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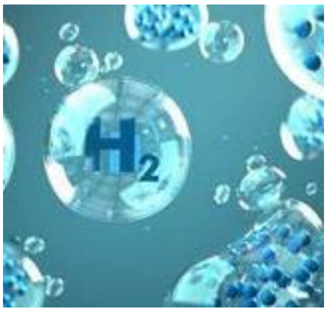

HYDROGEN STORAGE IN PORTUGAL

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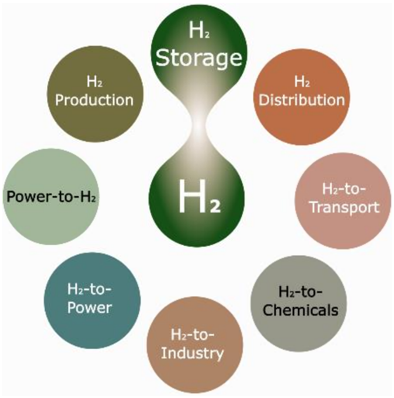
OBJECTIVE

This Policy Brief provides an overview of the technologies and challenges associated with **hydrogen storage**, a fundamental link in the hydrogen value chain.



OUTSTANDING HISTORICAL ACHIEVEMENT IN PORTUGAL

Portugal reached an electricity share of about 70% from renewable energy sources in 2023 (APREN, 2024). It is an outstanding historical achievement. The electricity share from wind energy was 27.3%, followed by hydropower generation with 24.7%, solar with 12.1%, and biomass with about 6%. The Portuguese energy mix has undoubtedly been diversified, but to achieve the national goal of becoming carbon-neutral, it is necessary to increase the efforts to decarbonise our industries, transport, residential, and agricultural sectors. The revised Energy and Climate National Plan (PNEC) 2030 states that about 3 GW of electrolysers shall be installed by 2030, and this will require renewable electricity generation capacity in the order of 8.6 GW from different onshore and offshore sources. Solar and wind energy are the technologies expected to grow the most in the next decade.

The increase in such renewable energy capacity implies greater integration challenges due to their variability in time. Therefore, incorporating energy carriers that can absorb the excess energy and supply it back to the electricity network when necessary is paramount to guarantee the flexibility needed to maintain our grids operating smoothly and continuously. This could be achieved through hydrogen (H_2) production, storage, distribution, transformation into other commodities, and use in different sectors. However, the hydrogen market is incipient. To develop it, it is necessary to rely on emerging technologies that must be tested and then upscaled, counting on the support and involvement of public and private actors.

CHALLENGES, STORAGE OPTIONS FOR H_2, AND HYDROGEN USES/CONSUMERS

H_2 Low volumetric energy density is a main challenge

The major challenge regarding H_2 storage is finding efficient solutions that comply with its high-gravimetric and low-volumetric storage densities, i.e., systems that can store the highest mass of hydrogen in the lowest volume possible.

Storing H_2 is challenging since H_2 is the lightest element in the periodic table. This means that although H_2 contains more energy per unit of mass than natural gas or gasoline (roughly three times more than natural gas, with 120 MJ/kg for hydrogen versus 47-49 MJ/kg for natural gas – Low Heating Values), it has a lower energy content per volume, roughly three times less than natural gas for H_2 at 1 atm of pressure and 0ºC (The Engineering ToolBox, 2008).

Therefore, larger volumes of gaseous hydrogen would be needed to meet energy demands identical to those of other fuels. In other words, if hydrogen were to replace natural gas today, **we would need 3-4 times more storage infrastructure**. Therefore, **cost-effective storage options are key to enabling green H_2 to be a feasible and widely used energy vector.**

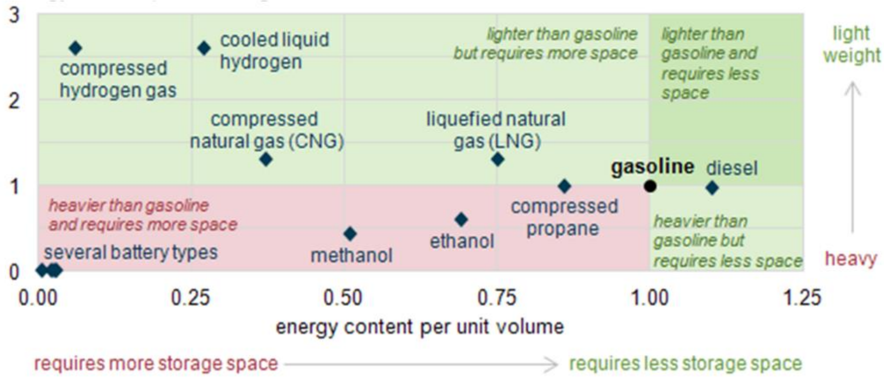


Figure 1. Energy density comparison of several transportation fuels (indexed to gasoline =1).
Source: https://www.eia.gov/todayinenergy/detail.php?id=9991.

Because H_2 has a low volumetric energy density at ambient conditions (pressure and temperature), its storage, for economic reasons, requires the use of processes that lead to the reduction of its volume, such as compression or liquefaction. These processes are energy intensive and require more resistant materials, which increase storage costs.

H_2 storage options: Established and under-development technologies

The following **H_2 storage options** exist currently (some are commercially available, whereas others are only prototypes requiring further development). Figure 2 summarises established and under development storage options for H_2 and provides reference information on typical temperature, pressure and storage capacity values. Storage capacity, when it comes to "material based" storage, is usually expressed in gravimetric hydrogen density [wt.%], i.e., the percentage of H_2 mass over the mass of the storage medium.

Storage options can be in gas, liquid, or in solid mediums. Nevertheless, only storage as gas and/or liquid has been proven at industrial scales, with different costs and commercial availability.

H_2 storage can involve compression, liquefaction, or can be achieved by diffusion, chemical reactions, solid-state reactions, absorption, adsorption processes, among others. Most of them are depicted in Figure 2.

Hydrogen is usually stored in cylindrical or spherical tanks. The conditions of tank storage vary significantly according to the hydrogen's physical state. For example, **tanks for hydrogen in gaseous** form must be maintained at high pressure, while tanks for **liquid hydrogen** must be at cryogenic temperatures close to -253 ºC. The latter are known as **cryogenic tanks.**

Tanks can be used in small-scale applications, such as the tanks in cars and buses driven by H_2, or they can be large, like the cryogenic tanks used at NASA to supply fuel to space aircraft. Also, the storage of gas and liquid hydrogen mixtures through **cryo-compressed tanks** has been proven. This storage method keeps the tank at higher temperatures than those with 100% liquid hydrogen, reducing partial costs and the boil-off (evaporating hydrogen and dangerous increase in tank pressure).

Tanks are usually deployed above ground. However, **for very large volumes of hydrogen, underground formations like salt domes (existing in Portugal)**

where caverns can be built are potentially convenient and cost-effective storage methods. The current obstacles are insufficient hydrogen production and a lack of an established market to justify their construction. However, they are expected to form part of the hydrogen economy in the future.

Although some of these are mature technologies, they are expensive and energy intensive. Some others are still being developed. Overall, there is still a need for research and innovation for cheaper and more efficient H_2 storage options (LNEG, 2019).

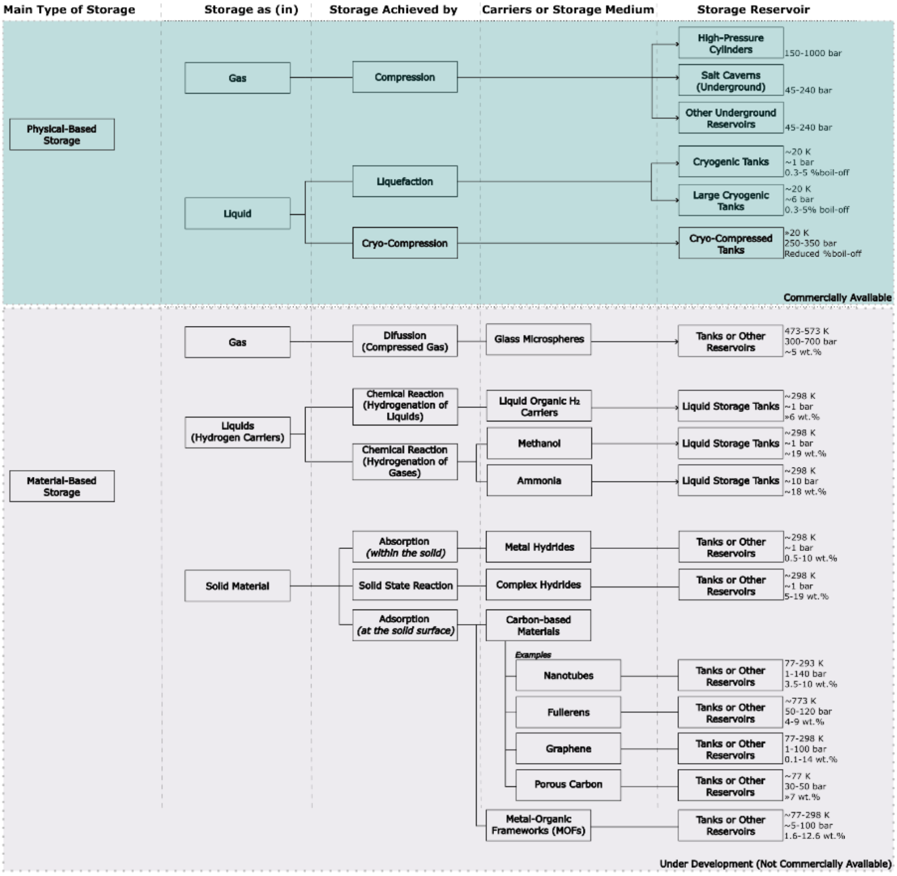


Figure 2. Storage options for hydrogen: established and under-development storage methods.

Power-to-H_2 and H_2-to-X: the key to promising solutions and development of the hydrogen economy

Power-to-H_2 is one of the most promising solutions for handling the energy surplus from renewable energy systems (RES) and achieving an energy mix compatible with carbon-neutral society goals. **Storing the H_2 produced and using it in various ways (H_2-to-X) when needed will enhance the electric energy network's flexibility and expand its range of uses**. Figure 3 summarises these concepts that are deemed critical to fostering the hydrogen economy.

The Power-to-H_2 concept should be focused on green hydrogen, which is based on water electrolysis using electricity from renewable sources to produce hydrogen that can be utilised directly or converted into different end-use products (e.g., methanol, ammonia, syngas, etc.) to satisfy end-users needs in different sectors (H_2-to-X).

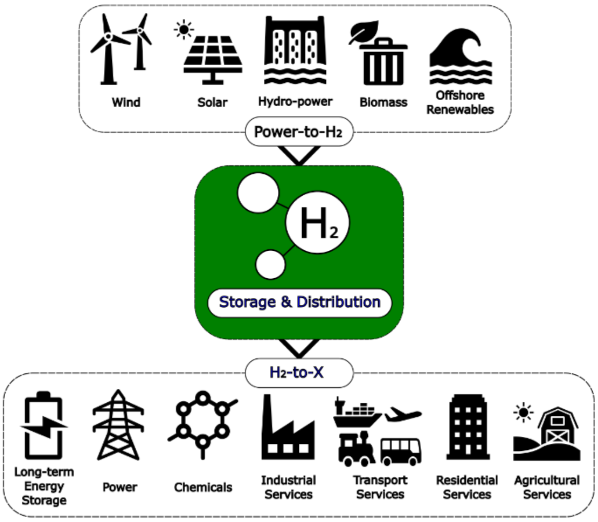


Figure 3. Power-to-H_2 and H_2-to-X example options representation.

What strategies can be outlined?

An energy storage strategy that outlines clear targets under the REPowerEU must be speeded up in a coordinated way.

The shift to renewable energies needs to address the big challenge of storage, which is keeping energy supply and demand in balance fostering security of supply. The current Portuguese H_2 Strategy (Resolution of the Council of Ministers Nº 63/2020), launched in 2020, is a strategic document that presents the national ambition for green hydrogen. Pilot projects like the Green Pipeline Project ongoing in Seixal are being implemented to test hydrogen injection in different concentrations in the national gas network. The target is to reach between 10 and 15% incorporation by 2030. Theoretically, the incorporation of 22% of hydrogen in volume to the natural gas network could keep the mixed gas inside the regulatory thresholds for its calorific power (Wobbe Index of 57.66 – 48.17 MJ/m^3 or a calorific power between 13.51 – 10.05 kWh/m^3).

H_2-to-X may be key to different services, such as those associated with the gas and electricity networks serving, keeping continuous energy supply to various sectors without the cost of curtailments or variability in time of renewable energy sources. In other words, it keeps the flexibility of the electricity network and enables the decarbonisation of sectors.

REPowerEU reinforces the relevance of hydrogen to the goal of reduction of European energy dependency, especially in those sectors that are harder to decarbonise. The target set is 10 million tonnes of domestic renewable hydrogen production in the EU. It suggests that a cross-border infrastructure project on the Iberian Peninsula could become the first element of the European hydrogen backbone, considering the region's important renewable hydrogen potential. However, in the current scenario of climate change, especially in the southern of the Iberian Peninsula, with increasing shortages of renewable water resources in the context of the natural hydrological cycle, the choices of the origins of the water necessary to produce H_2 through electrolysis, must be very judicious.

UNDERGROUND H_2 STORAGE AS AN ALTERNATIVE FOR LARGE SCALE STORAGE TO BALANCE SEASONAL VARIATIONS IN ENERGY DEMAND

Geological formations and potential underground H_2 storage

Depleted oil & gas fields, saline aquifers, abandoned mines, or even man-made salt caverns are potential geological storage (sensu latu) examples. Salt caverns do not have a porous structure. Due to this, designed salt caverns seem more promising as they can be operated at higher pressures with lower risks of H_2 leakages, avoiding the possible contamination of nearby aquifers and the mixing of H_2 itself (so expensively produced) with undesirable substances, namely brackish waters (in case of saline aquifers). Effectively, the risks associated with the multiplicity of hydrogeological, geomechanical, geochemical and microbiological processes that arise from the injection and storage of H_2 should support caves built in salt domes as the most predictable and preferred reservoirs for the preservation of H_2.

Portugal has the potential to store H_2 in salt caverns. The other potential storage sites, namely saline aquifers, have not yet been assessed and may bring contamination risks to the H_2 and surrounding areas that must be avoided. Nevertheless, further studies are needed.

Underground storage of natural gas, hydrogen and CO_2 has some similarities in terms of adequate geological conditions

A study of the potential CO_2 underground storage in Portugal is available (COMET, 2012; Poulsen *et al.*, 2014). Recently, under the framework of the Hystories project (European Union, 2023) assessed the potential sites to store H_2 in Portugal and Europa. However, we do not yet know many details on technical differences between underground storage of natural gas, hydrogen and CO_2, namely at the level of engineering (e.g. H_2 can embrittle steel pipes, whereas natural gas does not). It is important to consider these differences due to hydrogen gas' physical behaviour and properties (Lemieux *et al.*, 2019).

Natural gas has been stored in salt caverns

Natural gas has been successfully stored in salt caverns in Europe and the USA since the 70s. In Europe, there are more than 300 salt caverns used for gas storage (HyUnder Project, 2013), as well as circa 141 facilities for UGS-Underground Gas Storage, which includes depleted oil/gas fields, aquifers, and salt caverns. By the end of 2019, 661 underground gas facilities were in operation worldwide. Most natural gas storage (80% in working volume) occurs in depleted oil/gas fields, not salt caverns. Thus, Portugal, which started the process of storing natural gas underground in 2010, was not an early adopter.

SALT CAVERNS FOR HYDROGEN STORAGE

Salt caverns potential for hydrogen storage in Europe

The technical potential of salt caverns for hydrogen storage in Europe was addressed by Caglayan *et al.* (2020). The overall technical storage potential across Europe is estimated at 84.8 PWh_{H2}, 27% of which constitutes onshore (Caglayan *et al.*, 2020). Figure 4 shows the overall process of identifying, evaluating, and designing salt caverns.

H_2 has already been stored in salt caverns

H_2 has been stored in salt caverns in the UK since the 70s (350-450 m depth and with a total volume of 210,000 m^3) and in the USA since 1983, with a newer storage site since 2007 (800 m depth and circa 580,000 m^3 volume).

H_2 underground storage in 58 projects worldwide since 2013

The IEA reported 58 underground storage projects worldwide (Hydrogen Production and Infrastructure Projects Database - Data product - IEA), from which only two started operation between 2013-2016, five between 2021-2023, and 51 projects are planned or ongoing afterwards. Salt cavern projects account for the majority of all underground storage projects (64%), the others are for depleted gas fields (28%), followed by aquifers (5%) and hard rock caverns (3%). The vast majority of projects (49) are in Europe. **Portugal has one current project at Carriço. Since 2010, Portugal has stored natural gas in six caves built within salt formations in Carriço (municipality of Pombal), making up a useful storage volume of 3.2 million m^3. It was recently announced that two new caverns with capacities between 350 and 500 thousand m3 for gas, including H2, will be built.**

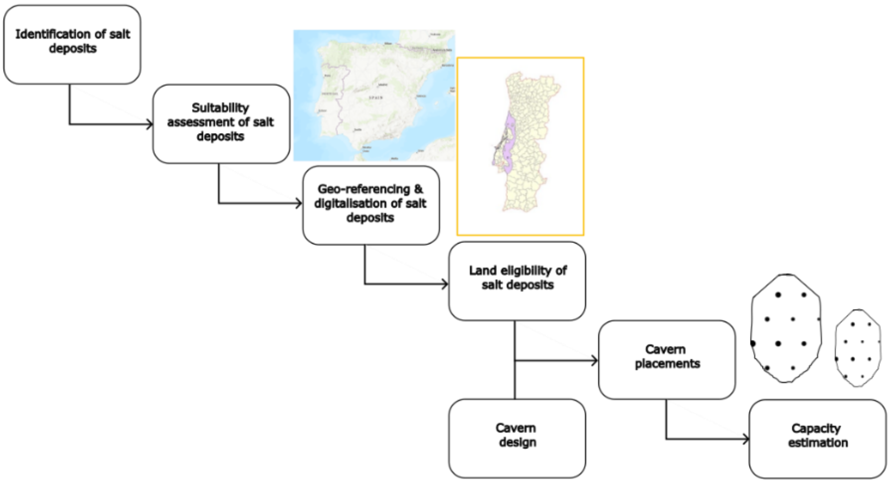


Figure 4. Process of identification of salt formations, evaluation, and design. Source: Adapted from Caglayan *et al.* (2020).

On the operation of salt caverns

The rate of injection and retrieval of H_2 from salt caverns is lower in comparison to natural gas. These rates for natural gas can reach about 105,000 kg/h, while for H_2 might be about ten times lower (~11,000 kg/h). However, actual values depend on the cavern's pressure, geometry (design and size), and pipe diameter. The minimum and maximum pressures of H_2 stored in salt caverns are typically 65-180 bar (http://hyunder.eu/). But this range can be wider depending on specific conditions. Gas storage in salt caverns also requires cushion gas to maintain the minimum pressure level within an acceptable range to avoid the collapse of the formation and aid in the retrieval of hydrogen.

What do we know about costs?

The specific construction costs of salt caverns decrease significantly with size, with **investments for caverns >500,000 m^3 in brownfield sites ranging from 40-60* €/m^3** (http://hyunder.eu/). Depending on the distance to a suitable brine processing or disposal site, the costs for a new brine pipeline may add significantly to the total cavern construction costs. Likewise, cushion gas, which accounts for up to one-third of the hydrogen gas volume, represents another significant cost element.

Electrolysis dominates the total costs of an integrated production and underground hydrogen storage facility with over 80% (considering 50% utilisation), **of which electricity costs have a major share.**

Although a cavern requires a significant upfront investment, it has a relatively small contribution to the total specific hydrogen costs of <0.5€/kg of H_2. Despite the higher specific costs of a smaller cavern of about 50,000 m^3 compared to a large cavern, **the impact of the cavern investment is still relatively small and may initially justify the development of smaller caverns.**

*The cost figures above are based on a mature market with a cavern size of 500,000 m^3 with a hydrogen net storage capacity of 4,000 tonnes. For example, assuming investment costs of 60 €/m^3, the total capital costs of a cavern with the characteristics above is about 30 million € (excl. cushion gas).

SALT CAVERNS FOR POTENTIAL HYDROGEN STORAGE IN PORTUGAL

H_2 potential storing in Portuguese salt caverns

The current estimated H_2 potential storage in salt caverns in Portugal is 3,000-4,000 TWh H_2 (of which *circa* 400 TWh H_2 are associated with onshore caverns). **Higher-resolution geophysical surveys and studies are required to improve the definition of the volume and geometry of the salt formations, especially offshore and in the Algarve Basin**.

H_2 potential storing in the Portuguese Lusitanian Basin

The potential area for underground hydrogen storage was mapped by LNEG using "depth structural maps" processed from seismic data from the Mohave Oil and Gas Corporation prospection (provided by DGEG) to obtain information on salt depth. LNEG focused on the Dagorda formation, which is composed of salt and other lithologies. Desirable depths for hydrogen storage should be between 500-1,500 m.

The resulting map is depicted here. It represents a rough estimate based on the limited available information. As aforementioned, a more detailed and proper assessment of underground storage sites entails further work to refine the potential areas identified until now, namely offshore and in the Algarve Basin. More geophysical surveys with the proper resolution and mechanical borehole data are required and extended to other regions of Portugal.

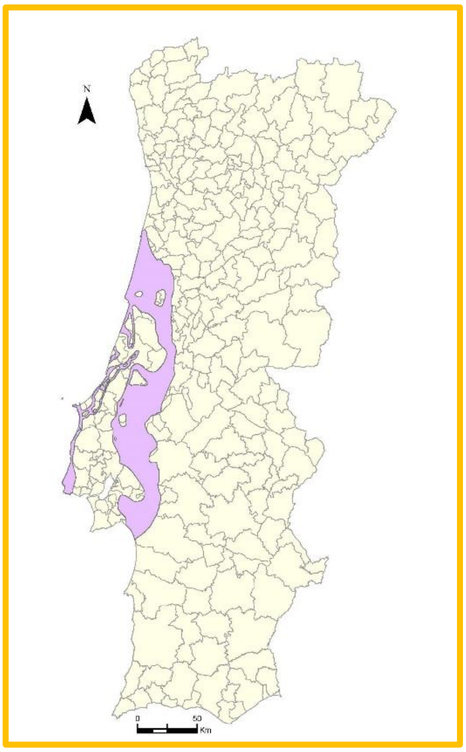


Figure 5. Portugal's onshore distribution of salt formations for potential underground hydrogen storage (in purple).

HOW DO WE REDUCE THE VOLUME OF HYDROGEN AND CONDITION IT FOR TRANSPORT?

Four ways to reduce the volume of hydrogen have shown a high potential [Ekcl *et al*., 2022]:

1. Hydrogen can be compressed (CGH_2) to several hundred bars.
2. Hydrogen can be cooled below the boiling point to its liquid state, further referred to as LH_2. The big advantage of LH_2 is the low volume of only 1/800 compared to CGH_2 (Kim *et al*., 2021). The disadvantages are relatively high energy costs and continuous "boil-off" losses during transport and storage. The boil-off losses occur due to heat transfer into the inside of the tanks that fosters the evaporation of hydrogen. These losses cannot be fully avoided at temperatures as low as -253ºC.
3. Liquid Organic Hydrogen Carriers (LOHC). Unsaturated organic compounds such as Toluol ($C_6H_5CH_3$) are "loaded" and "unloaded" with hydrogen through a reversible chemical reaction - hydrogenation and dehydrogenation (Niermann *et al*., 2019). As a result, the hydrogen can be stored and transported in a liquid state under standard conditions.
4. Other liquid compounds like Ammonia can serve as a hydrogen carrier. The Haber-Bosch process is used to obtain hydrogen from Ammonia, which could be "cracked" at the delivery point to provide hydrogen. Like the LOHC,

Ammonia can be stored as a liquid at ambient temperature and under low pressure with a high hydrogen storage capacity (Cha *et al*., 2021).

9 CURIOSITIES ABOUT HYDROGEN

1. **Burning hydrogen.** The flame is not detectable through human eyes.
2. **Storage Density**. Liquid H_2 has a higher storage density than gaseous hydrogen, gasoline, and diesel, but it requires extremely low (i.e., cryogenic) temperatures.
3. **Boil-off Losses**. Liquid H_2 storage suffers from boil-off losses, where some hydrogen evaporates over time.
4. **Refueling Time**. H_2 refuelling times are comparable to conventional fuels; for example, vehicles typically take 3-5 minutes.
5. **Hydrogen Embrittlement.** Metals used in H_2 storage can suffer from embrittlement, which weakens the material over time.
6. **Hydrogen Blending**. H_2 can be blended with natural gas and stored in existing gas infrastructure (up to a certain limit).
7. **Hydrogen Permeation**. H_2 molecules can permeate through certain materials, requiring special alloys and coatings.
8. **Seasonal Storage.** H_2 can be used for seasonal energy storage, balancing supply and demand over long periods.
9. **Solid-State Storage**. Solid-state storage methods, such as metal-organic frameworks (MOFs), are under development, and they have high H_2 storage capacity.

PORTUGUESE LEGAL FRAMEWORK

The legal framework related to H_2 has evolved continuously over the last decade. Table 1 summarises some of the main legislative documents associated with its storage.

Besides the documents presented in Table 1, there are a series of other related legislation (directives, decree-laws, orders and ordinances) that might (may) apply to the storage of hydrogen. One example is the **SEVESO Directive** (**Directive 2012/18/EU** aiming at the prevention of major accidents involving dangerous substances). This Directive was transposed to Portuguese Law by the **Decree-Law no. 150/2015** of 5th August, which establishes the regime to prevent and control major accidents involving dangerous substances and limiting its consequences for human health and the environment applied to processing and storage of dangerous substances within its Annex I Hazardous Substances / Part 2 “Nominated dangerous substances”.

Hydrogen (CAS Number 1333-74-0) is considered a dangerous substance when at least 5 tonnes of H_2 are stored, and several risk minimisation procedures apply. If more than 50 tonnes of H_2 are stored, then stricter procedures apply.

These thresholds should be reviewed to explicitly address the large-scale production of H_2 as an energy vector, and the prevention measures to be applied should be clarified with the authorities responsible for preventing major accidents involving dangerous substances.

The **Order Nº 1112/2022**, associated with the **Decree-Law Nº 62/2020,** relates only to the Underground Gas Storage in Natural Saline Formations, establishing the juridic regime for underground hydrogen storage. A broader scope regarding geological formations is found in the **Decree-Law n.º 60/2012** - *Diário da República* Nº 53/2012, *Série I de* 2012-03-14, which transposes **Directive 2009/31/EC** and establishes the legal regime for the geological storage activity of carbon dioxide (CO_2).

Table 1. Main legal instruments associated with H_2 storage relevant in Portugal

Name	Brief Description	Year	Access
A Hydrogen Strategy for a climate-neutral Europe COM/2020/301 final	It establishes the strategic framework for creating a hydrogen economy in Europe based on a value chain-wide approach.	2020	Link
Portuguese Hydrogen National Strategy (EN-H2) - Resolution of the Council of Ministers Nº 63/2020	The strategic document presents the national ambition for green hydrogen, the current and future investment needs, the need and type of support, the challenges facing hydrogen adoption, and the adequacy of the goals for its incorporation in the various sectors.	2020	Link
National Energy and Climate Plan 2030 - Resolution of the Council of Ministers No. 53/2020	It establishes the goals and strategic frameworks for Energy and Climate until 2030 for Portugal. The plan is currently being reviewed.	2020	Link
Law-Decree Nº 62/2020	It establishes the organisation and operation of the National Gas System and its legal regime and transposes Directive 2019/692. It relates to Orders Nº 806-C/2022, Nº 806-B/2022 and Nº 1113/2022. The decreet establishes the juridic regime applicable to the reception, storage and regasification of Liquefied Natural Gas (LNG), underground gas storage, gas transport and distribution, and links to hydrogen incorporation in the sector.	2020	Link
Order Nº 1112/2022	Regulation of Underground Gas Storage in Natural Saline Formations.	2022	Link
Law-Decree Nº 30-A/2022	It approves exceptional measures to simplify the procedures for producing energy from renewable sources, including hydrogen storage.	2022	Link
Law-Decree Nº 11/2023 and Declaration of Rectification Nº 7-A/2023	It is related to the reform and simplification of environmental permitting, including hydrogen storage.	2023	Link
Law-Decree Nº 131/2019	This decree-law approves the Regulations for installing and operating Simple Pressure Vessels (RSPS) and Pressure Equipment (ESP). This decreet seeks faster licensing procedures and cost reduction.	2019	Link

KEY-PLAYERS IN EUROPE

Some relevant European players mostly focused on underground storage

GOESTOCK; REN Armazenamento; ISQ; HyStock (Gasunie); ENGIE; LINDE; SOCON; UNIPER SE; STORENGY (ENGIE); CORRE.ENERGY; STORAG ETZEL; DEEP.KBB.

You can find relevant Portuguese H_2 economy players as members of these organisations:

HyLab - Hydrogen Collaborative Laboratory and AP2H2 Associates.

MORE INFORMATION

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