depth
- thickness
- geographic extent
- presence of insoluble impurities, e.g. anhydride or sedimentary interbeds (dolomite, limestone, or shale)

Criteria for selection of salt formations for UHS.

Criteria	Requirements
Geology Rock Type	Salt formations
Structure	Salt Domes or Bedded Salt
Composition	95% of Halite
Cap rock	Anhydrite, Gypsum, Limestone
Depth	200–2000m
Height of cavern (H)	Typical values around 300m
Diameter of cavern (D)	Typical values around 70m
Maximum Salt temperature	80 °C
Volume of Storage	300,000–750,000m^3 (Salt domes); 100,000m^3 (Bedded Salt)

H_2 value chain: Hydrogen Storage (9)

Underground H_2 storage in Lined or Unlined hard Rock Caverns (LRC):

Lined Rock Caverns (LRC)

- **Excavated** underground in **solid rock formations/hard rock formations**.
- **Reinforced** with a specialized lining system ⇨ ensures a secure & controlled storage environment.
- **Natural rock**: bears the structural load & withstands external pressures
- **Lining system**: protective barrier (maintains the integrity and safety of the storage space).

Suitable geological formations:

✓ The category of **hard rock formations**

1. Rocks of decomposition grade I to II (fresh / slightly decomposed).
2. Crystalline materials & with low primary porosity
3. Typically belong to the crystalline basement of most geological sequences

⇨ e.g., granite, gneiss, granodiorite, monzonite, basalt, gabbro, and other igneous / volcanic / metamorphic rocks.

To be avoided:

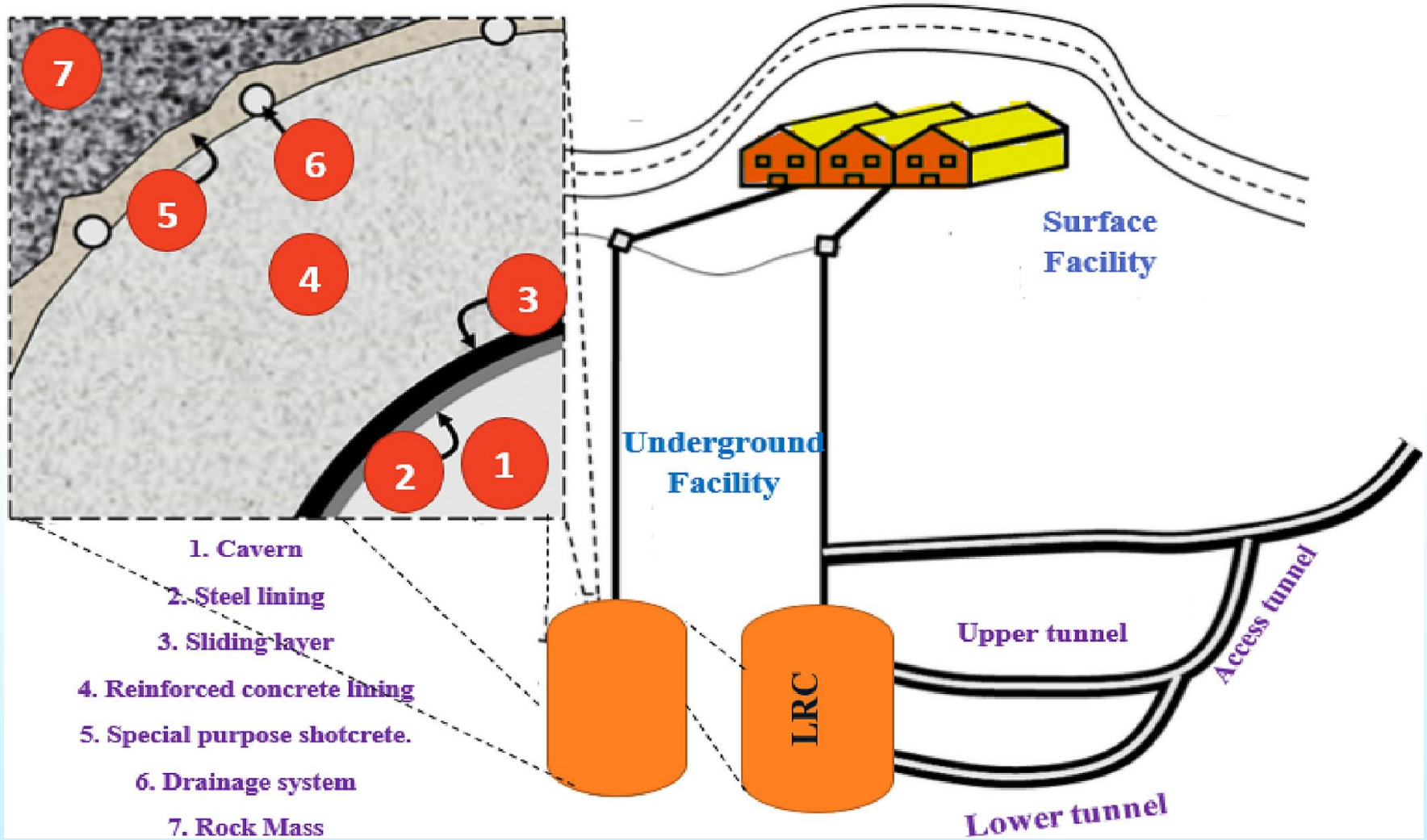
✓ Highly tectonic zones & Increased seismicity regions

✓ Karst systems

✓ High permeability rocks, sedimentary rocks

H_2 value chain: Hydrogen Storage (10)

Underground H_2 storage in Lined or Unlined hard Rock Caverns (LRC):



Components of Lined rock caverns

(Source: Taiwo et al., 2024)

Hydrogen Value Chain: Synopsis

H_2 Production

The H_2 production methods are codified by color.

- **Black/Grey H_2**: Generated via hydrocarbons. High CO_2 emissions.
- **Blue H_2**: Generated using hydrocarbons, combining CCUS.
- **Green H_2**: Produced by water electrolysis, using RES. Zero CO_2 emissions.
- **Purple H_2**: Produced by water electrolysis, using nuclear power.
- **Turquoise H_2**: Generated by fossil fuel pyrolysis.
- **White H_2**: Naturally occurring in underground geological formations.

H_2 Transmission and Distribution

The transportation of H_2 can be accomplished via various transport routes.

Pipeline Network

Road network

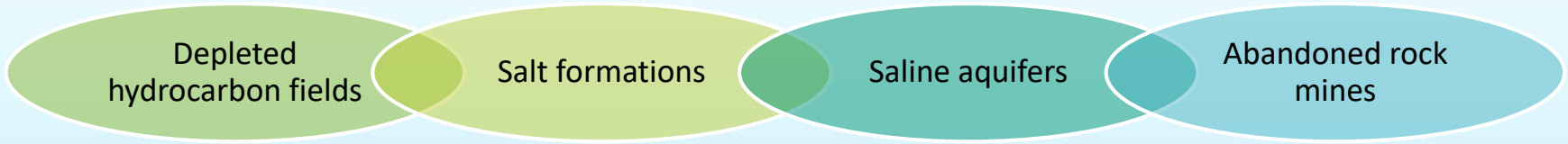
Railway network

Maritime transport

H_2 Storage

can be stored either **aboveground** in storage tanks, or **underground** in geological formations or in LRCs.

- **Geological settings** optimal for H_2 storage are:



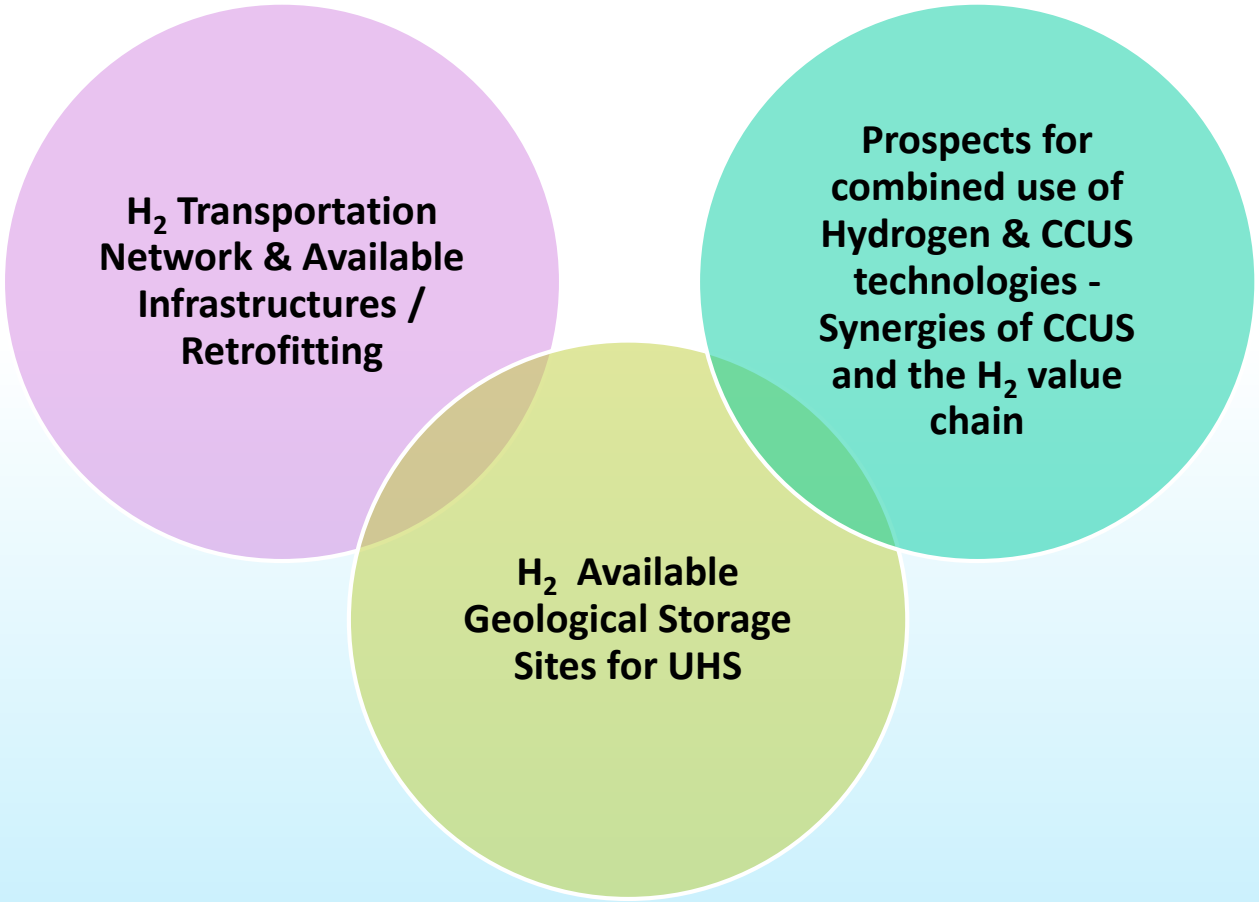
H_2 Utilisation

The already generated and stored H_2 can be utilised to cover the energy needs.

- H_2 is withdrawn from the storage site and properly processed to obtain a form that is suitable for use by consumers.
- H_2 can be utilised to **fuel vehicle**, **generate electricity** or **heat**.

How can H_2 Value Chain be applied in Greece?

Utilization of Available **H_2 Value Chain** Infrastructure:



*UHS = Underground Hydrogen Storage

H_2 Transportation in Greece – Available Infrastructure (1)

H_2 transportation infrastructure → **pipeline network plan for 2030 and 2040**

European Hydrogen Backbone plan for 2030 (Source: https://www.cehc.eu/h2-for-Europe/)

Projected expansion of the European H2 pipeline network by 2040 (Source: EHB)

H_2 Transportation in Greece – Available Infrastructure (2)

Existing gas pipeline network in continental Greece (Source: www.desfa.gr)

H_2 transportation infrastructure → pipeline networks

- **H_2 transport by retrofitting existing gas pipes:**

I. **Existing NG pipeline network →** can be **adapted** to transport H_2 **→ Reduces the costs** of constructing a new network.

II. **Different properties of H_2 gas** compared to NG **→ may cause corrosion** of the existing pipes **→ MUST adapt** the existing NG network.

- Greece-Bulgaria natural gas interconnection pipeline
- Turkey-Greece natural gas pipeline
- Trans-Adriatic natural gas pipeline system (TAP)
- Trans-Balkan pipeline
- EastMed pipeline (under design)

H_2 Transportation in Greece – Available Infrastructure (3)

- **H_2 transportation** infrastructure → **shipping** via Greek ports:

Ports (e.g., Piraeus port, Thessaloniki port) ➔ space for **industrial & commercial activity** ➔ can support numerous **ships & boats** (passengers / cargo)
➔ **Hydrogen hubs**

- Greek **railway network**:

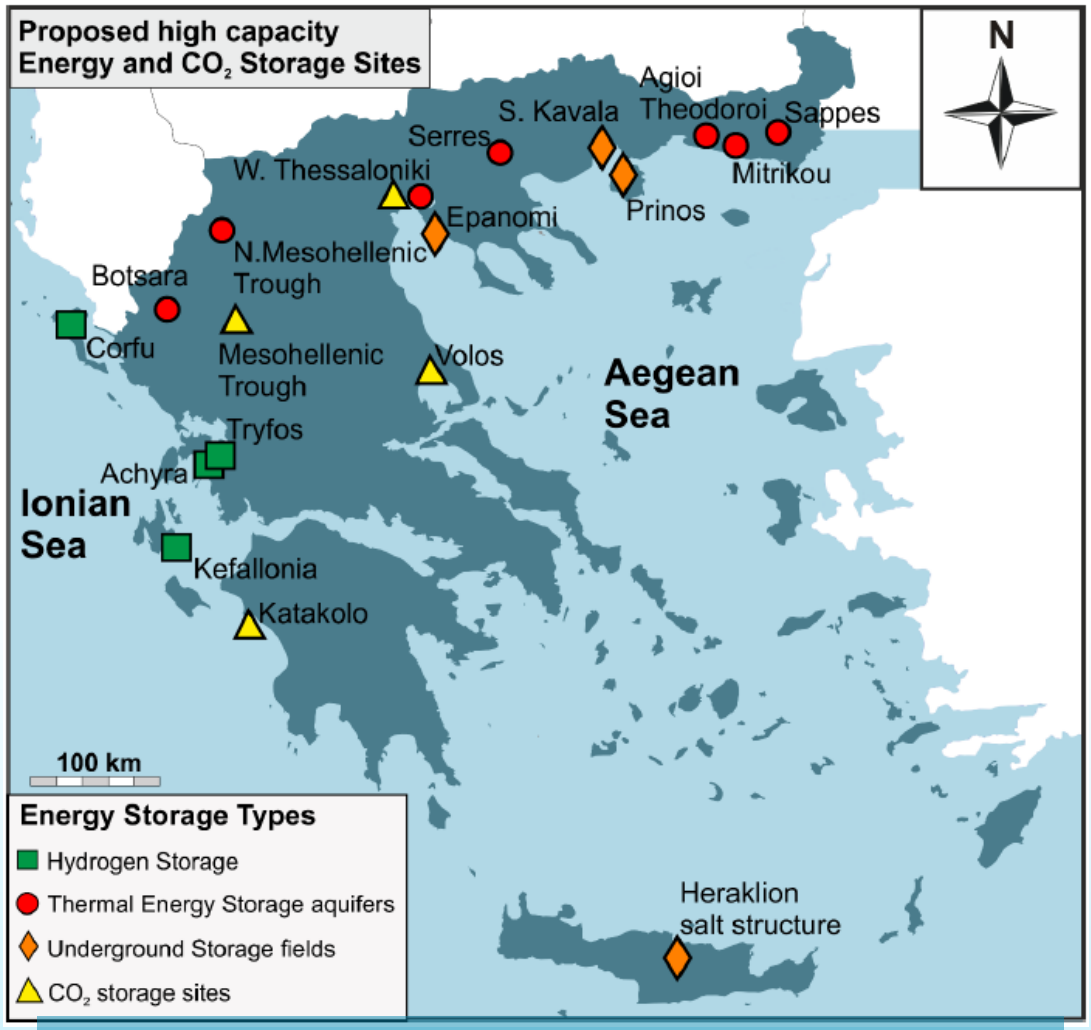
Western Macedonia (standard gauge line)	• Polykastro – Idomeni variant (new layout) • Kommanos – Kozani (Public Power Corporation)
Peloponnese (standard gauge line)	• Rododafni – Rio, Isthmus – Loutraki • Isthmus – Ag. Theodoroi (connection with Motor Oil facilities)

- **Larger volumes** of H_2 and **longer distances than trucks**.
- Transportation **tanks**: **materials compatible with H_2 properties** to **prevent** any **leakage due to corrosion**.

Existing railway network of continental Greece (Source: www.ose.gr)

H_2 Storage sites in Greece

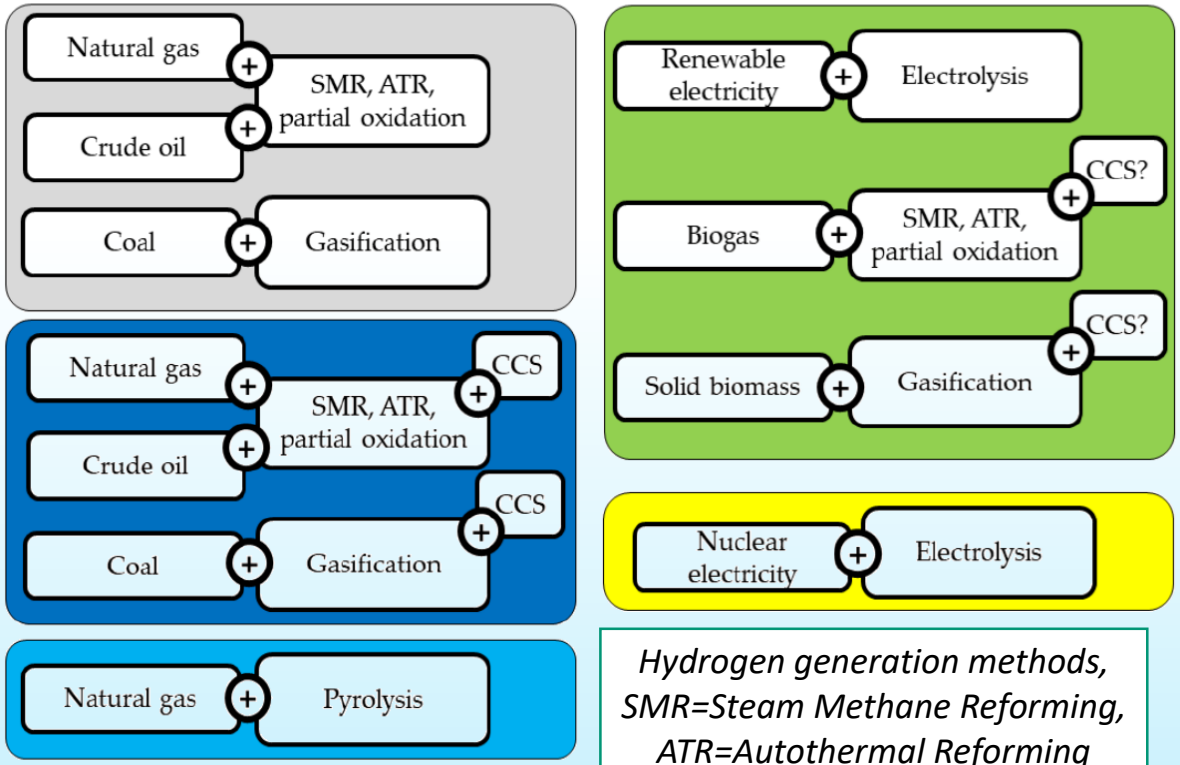
H_2 storage locations in Greece:	Capacity
1. Corfu	26.600 MWh(e) H_2
2. Achyra– Tryfos (Central Aitoloakarnania)	26.600 MWh(e) H_2
3. Kefallonia	26.600 MWh(e) H_2
4. Kavala (plans for underground gas storage facility)	1-2 TWh H_2



Potential H_2 & CCS storage sites in Greece
(Source: Arvanitis, Koukouzas, et al., 2020)

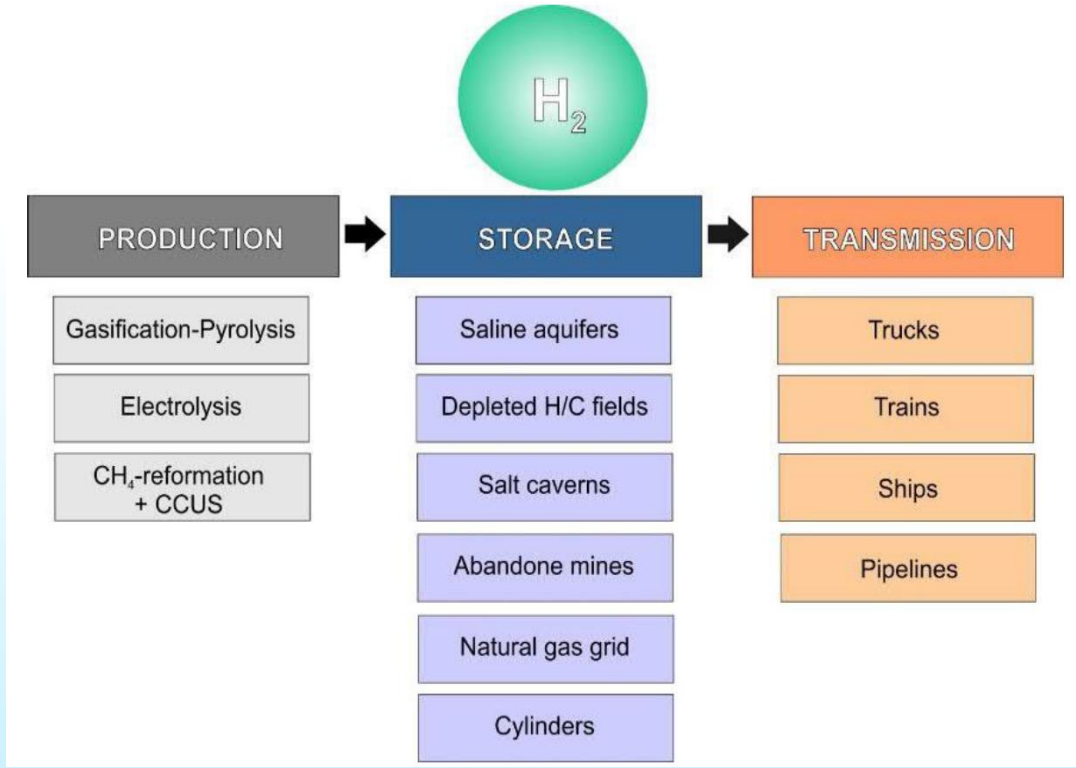
Synergies of CCUS and the H_2 value chain

- Potential synergies between CCUS & H_2 value chain → reduction of atmospheric CO_2 emissions → sustainable circular economy
- Hydrogen production methods → different colours depending on the generation source.



Hydrogen generation methods, SMR=Steam Methane Reforming, ATR=Autothermal Reforming (Noussan et al., 2021)

- Underground Hydrogen Storage (**UHS**) can be applied at:
  a) porous lithological formations
  b) abandoned rock mines
  c) salt formations



Schematic diagram of the H_2 value chain

H_2 Applications In Europe: Projects & current trends (1)

How have these been applied so far in Europe & Greece?

The interest of the **private sector** and **public bodies** has shifted towards **hydrogen** and the development potential of its value chain due to:

- the **potential** of hydrogen as an **energy source**.
- its **ability** to be **stored** in order to **satisfy energy requirements** during high-demand periods.

In recent years → increasing number of **partnerships** to develop the various stages of the **hydrogen value chain** → through **implementing H_2 projects**.

H_2 Applications In Europe: Projects & current trends (2)

- **H_2 projects** in Europe :

hystories	H_2 geological storage in aquifers and depleted hydrocarbon fields	Partners from: Austria, Belgium, Croatia, Czech Republic, Denmark, England, Estonia, France, Germany, Greece, Italy, Norway, Poland, Portugal, Romania, Spain and Turkey
HyUnder	H_2 geological storage	Partners from: Germany, Spain, France, Romania, the Netherlands and the UK
Hydrogen Underground Storage in Porous Reservoirs yUSPRe	H_2 geological storage in porous formations involves potential storage sites located in SEE (Bulgaria, Serbia, Romania, Greece, Turkey)	Partners from: Netherlands, Austria, the UK, Germany, Italy, Slovakia, Hungary and Norway
hypster Hydrogen Storage	Green H_2 geological storage in salt caverns	Partners from: Germany, France and the UK
HyGreen Provence	Green H_2 generation using solar power and storage in salt caverns	

H_2 Applications In Europe: Projects & current trends (3)

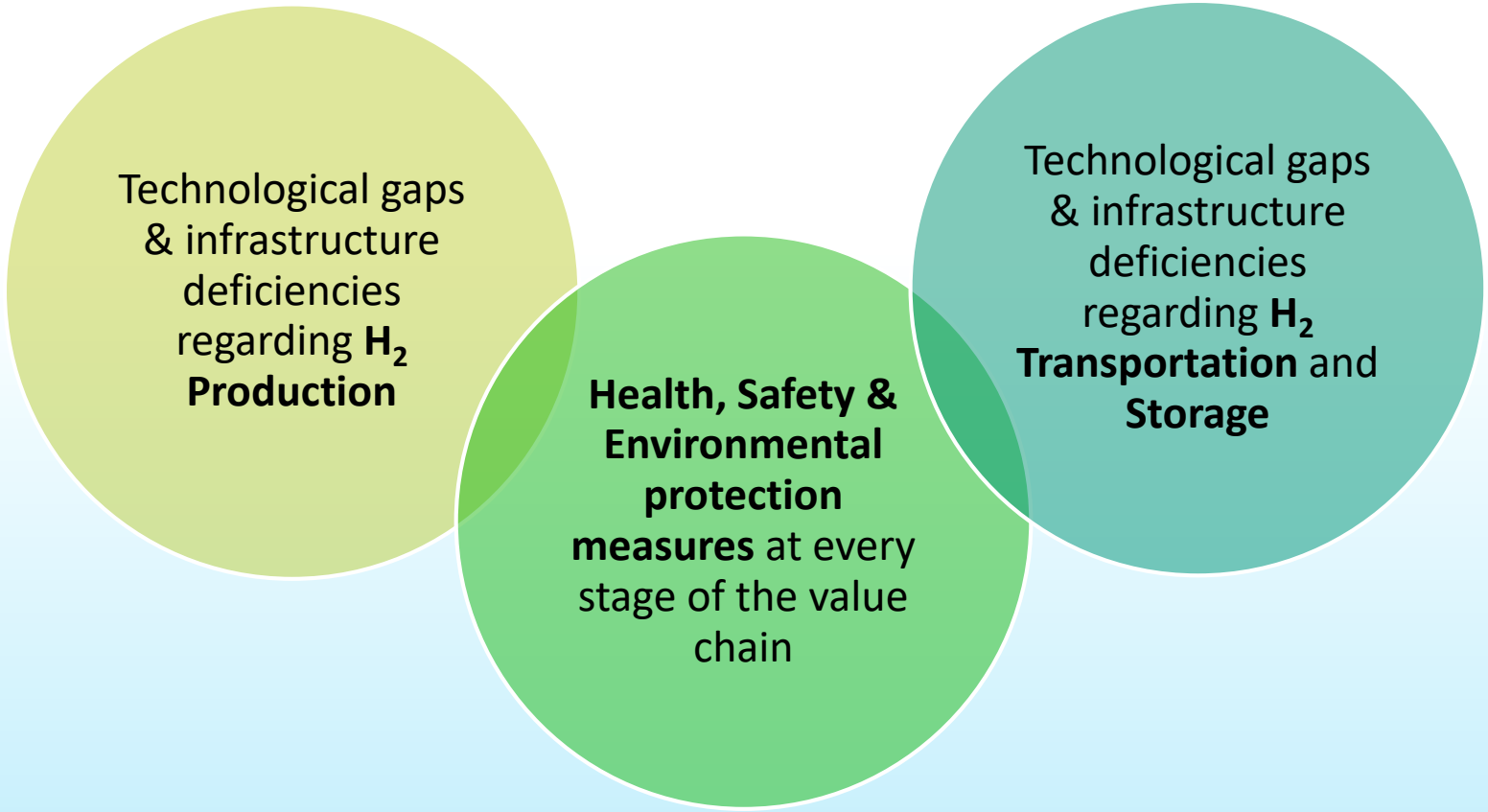
- **H_2 projects** in Europe :

CRAVE H_2	H_2 storage, aggregation activities and green mobility applications in the Hydrogen Valley of Crete-Aegean	Partners from Greece, Italy and Denmark
TRIĒRĒS H2V	Build a valley by exploiting the refinery facilities as H_2 producers in the Motor oil refinery in Corinth	Involves partners from 5 countries: Greece, Cyprus, Egypt, Netherlands and Austria
HY South Marmara	A green H_2 valley to achieve carbon neutrality in South Marmara, Turkey (production, storage, transportation)	Partners from Turkey, Morocco, Italy and Germany
GH2Cy Green Hydrogen Cyprus	Green H_2 production from RES for the transport sector, to refuel trucks and replace diesel vehicles in Cyprus	Partners from Cyprus

What needs to be filled in?

Gaps & Requirements in Greece

- **Technological Gaps & Requirements:**



What needs to be filled in?

Gaps & Requirements in Greece

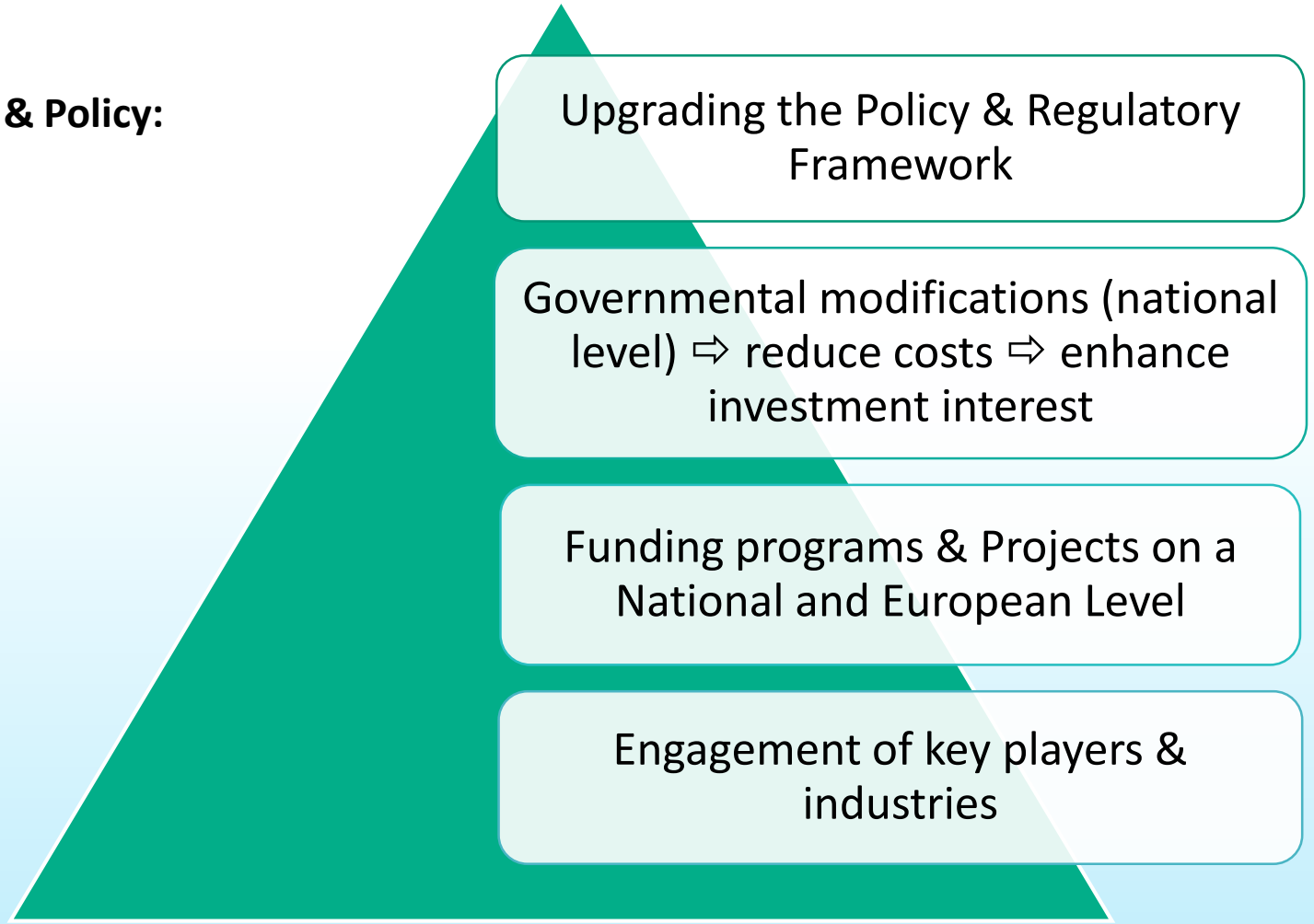
- **Knowledge & Expertise Deficiencies:**

Institutions, Universities & Companies	Industrial sector employees	Students & junior employees related to the industrial sector	Universities & Research Institutes	Funding of R&I actions
Training programs for the workforce	Training & reskilling programs	Education & training to acquire the required knowledge & expertise	Promotion of Research & Innovation (R&I) actions	Obtain: • High TRL for every H_2 value chain stage • High efficiency & durability • Low cost & risk

What needs to be filled in?

Gaps & Requirements in Greece

- **Legislation & Policy:**



Thank you for your attention

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Acknowledgements

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