Preliminary evaluation of different underground hydrogen storage systems in Spain

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Abstract.
In the future energy system with a high share of renewable sources, the role of hydrogen will be essential to deal with the fluctuations in the electricity production. Hydrogen is understood as a system capable of storing energy for a later use in a controlled way. In this way, surplus electricity coming from renewable energies is used for generating hydrogen by the electrolysis process. Once produced, hydrogen is stored in one of the different underground storage structures to be used when needed. In this context, the aim of this research is to provide a preliminary evaluation about the potential for underground hydrogen storage in the country of Spain, considering the usual geological formations of these systems (deep aquifers, salt caverns and depleted hydrocarbon fields). The analysis of each alternative has allowed highlighting that Spain presents potential locations where future hydrogen storage could be feasible. Regarding salt caverns, this country has high onshore storage capacities, with a total of located 24 caverns. Furthermore, the Spanish potential of hydrogen storage in aquifers is also relevant especially in Tertiary sedimentary basins as the Ebro, Duero and Guadalquivir basins. The storage potential in depleted oil and gas fields is however reduced due to the limited hydrocarbon activity of the country.

Keywords: Renewable energies, Electricity production, Hydrogen, Underground storage, Spain.

1 Introduction

The reduction of fossil energy sources with the aim of meeting the climate protection International Agreements will inevitably require an increase in the generation of renewable energy [1-2]. The progressive growth in the share of variable renewable energy sources in the global energy mix brings to light the essential role of these systems in the future energy sector. However, the intermittency associated to these sources means an important obstacle that must be solved through storage technologies at different time scales (hourly, daily or seasonal). Energy storage systems will be then indispensable as renewable installations become the major source of energy. In this sense, Underground Hydrogen Storage (*UHS*) could mean an effective solution as large-scale storage of energy surplus to deal with seasonal demands [3]. Hydrogen can be produced by using the "Power to Gas" concept through electrolysis utilizing electricity coming from renewable sources [4]. This gas presents a high energy density and can be used in a wide range of applications such as methanation, fueling vehicles or re-electrification. In addition, hydrogen can be also fed into fuel cells to produce electricity in low generation periods ("Power to Power" concept).

As in the case of the natural gas, geological formations provide the required capacity to store the large volumes of hydrogen that could be used to cover the seasonal demands with a reasonable cost [5-6]. However, the properties and physical behavior of hydrogen are not the same of the natural gas or air. Under the same conditions hydrogen has inferior calorific value than the one of the natural gas, its molecular weight makes it more susceptible to leakage and its diffusion coefficient in air is four times greater than it is for natural gas at standard pressures and temperatures [7-8]. In this context, higher storage pressures are required to store the same mass and special preventive measures must be taken into account. It is also recommended to consider the chemical reactivity since hydrogen gas could affect the structural integrity of steel alloys and interact with clay or other minerals of the reservoir that could dissolve sulfate minerals, carbonates or feldspars, among others [9-10]. These phenomena must be also evaluated to avoid alterations in the reservoir quality such as primary flow paths or its preliminary porosity [11].

Geological formations usually considered for UHS are caverns in salt deposits (lined or unlined caverns in hard rock) and deep porous media such as depleted gas and oil fields and saline aquifers [12-13]. While there are numerous researches focused on the potential of UHS, practical experience for large-scale storage of hydrogen gas is limited to salt caverns in four locations worldwide (three of them are located in the United States and one in the United Kingdom [14-15].

1.1 Underground gas storage in the world

As already mentioned, an underground gas storage system is an artificially accumulation of gas in the environment at a significant depth (hundreds of meters or more). The potential of these facilities derive from the advantages provided:

- The underground storage systems are easier to integrate with the landscape and the existing structures.
- These facilities are less susceptible to fire, military actions or terrorist attacks.
- The construction costs are much lower than the ones associated to surface structures with similar capacity.

- Suitable geological structures are commonly available in a large number of countries.

The above advantages have contributed to the global expansion of these storages. In this way, the number of underground gas storage structures and their capacity have grown considerably in the las 100 year, in special in those countries of the Northern Hemisphere. As shown in Figure 1, most of these facilities are located in depleted hydrocarbon deposits and then in aquifers and salt caverns.

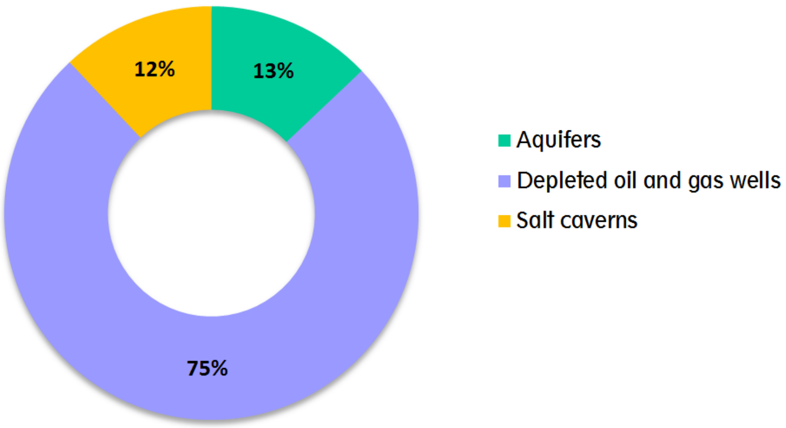

Fig. 1. Share of UGS by storage type in the world (2010) [16].

Additionally, Figure 2 presents the distribution of UGS by regions. As can be observed in the mentioned Figure 2, most UGSs are located in North America (USA and Canada) followed by Europe.

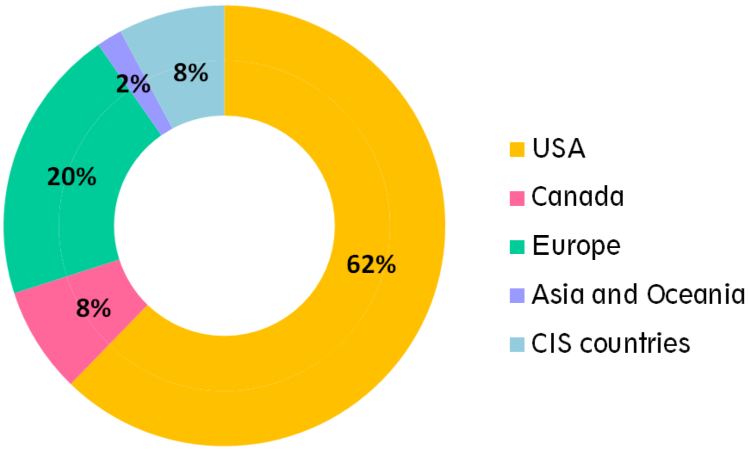

Fig. 2. Share of UGS by regions (2010) [16].

The development of the underground gas storages, especially the hydrogen systems considered in this research is quite limited in some European countries, such as Spain. For this reason, the aim of this work is to provide an overview of the possibilities of constituting effective underground hydrogen storages in Spain. Thus, each of the UHS alternatives will be evaluated to estimate the potential of the country within the hydrogen storage. The following sections include a description in terms of energy, geological, lithological and geotechnical information of Spain as well as the analysis of each type of underground structure in the country.

2 Description of the country under study

2.1 Energy perspectives in Spain

There is a current need among numerous countries of introducing governmental policies focused on the transformation of their energy systems. According to the European Union Energy and Climate Package, Europe is planned to increase the share of renewable generation from 28 % in 2015 to 36 % in 2020, exceeding 50 % in 2050 [17].

In Spain, the electricity sector is constituted by a reliable power generation mix in the frame of the fossil-renewable transition. The trend in the last ten years clearly shows a reduction in the contribution of fossil-based technologies leading to a growth of renewable sources, in special the wind and solar power production. This fact is in line with the objectives expressed in the Spain's National Renewable Energy Action Plan (2011-2020) [18].

Regarding the large power generation (nominal power ≥50 MW), Spanish coal-fired plants are now part of the Transitional National Plan (2016-2020) [19] that allows them to be exempt from complying with the emission limits of the Directive 2010/75/EU [20]. After the mentioned plan, all plants exceeding the limit values will be obliged to close down. In the context of the nuclear energy, five plants are in operation, being their licenses expired in the next 11 years.

Considering now the renewable sector, up to the year 2008, Spain was a global leader in the promotion of renewable energy. Wind energy systems progressively grew since the mid-1990s, while the number of photovoltaic (PV) installations remained low until 2004 [21]. After that, 2007 brought a boom in solar PV systems, rising from 103 MW in 2006 to 544 MW in 2007 and to 2708 MW in 2008. This increase caused the application of several amendments to the renewable energy scheme, paying special attention to the solar PV sector [22]. After years of standstill, Spain restarted the auctions of renewable electricity in 2017. The following Figure 3 describes the global electricity production by source for the period 1990-2018 in Spain.

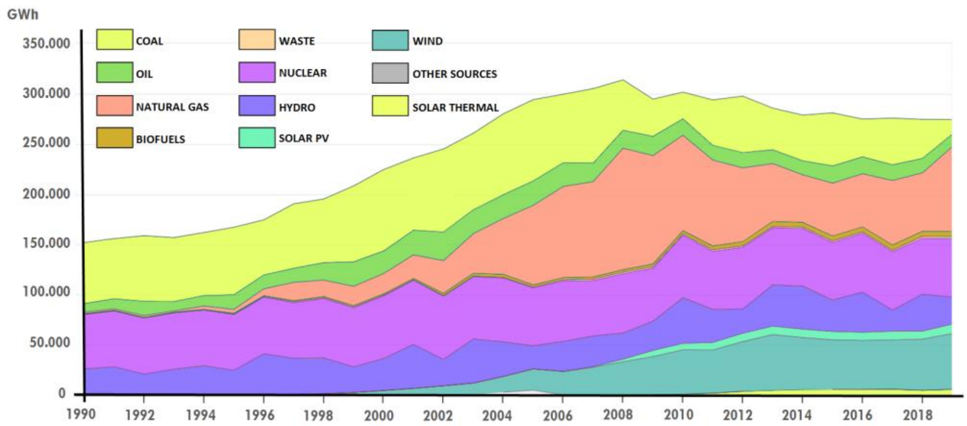

Fig. 3. Spanish electricity production by source during the period 1990-2018 [23].

In general terms, it can be assumed that Spain has significant overcapacity in its electricity system, that is to say, high installed capacity compared to the electricity demand. In addition, the Spanish electricity system constitutes an energy island with limited possibilities to export the produced energy. All the above causes that nearly all the power produced in the country has to be consumed on it.

In this sense, the management of surplus energy could be achieved in Spain by one of the possible alternatives of UHS systems. Focused on this aim, this research provides a preliminary overview of appropriate sites for UHS in Spain based on the available information.

2.2 Geology and seismic hazards

It can be assumed that the geology of Spain is hugely diverse, including one of the most complete Paleozoic sedimentary successions in Europe. These successions reveal a unique Iberian paleogeography influenced by the Atlantic Ocean and by events in the Tethys Ocean and Alpine-Himalayan orogeny. The underlying geology has been created by Cenozoic events linked to the Alpine orogeny. Apart from the mountainous northern and southern margins of Iberia, the center of Spain is dominated by two large Cenozoic basins, drained by the Duero River in the north and the Tajo River in the south [24].

An important concern when considering UHS is the seismic activities of the area which could compromise the integrity of the storage system. In Spain, Quaternary and Neogene volcanism has appeared in southern, south-central and eastern mainland Spain. The most remarkable phenomenon is the Canarias volcanoes which exposes one of the most known hot spot related ocean island chains. Beyond this, the seismic map of Spain presented in Figure 4 shows that most of the country fall into low hazard zones. However, the potential areas identified in this work must be submitted to an arduous analysis that ensures the technical viability of the future system.

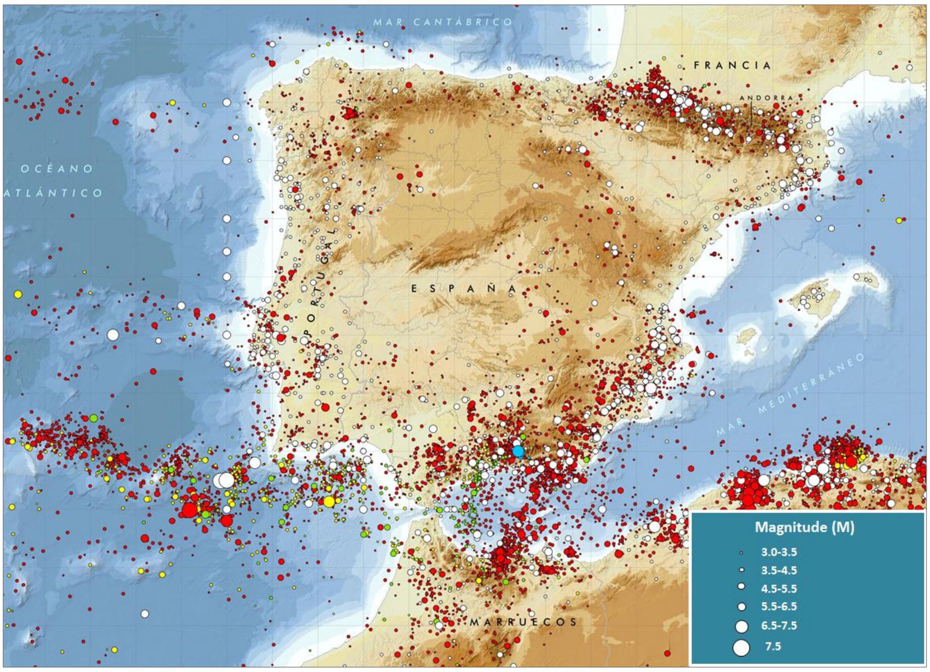

Fig. 4. Seismicity in the Iberian Peninsula and the vicinity areas [25].

3 Potential UHS structures

3.1 Salt caverns

Salt caverns are commonly considered the most promising underground storage option due to the low cushion gas requirement, the inter nature of the salt structure and the sealing capacity of the rock, which prevent the contamination of the stored hydrogen. As already mentioned in the introduction section, there are only a few sites being used for hydrogen storage in salt caverns (one in United Kingdom and three more in the United States). These projects have, however, proven for decades the technical feasibility of underground hydrogen storage systems.

Several authors have investigated the potential for hydrogen storage in underground formations such as the salt caverns, paying special attention to appropriate storage locations [26-27]. In particular, The *HyUnder project* addresses the study of caverns for hydrogen storages of 5 European countries; Germany, the Netherlands, the United Kingdom, Romania and Spain [28]. Focusing on the particular case of Spain, according to this project, this country presents four main locations for UHS. These sites were defined by considering the location near wind resources and electric and natural gas grids but also because of geological conditions and local hydrogen demand [29]. The following Figure 5 shows the potential areas selected in the project.

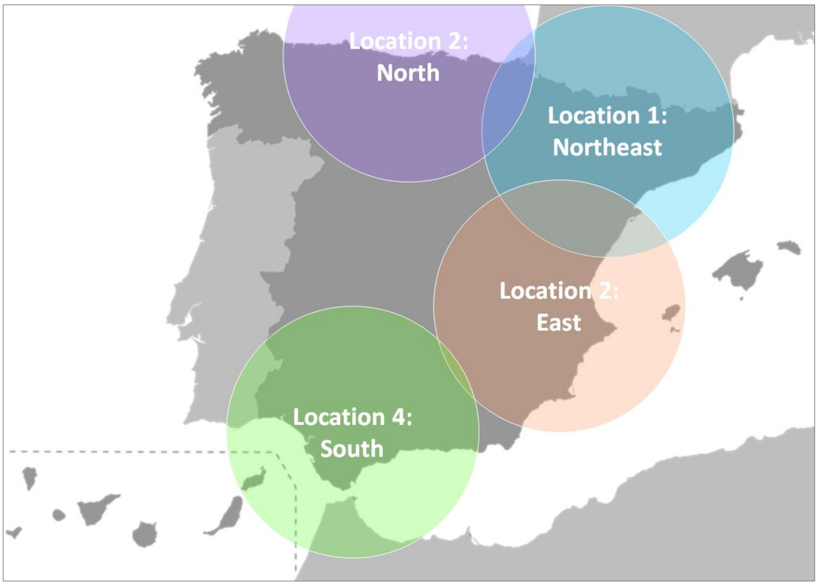

Fig. 5. Spanish salt cavern sites selected in the *HyUnder* project for underground hydrogen storage stablishing a radio of utilization of 250 km [29].

Since the application of Power to Power or hydrogen re-electrification is not considered in the *HyUnder project*, this work also presents a general overview about the geological formations (salt caverns) that constitute the country under study and that could mean potential future UHS.

Spain is characterized by Mesozoic evaporite deposits covering large areas of the subsurface from the Betic Cordillera over the Iberian Range to the northern coast, up to the Bay of Biscay. Based on existing prospecting campaigns, the top salt of these deposits exceeds depths of 2000 m. Regarding Tertiary evaporitic formations; these can be found in the Ebro, Duero and Tagus Basin. The thickness of these halite beds is considerable but highly folded facies are present as well as high concentrations of anhydrite and gypsum.

When talking about storage potential of salt caverns, three main classifications are commonly established: onshore, onshore constrained and offshore. In this way, offshore caverns are placed in salt domes under the Sea; whereas the onshore ones are those located on land (once applied the eligibility constraints). The constrained caverns are defined considering a constraint of 50 km distance from shore. According to published report [28], the highest onshore storage potential is observed in Germany (9.45 PWh), followed by Poland (7.24 PWh) and Spain (1.26 PWh), constituting these three countries 77 % of the total potential. Hence, Spain has high onshore storage capacities, counting with a total of located 24 caverns. However, more than a half of these formations are placed less than 50 km from the coast.

The most important of all the Spanish salt caverns is known as the Salt Mountain of Cardona in Catalonia. It is in the shape of an elongated ellipse and has an area of 1.800 m long by 600 wide and an area of approximately 100 hectares. These caverns are constituted in some areas by a layer of salt of approximately 300 meters of thickness, constituting an excellent site for hydrogen storage.

The total storage capacity of Spain has been then estimated in 1.26 PWh of hydrogen, being all this potential onshore. In the case of offshore storage, Norway leads the European countries with 7.5 PWh-H_2 of storage potential for caverns in the high seas, all in the North Sea. The following Figure 6 summarizes the global cavern storage capacity for several European countries, including Spain.

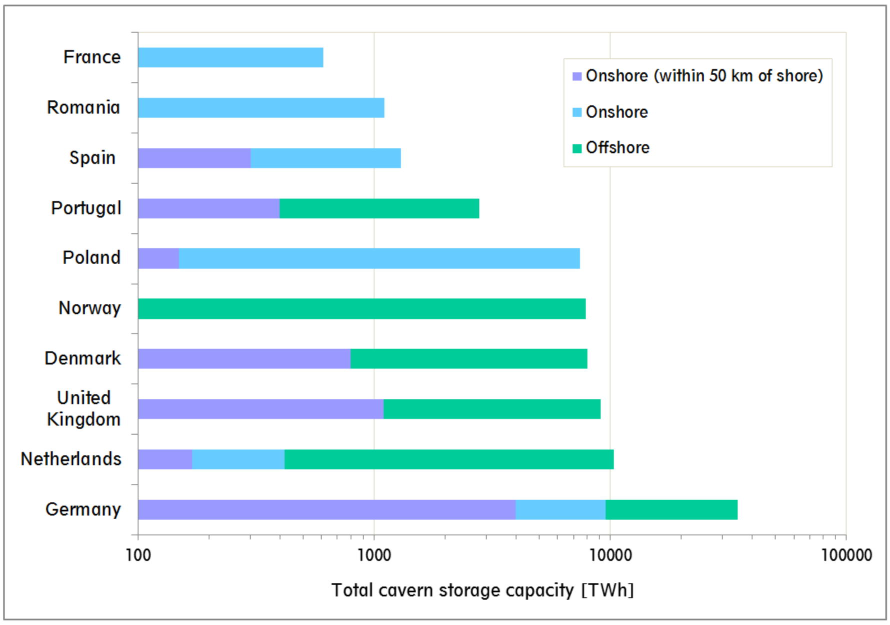

Fig. 6. Total cavern storage capacity for different European countries, including the one considered in this research [31].

3.2 Saline aquifers

Saline aquifers constitute geological structures distributed worldwide that present large potential storage capacity (around hundreds of Mm^3). Despite these formations accumulate the majority of the natural gas storage in the subsurface, at date there are not pure hydrogen storages. Different aquifers are however being used to store town gas (with around 50 % of H_2 and 50 % of CH_4) in Germany, France and in the Czech

Republic [32]. These experiences confirm that storage in deep aquifers is a cost-effective option and a promising alternative for seasonal hydrogen storage.

A potential underground storage formation must be constituted by impervious overlaying seal that ensure the confinement of the injected fluid and prevent the migration of the gas to the surface. The aquifer requires also having enough capacity and high permeability to allow the migration of the gas and to dissipate the pressure. The best situation is that in which the structure is located in appropriate tectonic traps such as domes to recovery the hydrogen in a high quality way.

When analysing the effective gas storage capacity of deep aquifers, the expression presented in Equation 1 can be used [33].

$$C_T = A \cdot h \cdot \emptyset \cdot \rho_G \cdot S_{eff} \tag{1}$$

Where:
C_T = total effective storage capacity (t)
A = area covered by regional aquifer (m^2)
h = average height of aquifer · average net to gross ratio (m)
$\emptyset$ = average reservoir porosity (%)
ρ_G = density of the gas at reservoir conditions (t/m^3)
S_{eff} = storage efficiency (% of pores expected to be filled with the gas)

From Equation 1, the EU *GeoCacity project* estimated the gas storage capacity of different basins belonging to European countries, as Spain. This project was focused on the evaluation of three main areas [34]:

- *Iberian Massif*
  Covering the Western part of Spain and almost the whole territory of Portugal, it is constituted by Palaeozoic materials affected by Hercinian tectonics. In this area, it is common to identify igneous and metamorphic rocks, along with faults, steep folding and compression. From the results of this analysis, this region was discarded as storage for CO_2 and therefore it will be probably rejected for storing hydrogen.
- *Alpine mountain ranges*
  Three main mountains were formed during the Alpine movements: The Pyrenees and Cantabrian Mountains in the North with an E-W strike, the Iberian Mountains in central Spain with NW-SE strike and the Betican Chain on the Mediterranean coast with a SW-NE strike. This area has been considered appropriate for the gas storage, in special in those formations with sandstones and karstic carbonates.
- *Cenozoic Basins*
  This kind of deposits is present in areas of great Iberian rivers (Ebro, Tajo, Duero and Guadalquivir). Prospecting analysis have shown that the thickness of sediments in some of these regions is over 5.000 m, including deposits of sands, sandstones and karstic carbonates filled with salty water.

The characteristics and conditions of these deposits denote that the structures could constitute potential hydrogen storage.

In summary, in the case of Spain, the principal potential storage aquifers have been found in Tertiary sedimentary basins as the Ebro, Duero and Guadalquivir basins. In particular, in the Duero basin different structures have been identified for gas storage in previous carbon storage projects. The formations are located in the NW margin of the basin, close to the boundary with the Basque-Cantabrian basin. As described below, different Spanish projects and researches are addressing the evaluation of deep aquifers for CO_2 storage and could be the basis for the future UHS.

- In the north of Spain (Asturias), Palaeozoic sedimentary basins constituted by carbonated and siliciclastic aquifer formations are considered potential reservoirs of great thickness and suitable cap rocks in Carboniferous and Devonian materials [35].
- In the southeast of Spain, the Gañuelas-Mazarrón Tertiary basin hosts a deep saline CO_2-rich aquifer, being catalogued as a natural analogue for gas storage and recovery.
- The Utrillas formation (Teruel) in the San Pedro Dome saline aquifer has been numerically evaluated through computer simulations showing that the structure could be operated with optimal recovery ratios for seasonal energy demands. The formation is hosted by quartz-rich Albian sandstones, with high permeability ($1 \times 10^{-13}\ m^2$), high salinities (>50,000 ppm of total dissolved solids) and thickness up to 350 m in the top of the dome, being the porosity of the sandstones in the ranges of 13-20 %. On top of that, the formation is covered by low permeable rocks of Late Cretaceous age that ensure the isolation of the stored gas [36].
- Another Spanish CO_2 storage prospecting project in deep aquifers is The Hontomín URL led by the Fundación Ciudad de la Energía – CIUDEN. The Hontomín site (Burgos) is located in the southern sector of the Basque-Cantabrian Basin. The mentioned project has allowed defining the boundaries of the saline aquifer and identifying the most probable leakage pathways [37].

3.3 Depleted petroleum and gas fields

Depleted hydrocarbon deposits are geological structures usually adapted as gas storage facilities. These formations consist of a reservoir (hydrocarbons accumulated in the pore space of the rocks), a seal and an underlying aquifer.

Nowadays, depleted gas deposits are the most common option of underground storage sites. In this sense, costs may be reduced when adapting the deposits to the needs of underground hydrogen storage. The main advantage of these structures is that they were well recognised during the exploration and exploitation phases. Thus, as the original gas remained in the deposit for millions of year, its tightness is already guaranteed.

Regarding depleted oil deposits, they are not very common at underground gas storage facilities. The principal reason is that the large amounts of hydrogen could enter into chemical reactions with the residual oil. Hydrogen could, in this way, become converted into methane, dissolve in the oil and become irreversibly lost.

Focusing now in the country under study, first of all, it is important to highlight that Spain cannot be considered a prolific hydrocarbon country. Several deposits have been discovered, the first of which was oil, in 1964, in Ayoluengo (Burgos), and the later ones in the Mediterranean Sea, the Gulf of Valencia, the Cantabrian Sea, the Guadalquivir Valley and the Gulf of Cadiz.

The hydrocarbon exploration in Spain started in the early 20th century. In this context, 708 exploration wells have been drilled; 438 onshore and 270 offshore, 126 in the Mediterranean and 144 in the Atlantic. In spite of these exploration experiences, only 20 have been used for production.

There are currently five oil wells in production that contribute 0.15 % to the country's global demand. The production of these sites is progressively decreasing and is expected to be nil in the near future. Table 1 includes the production of the last twelve months of the five hydrocarbon wells currently operating in Spain.

Table 1. Spanish hydrocarbon wells currently in production.

Hydrocarbon well	Last 12 months production (kt)
Boquerón	17
Casablanca	45
Montanazo-Lubina	8
Rodaballo	2
Viura*	8
TOTAL PRODUCTION	**80**

* Mainly natural gas production

Additionally, in Figure 7 it is possible to observe the decreasing evolution of the hydrocarbon production in Spain for the period 1965-2015.

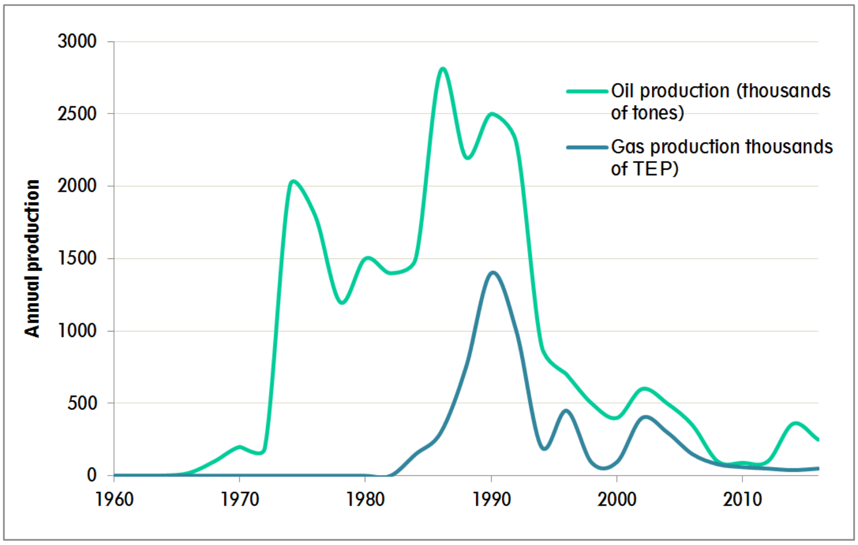

Fig. 7. Evolution of the gas and oil production is Spain 1960-2015 [38].

It is also important to mention that the new Spanish climate regulation prohibits the research and exploration activities of new hydrocarbon sites both in the marine and terrestrial subsoil. The prohibition of new permits does not affect, however, current applications in process.

4 Discussion

The analysis performed in the previous sections is crucial for identifying the real potential of the Spanish geological structures to become underground hydrogen storage. The experience of the country in storing other gases, such as the natural gas or the CO_2, means a valuable starting point to define the possibilities in the context of the hydrogen storage. Based on the information previously provided, the following statements can be deduced:

- The analysis of the energy perspectives in Spain shows that derived from the rising renewable electricity production, underground energy storages will be key for effective energy transition.
- From the existing experience in the natural gas storage, UHS is considered as a promising future option in the near future of the country.
- Among the geological structures considered as UHS, salt caverns and deep aquifers stand out in the country over the depleted hydrocarbon fields.
- Regarding the potential of storing hydrogen in salt caverns, previous works point out that Spain presents four principal locations for UHS, in the north, northeast, east and south of the country. On top of that, Spain is the third country with the highest onshore storage capacities in this kind of formations (counting with 24 caverns).

- Considering now the underground storage in saline aquifers, the most relevant potential of Spain has been found in Tertiary sediments basins, as the Duero, Ebro and Guadalquivir basins. However, other areas such as the formations of sandstones and karstic carbonates in the alpine mountain ranges could also constitute suitable gas storage structures. The high number of projects in the field of the CO_2 in the country lays the foundations for the future hydrogen storage in these formations.
- Concerning the depleted hydrocarbon fields, since Spain is not a prolific gas and petroleum country, the possibilities of using these structures as UHS is limited. Despite this fact, the wells that were in production (around 20) and are now depleted, constitute a promising structure with known storage conditions. In addition, the five fields currently operating in Spain are expected to be close down in the near future, so they will also constitute possible structures for the underground hydrogen storage.

5 Conclusions

The Spanish scenario for the year 2030 includes the replacement of a considerable amount of installed power from conventional sources with renewable energy systems. Derived from the generation of renewable electricity, the country will be obliged to face an important surplus of energy in spring and summer. Moreover, by the year 2050, the objective of Spain is to achieve 100 % renewable power generation. Having this information in mind, it is obvious that the seasonal energy storage will have to be complemented in order to avoid the need of importing so much natural gas in the cold months. In this sense, the use of hydrogen as underground energy storage will become essential in the near future of Spain.

This work analyzes the feasibility of UHS in the country of Spain by considering the usual geological structures (salt caverns, deep aquifers and depleted oil and natural gas deposits). Results clearly indicate that several rock structures in the country are favorable for the future storage of hydrogen. Numerous salt caverns are present with high onshore store capacities as well as the deep aquifers of the Tertiary sedimentary basins. Depleted hydrocarbon fields, although limited, could also constitute a defined reservoir for the underground hydrogen storage.

Further work is required in this field to study in-depth not only the geological and technical possibilities of the UHS but also the economic concern (proximity to renewable power installations and energy demand) that will ultimately define the global feasibility of the system.

References

1. European Commission. "Energy 2020. A strategy for competitive, sustainable and secure energy." (2011).
2. UNITED NATIONS PUBLICATIONS. UNITED NATIONS TREATY SERIES. UN, (2016).

3. Tarkowski R.: Underground hydrogen storage: characteristics and prospects. Renew Sustain Energy Rev 105, 86-94 (2019).
4. Schiebahn S, Grube T, Robinius M, Tietze V, Kumar B, Stolten D.: Power to gas: technological overview, systems analysis and economic assessment for a case study in Germany. Int J Hydrogen Energy 40, 4285-94 (2015).
5. Taylor, J. B., Alderson, J. E. A., Kalyanam, K. M., Lyle, A. B., & Phillips, L. A.: Technical and economic assessment of methods for the storage of large quantities of hydrogen. International Journal of Hydrogen Energy 11(1), 5-22 (1986).
6. Carr, S., Premier, G. C., Guwy, A. J., Dinsdale, R. M., & Maddy, J.: Hydrogen storage and demand to increase wind power onto electricity distribution networks. International journal of hydrogen energy, 39(19), 10195-10207 (2014).
7. Crotogino F, Wasserstoff-Speicherung Hamelmann R. In: Salzkavernen zur Glättung des Windstromangebots.: KBB Underground Technologies GmbH; (2007).
8. Reitenbach V, Ganzer L, Albrecht D, Hagemann B.: Influence of added hydrogen on underground gas storage: a review of key issues. Environ Earth Sci 73(11), 6927-37 (2015).
9. Szummer A, Jezierska E, Lublinska K.: Hydrogen surface effects in ferritic stainless steels. J Alloy Comp, 293-295:356-60 (1999).
10. Kanezaki T, Narazaki C, Mine Y, Matsouoka S, Murakami Y.: Effects of hydrogen on fatigue crack growth behavior of austenitic stainless steels. Int J Hydrogen Energy, 33(10), 2604-19 (2008).
11. Henkel S, Pudlo D, Werner L, Enzmann F, Reitenbach V, Albrecht D.: Mineral reactions in the geological underground induced by H_2 and CO_2 injections. Energ Proc 63, 8026-35 (2014).
12. Lord, A. S.: Overview of geologic storage of natural gas with an emphasis on assessing the feasibility of storing hydrogen. SAND2009-5878, Sandia National Laboratory, Albuquerque, NM. (2009).
13. Ozarslan, A.: Large-scale hydrogen energy storage in salt caverns. International Journal of Hydrogen Energy, 37(19), 14265-14277 (2012).
14. Felseghi, R. A., Carcadea, E., Raboaca, M. S., Trufin, C. N., & Filote, C.: Hydrogen Fuel Cell Technology for the Sustainable Future of Stationary Applications. Energies, 12(23), 4593 (2019).
15. HyUnder. Overview on all known underground storage technologies for hydrogen. https://www.fch.europa.eu/sites/default/files/project_results_and_deliverables. (2018).
16. Gąska K, Hoszowski A, Gmiński Z, Kurek A. Monografia podziemnych magazynów gazu w Polsce. Stowarzyszenie Inżynierów i Techników Przemysłu Naftowego i Gazowniczego Oddział Warszawa II, Warszawa; (2012).
17. Capros, P., De Vita, A., Tasios, N., Siskos, P., Kannavou, M., Petropoulos, A., ... & Paroussos, L.: EU Reference Scenario 2016-Energy, transport and GHG emissions Trends to 2050, (2016).
18. Zeeshan Shirazi, S., & Mohammad Zeeshan Shirazi, S.: Review of Spanish renewable energy policy to encourage investment in solar photovoltaic. Journal of renewable and sustainable energy, 4(6), 062702 (2012).
19. Spanish Ministry of Agriculture, Fishing, Food and Environment. Spanish transitional national plan (TNP)-Directive 2010/75/EU-large combustion plants. Madrid: MAPAMA; (2016).
20. European Union. Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control). Off J Eur Union, L334:17-119 (2010).

21. Del Rio, P., & Mir-Artigues, P.: A cautionary tale: Spain's solar PV investment bubble. International Institute for Sustainable Development (2014).
22. Real Decreto 1578/2008, de 26 de septiembre, de retribución de la actividad de producción de energía eléctrica mediante tecnología solar fotovoltaica para instalaciones posteriores a la fecha límite de mantenimiento de la retribución del Real Decreto 661/2007, de 25 de mayo, para dicha tecnología. Agencia Estatal Boletín Oficial del Estado (BOE), (2008).
23. IEA, International Energy Agency. World Energy Balances, Database documentation (2020).
24. Gibbons, W., & Moreno, T. (Eds.).: The geology of Spain. Geological Society of London (2002).
25. IGN, Institute Geográfico Nacional. Seismic hazards map, general seismic map of the Iberian Peninsula (2015).
26. Tarkowski R, Czapowski G.: Salt domes in Poland – potential sites for hydrogen storage in caverns. Int J Hydrogen Energy, 43, 21414-27 (2018).
27. Michalski J, Bünger U, Crotogino F, Donadei S, Schneider G-S, Pregger T, et al.: Hydrogen generation by electrolysis and storage in salt caverns: potentials, economics and systems aspects with regard to the German energy transition. Int J Hydrogen Energy, 42, 13427-43 (2017).
28. Assessment of the potential the A and RBC for LS and LTS of RE by HUS in E, editor. HyUnder Project, 18 (2014).
29. Simon, J., Ferriz, A. M., & Correas, L. C.: HyUnder-hydrogen underground storage at large scale: case study Spain. Energy procedia, 73, 136-144 (2015).
30. Gutiérrez, F., Calaforra, J. M., Cardona, F., Ortí, F., Durán, J. J., & Garay, P.: Geological and environmental implications of the evaporite karst in Spain. Environmental Geology, 53(5), 951-965 (2008).
31. Caglayan, D. G., Weber, N., Heinrichs, H. U., Linßen, J., Robinius, M., Kukla, P. A., & Stolten, D.: Technical potential of salt caverns for hydrogen storage in Europe. International Journal of Hydrogen Energy, 45(11), 6793-6805 (2020).
32. Panfilov, M., Gravier, G., & Fillacier, S.: Underground storage of H2 and H2-CO2-CH4 mixtures. In ECMOR X-10th European conference on the mathematics of oil recovery (pp. cp-23). European Association of Geoscientists & Engineers (2006).
33. Dalhoff,F., Vangkilde-Pedrsen,T.: Storage capacity calculations in saline aquifers. CO_2 Net Annual Seminar, November 6-7 (2007).
34. Martínez, R., Suárez, I., Zapatero, M. A., Saftic, B., Kolenkovic, I., Car, M., ... & Donda, F.: The EU GeoCapacity project—saline aquifers storage capacity in group south countries. Energy Procedia, 1(1), 2733-2740 (2009).
35. Loredo, J., Cienfuegos, P., & Pendás, F.: OPPORTUNITIES FOR CO2 GEOLOGICAL STORAGE IN CENTRAL COAL BASIN (NORTHERN SPAIN). CO_2SC (2006).
36. Sáinz-García, A., Abarca, E., Rubí, V., & Grandia, F.: Assessment of feasible strategies for seasonal underground hydrogen storage in a saline aquifer. International Journal of Hydrogen Energy, 42(26), 16657-16666 (2017).
37. Ogaya, X., Queralt, P., Ledo, J., Marcuello, Á., & Jones, A. G.: Geoelectrical baseline model of the subsurface of the Hontomín site (Spain) for CO2 geological storage in a deep saline aquifer: A 3D magnetotelluric characterisation. International Journal of Greenhouse Gas Control, 27, 120-138 (2014).
38. CORES, Corporación de Derecho Público tutelada por el Ministerio para la Transición Ecológica y el Reto Demográfico (2020).