CERTH
CENTRE FOR RESEARCH & TECHNOLOGY HELLAS

CPERI
Chemical Process and Energy Resources Institute

Achieving a Carbon-Neutral Future: Sustainable Hydrogen

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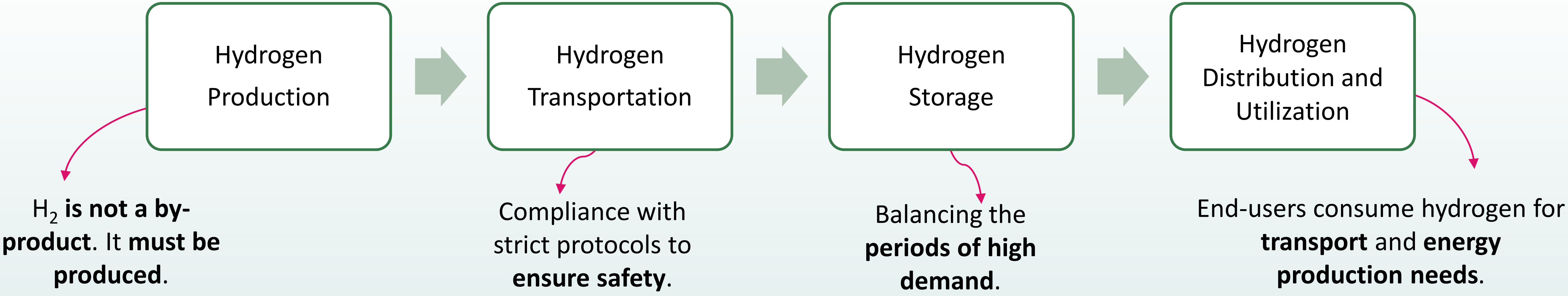
Hydrogen Value Chain

Why are we interested:

- Indicative **applications** of hydrogen: fuel for vehicles, ammonia production for fertilizers, metal refining.
- It can be used for **electricity generation, without harmful by-products**.
- 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.**

❖ The **hydrogen value chain from production to end use** and consists of **four fundamental stages**:



Hydrogen Production

H_2 Production Methods

- There are several production methods for H_2 → **steam methane reforming**, **electrolysis** and **biomass gasification**.
- They are **coded using colors**.
- Some of them **emit greenhouse gases (GHGs) as by-products**, while others **do not**.

Black / Brown Hydrogen: Produced by coal. Very high CO_2 emissions *(>180 kg CO_2-e/GJ H_2)*.

Grey Hydrogen: Generated using hydrocarbons (natural gas). High CO_2 emissions (*~94 kg CO_2-e/GJ H_2*).

Blue Hydrogen: Generated using hydrocarbons, combining the CCUS technology.

Green Hydrogen: Produced by water electrolysis, using RES. No GHGs emissions.

Turquoise Hydrogen: Generated by fossil fuel pyrolysis. Solid carbon is a by-product.

Purple / Pink Hydrogen: Produced by water electrolysis, using nuclear power. Generation of radioactive waste.

White Hydrogen: Naturally occurring H_2 in underground geological formations.

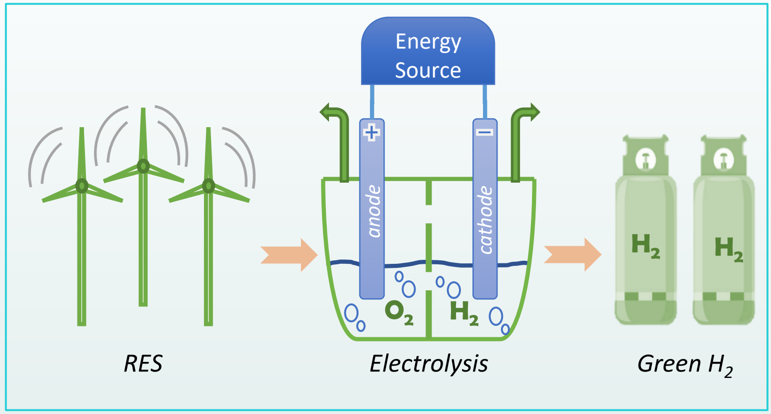
Blue & Green Hydrogen

Blue H_2

- It is produced **using natural gas** as a raw material.
- Joint application of **SMR technologies** for the H_2 producing **and CCUS technologies** for capturing the produced CO_2.
- Instead of SMR, **other** proposed **methods** include chemical looping reforming (**CLR**) and sorption enhanced reforming (**SER**).
- The **required CO_2 capture rate** for a facility to be regarded as producing blue hydrogen is **not specified**, but a percentage of **75-90%** has been **proposed**.
- Blue H_2 production results in **up to 90% CO_2 capture** compared to black/brown and grey H_2.
- **Methane leaks** during the generation process and transportation could **significantly increase pollutants**.

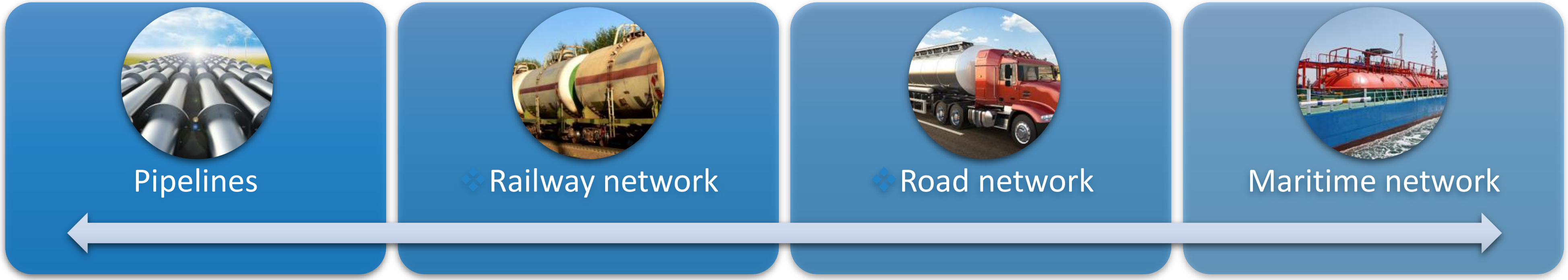
Green H_2

- **Water** is used as feedstock.
- **The production method is electrolysis** using only **renewable energy sources** (RES), mainly solar energy, wind energy.
- **Green H_2** reaches a **purity of > 99.95%**.
- There are 3 main **electrolysis methods**:
  - Alkaline water electrolysis (ALK)
  - Polymer electrolyte membrane (PEM)
  - Solid oxide electrolyzer cell (SOEC)
- **Zero greenhouse gases** (GHGs) are emitted. The only by-product is the oxygen released during the electrolysis of water.



Hydrogen Transportation

H_2 can follow various transport routes:



Pipelines: H_2 can be mixed with natural gas and transported through the existing gas pipeline network. This method is called gas blending.

Railways: Stored in tanks under pressure that can range from 350 to 700 bars. Suitable for large volumes of H_2 and longer distances.

Road network: offers flexibility, as they do not cover predefined routes. H_2 is transported in its gaseous or liquid form.

Maritime network: a flexible method that can serve multiple end-users. Transported in liquid form or in the form of ammonia or via LOHC (liquid organic hydrogen carriers), storage space is maximised.

Underground Hydrogen Storage

Saline aquifers

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

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.**

Abandoned mines

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

Salt formations

- **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.

European Projects

- The interest of the **private sector** and **public bodies** has shifted towards **hydrogen** and the potential for the development 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, an increasing number of **partnerships** have been established to **develop the various stages of the hydrogen value chain** through the **implementation of projects**.

- **Indicatively**, some **H_2 projects** in Europe are mentioned:

hystories: H_2 geological storage in aquifers and depleted hydrocarbon fields

HyUnder: H_2 geological storage

HyUSPRe (Hydrogen Underground Storage in Porous Reservoirs): H_2 geological storage in porous formations

hypster (Hydrogen Storage): Green H_2 geological storage in salt caverns

HyGreen Provence: Green H_2 generation using solar power and storage in salt caverns

H_2 projects & current trends
International Projects

- Several **H_2 projects** have already been **implemented** successfully or are **under operation** around the **world.**
- Indicatively, some **operational Green H_2 projects around the world** are mentioned:

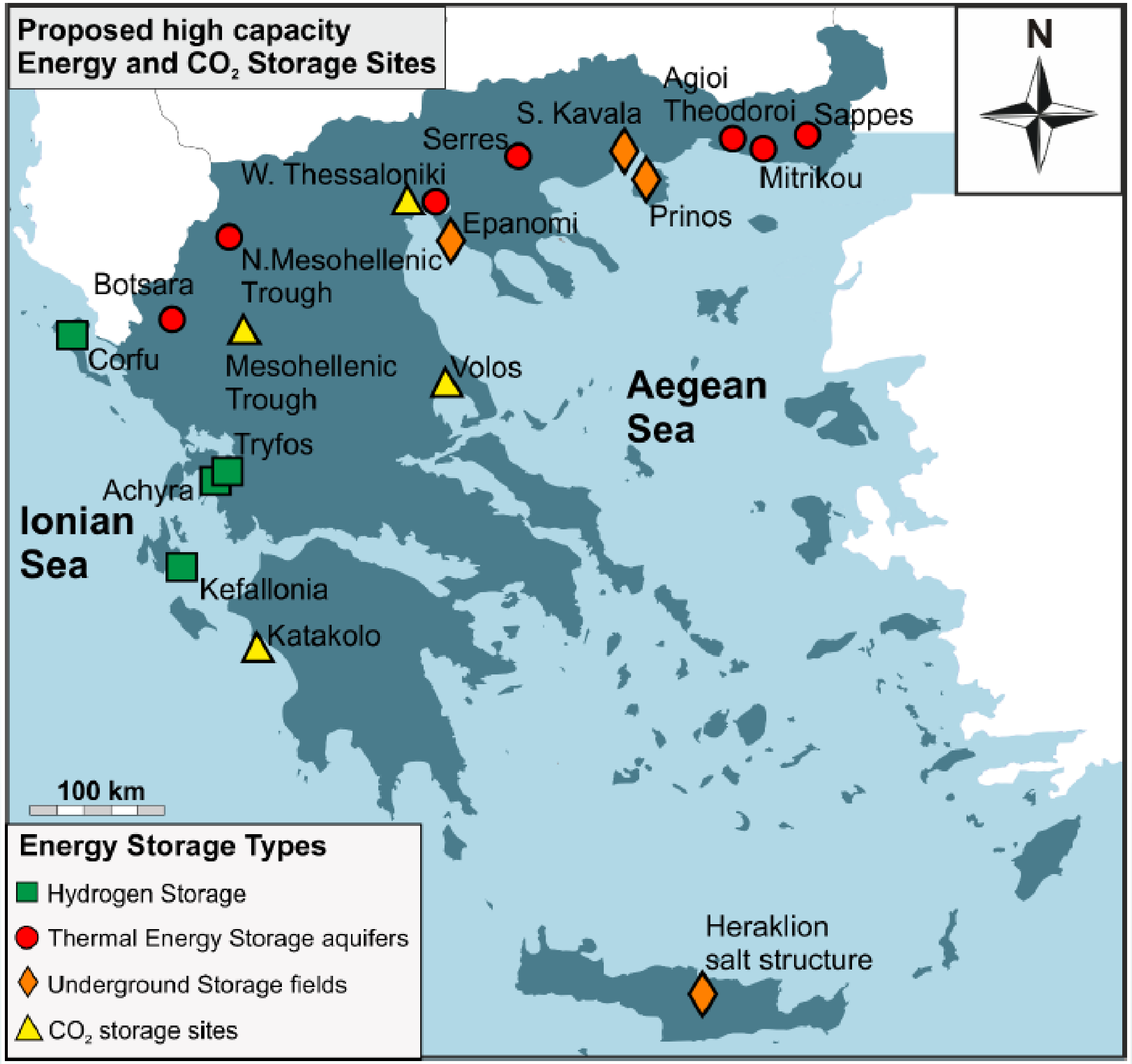
Name	Description	Location	Project Start
Clean Energy Center (CEC)	A photovoltaic-hydrogen production system	Turkey, Pamukkale, Denizli	2007
Hydrogen production plant	Plant involving the stages of production, purification, compression, storage, quality control, transport & final use.	Brazil, Paraná	2014
Lam Takhong Wind Hydrogen Hybrid Project-EGAT	The facility consists of Hydrogenics' ultra-compact 1 MW PEM HyLyzer® electrolyzer, hydrogen storage and a HyPM® fuel cell plant.	Thailand, Nakhon Ratchasima	2017
Musashi-Mizonokuchi Station	A Toshiba H_2One system was installed at Musashi-Mizonokuchi Station on the JR Nambu Line in Kawasaki City.	Japan, Kanagawa, Kawasaki	2017
Tongji solar hybrid hydrogen refueling station	China's first 70MPa hydrogen refueling station (Tongji-Xinyuan Hydrogen Refueling Station) to produce H_2 with wind-solar hybrid generation.	China, Shanghai	2018
ATCO clean energy innovation hub	The Hub generates clean hydrogen through solar-powered electrolysis, and was a significant step in Western Australia's moves toward a hydrogen economy.	Australia, Western Australia, Jandakot	2019

H_2 projects & current trends
International Projects

Name	Description	Location	Project Start
Hydrogen production (Bruce nuclear power plant)	H_2 mass production using nuclear technology and prospects for alignment with oil & gas, transportation and electricity generation sectors.	Canada, Ontario, Tiverdon	2020
Air Liquide Canada	A 20MW electrolyzer system for a H_2 production facility: plant with an annual H2 output of just under 3,000 tons.	Canada, Quebec, Becancour	2021
Baofang Energy	The largest solar-powered hydrogen pilot plant in the world by Baofeng Energy Group: a 200-MW solar power plant to make hydrogen via electrolysis.	China, Ningxia	2021
Haru Oni project (phase 1)	The world's first integrated and commercial large-scale plant to produce climate neutral e-methanol and e-gasoline. Phase 1 relies on an electrolyxer using Silyzer 200 PEM technology.	Chile, Magallanes region	2022
Sinopec green hydrogen pilot project	The project mainly includes five major parts: photovoltaic power generation, power transmission, electrolytic water hydrogen production, hydrogen storage and hydrogen transmission.	China, Xinjiang	2023
Floating wind farm green hydrogen production plant	The first phase of the project will be to build a 100 MW green hydrogen pilot plant in a floating wind farm in the East Sea by 2025. By 2030, their second phase project will consist of the construction of a 1.2 GW large-scale green hydrogen production facility.	Korea, Republic of, Donghae, East Sea	2025

H_2 projects (operational) around the world

Hydrogen Potential in Greece



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

- In Greece, there are several sites that could be utilized for **H_2 storage**.
- Greek **evaporites** (saline formations) are the most **favorable for geological H_2 storage**.
- The **potential of H_2 storage** have been calculated at **26.600 MWh(e)** for **each one** of the areas of **Corfu**, **Achyra - Tryfos** and **Kefallonia**.
- In these areas, **gas turbines exist** that can be used for **wind energy** generation to implement **green H2 production**.
- There is also the potential for the storage of **1 – 2 TWh H_2** at the underground natural gas storage facility at **Kavala**.

Combined use of CCUS & H_2 technologies

Underground Hydrogen Storage using CO_2 as cushion gas

Combined use of **CO_2 and H_2 storage** technologies

Cushion gas occupies **up to 1/3** of the **reservoir volume**

- Using CO_2 as cushion gas:
  - maintain sufficient pressure
  - cost-effective solution
  - mitigate CO_2 emissions

CO_2 Hydrogenation

Combined use of **CO_2 and H_2 utilization** technologies

Captured CO_2 is combined with **H_2** to **produce methane**

- **Methane** can be used as an **energy carrier**, due to its high density → safe storage and transportation.

Blue H_2 Production

Combined use of **CO_2 capture and storage**, with **H_2 generation** technologies

Captured CO_2 can be **utilized in industrial applications** after proper treatment

Retrofitting existing refineries by creating a CO_2 capture unit can **reduce investment costs**

CCUS value chain

Carbon capture, utilization and storage (**CCUS**) refers to a suite of technologies that can play a diverse role in meeting global energy & climate goals.

Such technologies are valuable tools for the decarbonisation of the industrial sector.

CO_2 Capture

CO_2 along with other flue gases is captured via the deployment of capture technologies from industrial source points.

CO_2 Separation from fuel gases

CO_2 is isolated from other flue gases.

CO_2 Transportation

CO_2 is collected and transported to areas of interest.

CO_2 Utilization / Storage

CO_2 is either utilized into new ways or is safely stored away from the atmosphere.

CO_2 Geological Storage

- CCUS captures CO_2 from large point sources (power generation or industrial facilities). If not being used on-site, CO_2 is compressed, transported & **injected into geological formations for CO_2 storage**.
- There are **3 main technologies for long-term CO_2 storage**: geologic storage, ocean storage & mineral carbonation.

- CCS suggests the confinement of CO_2 into geological formations. A potential CO_2 reservoir shall present the appropriate: (1) **permeability**, (2) **thickness**, (3) **depth**, (4) the occurrence of an overlying **caprock**.

- **Injecting CO_2 into deep geological formations** has applied by the oil and gas industry for many years.

- Using **CO_2 for EOR is also a form of geologic storage**.

- **Underground geological formations** suitable for CO_2 sequestration are:

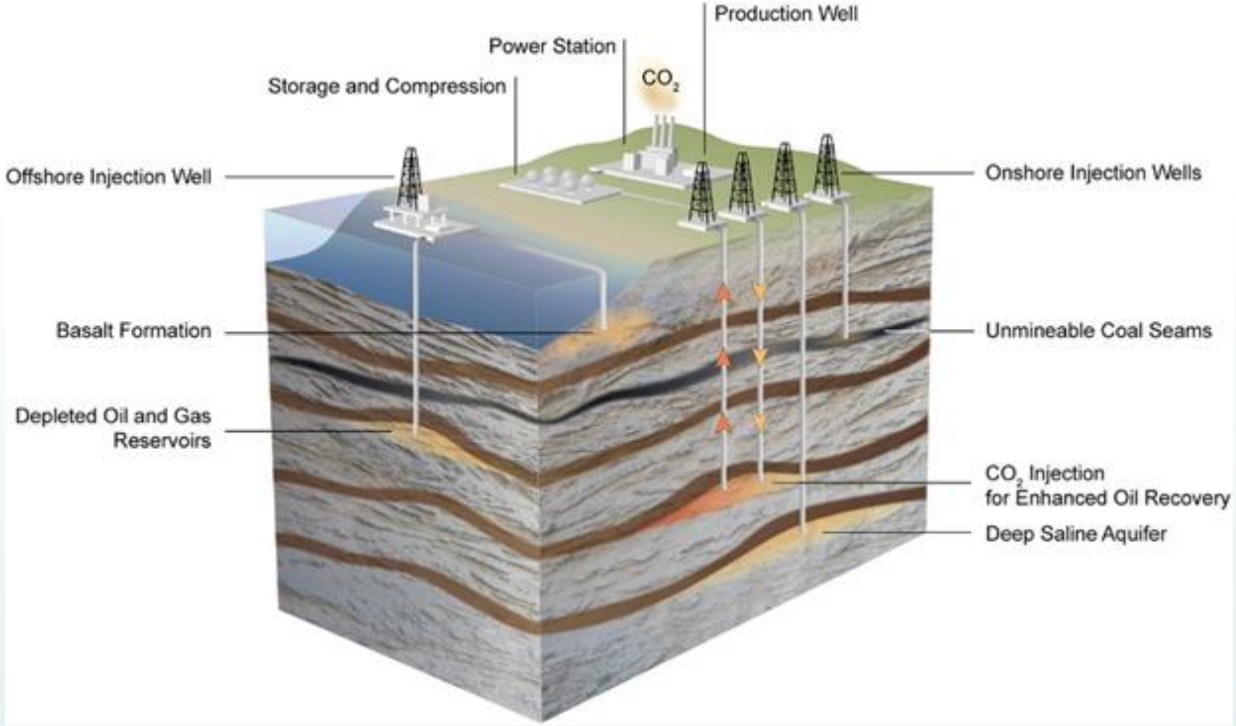
Deep Saline Formations

Abandoned Coal Mines/Salt Caverns

Depleted Hydrocarbon Fields

Coal Seams

Basaltic, ultramafic rocks and sandstones (CO_2-mineralization)



Overview of potential geological CO_2 media. (Source: Ali et al., 2022)

Indicative References

- Ajanovic, A.; Sayer, M.; Haas, R. The economics and the environmental benignity of different colors of hydrogen. International Journal of Hydrogen Energy, 2022, 47, 57: p. 24136-24154.

- Ali, M.; Jha, N.; Pal, N.; Keshavarz, A.; Hoteit, H.; Sarmadivaleh, M. Recent advances in carbon dioxide geological storage, experimental procedures, influencing parameters, and future outlook, Earth-Science Reviews, 2022, 225, 103895. https://doi.org/10.1016/j.earscirev.2021.103895

- Arvanitis, A.; Koutsovitis, P.; Koukouzas, N.; Tyrologou, P.; Karapanos, D.; Karkalis, C.; Pomonis, P. Potential Sites for Underground Energy and CO_2 Storage in Greece: A Geological and Petrological Approach. Energies, 2020, 13, 11: p. 2707.

- https://www.thehydrogenmap.com/ (Accessed on 7/11/2023)

- Koukouzas, N.; Tyrologou, P.; Karapanos, D.; Carneiro, J.; Pereira, P.; de Mesquita Lobo Veloso, F.; Koutsovitis, P.; Karkalis, C.; Manoukian, E.; Karametou, R. Carbon Capture, Utilisation and Storage as a Defense Tool against Climate Change: Current Developments in West Macedonia (Greece), Energies, 2021, 14, 3321. https://doi.org/10.3390/en14113321

- Tarkowski, R., Underground hydrogen storage: Characteristics and prospects. Renewable and Sustainable Energy Reviews, 2019, 105: p. 86-94.

Thank you for your attention

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