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HyUnder – Hydrogen Underground Storage at Large Scale: Case Study Spain.

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Abstract

Hydrogen as an energy carrier is understood as a system capable of storing energy for a later use in a controlled manner. Surplus electricity from renewable energy serves for green hydrogen generation via electrolysis. Once produced, the hydrogen is stored for later consumption.

This paper describes the Spanish Case Study of the HyUnder project which aims to evaluate the potential of underground hydrogen storage for large-scale energy storage along Europe, analysing besides the Spanish Case, France, Germany, the Netherlands, Romania, and the United Kingdom.

This case study has considered for the assessment, the competitiveness of hydrogen storage against other large scale energy storage concepts, the geological potential for hydrogen storage in the region, how to embed the hydrogen energy storage in the energy market and the possible business cases in four different applications: transport, Power to Gas, re-electrification and industry, taking into account all the economic aspects such us the electrolyser OPEX and CAPEX or the cavern, electricity and water costs.

It is shown that the Spanish geology can provide four technical options for hydrogen underground storage. Results have shown the interest of the technology in short – medium term especially linked to certain conditions of high intermittent renewable energy penetration in the Spanish power grid that result in surplus or residual electricity. Hydrogen storage is interesting because it can integrate renewable energy systems in other sectors which do not have overcapacity and a high use of fossil fuels as the natural gas sector and the transport sector.

Moreover, all the economic issues have been analysed for two different horizons, 2025 and 2050; concluding that the average price of electricity is the main cost. From the financial results, transport application represents a business case which, although in order has enough values of hydrogen demand to be stored, combination of different applications must be needed in order to make sense to the development of the cavern.

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Keywords: Large-scale hydrogen underground storage; Power-to-Gas.

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1. Introduction

At present, the EU energy generation system and energy mix is highly dependent on fossil fuels, and only nearly 45 % of European electricity generation is based on low carbon energy sources, mainly nuclear and hydropower. In 2012, EU energy dependency from imported energy resources reached about 53 %, increasing since 1995 (43 %) [1]. The EU energy system faces different challenges: the ambitious target to reduce GHG emissions by 80 % - 95 % in 2050 at European level, reduce the EU energy dependency for imported energy sources and the expected renewable electricity curtailment at medium term due to the expected increase in the penetration of intermittent renewable sources in the energy mix [2].

Use of renewable electricity for the production of hydrogen from water in combination with buffering of hydrogen in underground storages provides an appealing solution for realizing a high penetration of renewable energy sources, not only in the European power grid, but also in the wider European energy system as a whole. In the HyUnder project it has been assumed that underground storage of hydrogen will initially be driven by an increase in surplus renewable electricity. A surplus of renewable electricity has further been defined to occur when the difference between the electricity generation from renewable sources and conventional must-run power plants exceeds the overall demand at any given point in time.

The main objective of the project was to identify potential business cases for the use of hydrogen storage in future energy markets for regions with a potential of storing hydrogen in geologic formations underground, i.e. Germany, the UK, France, The Netherlands, Romania and Spain. The present report combines the findings and conclusions of the Spanish case study.

Nomenclature

B€	Billion of Euros
CAPEX	Capital expenditure
CCGT	Combined Cycle Gas Turbine
EU	European Union
FCEV	Fuel Cell Electric Vehicle
FHa	Aragon Hydrogen Foundation
GHG	Greenhouse Gas
GW	Gigawatt
H_2	Hydrogen
kg	Kilogram
km	Kilometre
kt	Kiloton
kW_{el}	Electric kilowatt
M€	Million of Euros
m^3	Cubic meter
MW	Megawatt
NG	Natural Gas
OPEX	Operating expense
P2P	Power to Power
P2G	Power to Gas
PHES	Pump Hydro Energy Storage
PtG	Power to Gas
REE	Red Electrica de España (Spanish system operator)
RES	Renewable Energy Source
TWh	Terawatt hour

UK	United Kingdom

2. Methodology

The economic analysis of the underground hydrogen storage in the HyUnder project and in all case studies is based on the utilization of the hydrogen storage in four different applications: transport, injection into the NG grid, industry and re-electrification and in two time horizons: early market (2025) and established market (2050).

A joint methodology has been developed to carry out business case type of analysis at a typical plant scale, which should be representative for one country's / region's conditions and reflect the specific framework conditions.

As presented in

Figure 1 the system boundaries are defined such that the analysed cavern plant includes electrolysis, compression prior to the underground salt cavern as hydrogen storage and all topside equipment after the cavern (i.e. hydrogen drying, purification, compression for trailer filling, re-electrification unit and NG grid injection unit). In this context, the analysis does not take into account any infrastructure between the cavern site and the end user (e.g. no trucks for H_2 transportation to hydrogen refueling station).

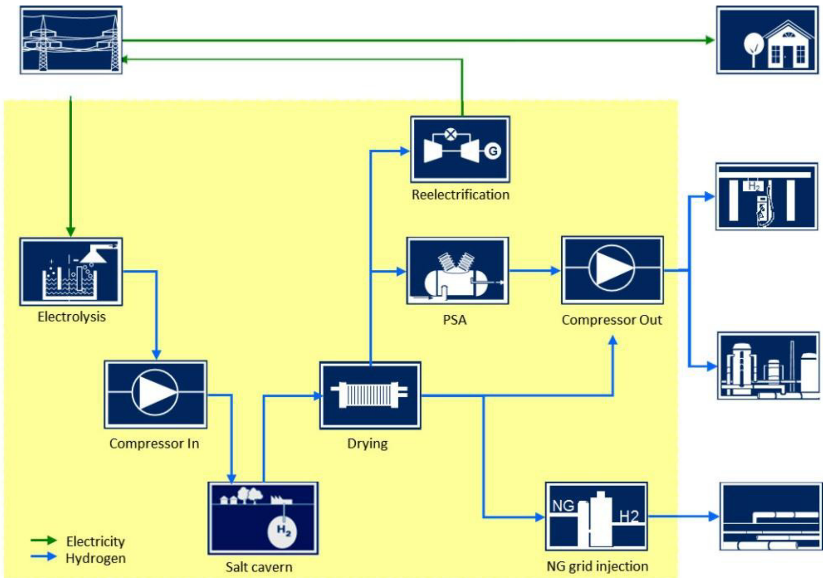

Figure 1. Cavern plant operation. Source: LBST.

In general, the modelling approach consists of two major consecutive steps. In the first step each case study analyses the regional potential for hydrogen production and underground storage including geological conditions, existing energy infrastructure at individual sites and future hydrogen demand. This step results in a selection of one or more cavern sites or areas most suitable for hydrogen production and storage. In the second step a techno-economic analysis for a prototypical cavern site is conducted in order to provide an in-depth evaluation of the required investments and optimal site operation resulting in calculation of most important key performance indicators such as net present value of the selected site or specific hydrogen costs [3].

In this project, hydrogen storage has been justified in an initial phase because of the expected renewable surplus electricity motivated by the estimations of increase renewable power installed. The final annual surplus electricity comes from the difference between the electricity generation from renewable sources and conventional and the overall electricity demand considering only the excess of generation from intermittent renewable sources.

Taking into account the Spanish electricity market and the manageability of the different technologies, FHa has calculated the total surplus electricity. As a result, the total amount of surplus electricity in Spain by 2025 has been estimated in 8.23 TWh, which represent 8 % of the total renewable electricity generated and appears 2 000 hours along the year, which at the same time correspond to 162 kilotons of hydrogen. Same values have been obtained for 2050 horizon where in this case, 23.8 TWh surplus during 3 100 hours is produced, which related to the total renewable electricity generated implies by 11 % and a hydrogen production of 471 kilotons. Just to provide an example and considering 500 000 m^3 caverns and 5 cycles per year for each cavern, 8 and 24 caverns will be needed for both horizons.

Table 1 provide an overview of the potential hydrogen demand that could be covered in each application taking into consideration 100 % conversion of the renewable surplus electricity into hydrogen. It also provides rough values of potential number of caverns and electrolyser capacity that need to be installed and its investment.

Table 1. Overview of potential hydrogen demand.

	Year 2025	Year 2050
Surplus per year [TWh_{el}]	8.23	23.8
% intermittent RES of total electricity demand	32 %	65 %
% surplus of RES generation	8 %	11 %
H_2 equivalent [kt][1]	162	471
#FCEV (million)[2]	3.2	9.2
% passanger car fleet[3]	13 %	38 %
% natural gas use	2 %	5 %
% H_2 demand industry	24 %	88 %
No. of caverns[4]	8	24
Electrolyser capacity [GW][5]	3	8
Investment in electrolysis [B€][6]	3.0	6.0

[1] Assumes 100 % conversion to hydrogen, 66 % efficiency.
[2] Based on 0.54 kg H_2/100 km and 9 500 km per year.
[3] Based on the current passenger car fleet (2013: 24 184 560)
[4] Assumes a mature-market cavern size of 500 000 m^3 with a hydrogen net storage capacity of 4 kt; based on simulations of charging/discharging patterns and the hydrogen inventory of the cavern, the required total storage capacity is roughly 20 % of the total amount of hydrogen produced from surplus; cavern construction costs for brown field sites of 60 €/m^3, resulting in some 30 M€ (excl. cushion gas).
[5] Based on 2 000 full load hours.
[6] Assumes investment of 700 €/kW_{el} for electrolysis in 2025 and 500 €/kW_{el} in 2050.

3. Methodology

3.1. Location analysis

Regarding the underground storage sites, the Spanish Case Study has decided to study brown field sites, where the prospection of the geology is already done and paid, in order to minimize the cost for the creation of the cavern. Also locations where salt caverns are currently under production and with no specific final used for gas storage at their end life has been carefully analysed for the advantages that present, as reduction in the duration driver parameter and reduction of cost, as the brine produced has been already used for productive aspects.

In Spain four good locations have been found (Figure 2**Fehler! Verweisquelle konnte nicht gefunden werden.**). All locations are brown field sites and since the beginning all sites were defined as interesting options due to its good location near wind resources and also vicinity to the electric and natural gas grids. Other parameters took into account have been the geological conditions, local hydrogen demand, level of public support and short-term relevance. The radio of utilization of the hydrogen storage for the transport and industry application has been fixed to 250 km.

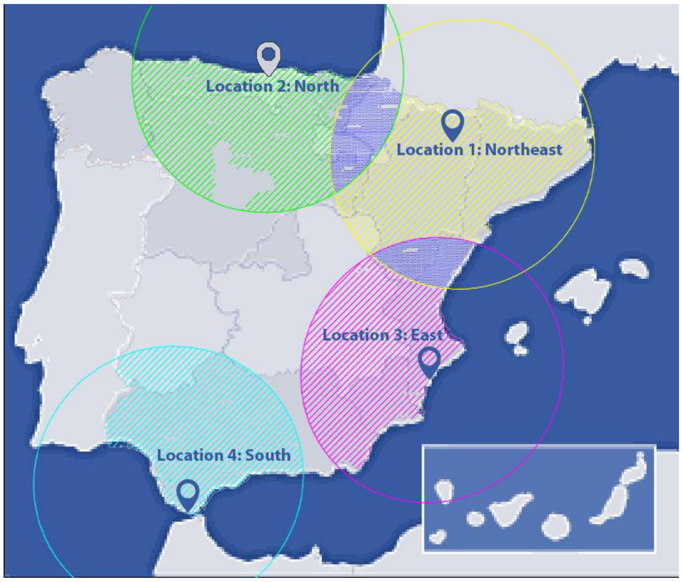

Figure 2. Selected Spanish salt cavern sites for underground hydrogen storage.

3.2. Business Case

In order to analyze the economic feasibility of hydrogen storage in salt caverns is essential to consider the different agents involved in the task. In this regard, different potential hydrogen consumer groups have been considered: hydrogen as fuel for the mobility sector, as raw material for the industry sector, as renewable energy carrier for the natural gas industry and as medium storage for the electricity industry in two time horizons: early market by 2025 and established market by 2050.

In the industry case this way of hydrogen production would be a substitution of today's fossil-based hydrogen production, whereas the other sectors would generate new markets for hydrogen and new demand.

In the Spanish case study the application of power to power or re-electrification is not considered, the reasons are the presence of high inner flexibility in the power grid in Spain derived from combined cycle power plants (CCGT), the modern power system infrastructure and management of the system operator and the low efficiency of the cycle of hydrogen for re – electrification. Nevertheless, due to this overcapacity, most in CCGT, it could be considered to redirect part of the injected hydrogen into the natural gas grid to these plants in order to produce electricity, but at this moment of the analysis this part is covered with the power to gas analysis.

For the Spanish case almost 24 millions of vehicles are expected by 2020 and near 30 million by 2050 taking into account the population growth. Taking into consideration a hydrogen vehicle consumption of 0.54 kg H_2/100 km, the total hydrogen demand by 2025 will be 43 kilotons of hydrogen per year while by 2050 the demand rises to 791 kilotons of hydrogen per year considering a fuel cell electric vehicle penetration of 2.8 % and 36 % respectively [HyWays 2008].

Related to the industry the total amount of hydrogen needed has been estimated in 672 kilotons of hydrogen per year by 2025 and 533 kilotons of hydrogen per year in the long term.

The hydrogen consumption in the natural gas grid will be based on the penetration which is directly related to technical issues, 2 % has been considered for a short-medium term and 5 % by 2050, taking into consideration different sources which point into a range between 2 % and 10 %. As a result a total amount of 212 kilotons of hydrogen per year will be needed for 2025, and 531 kilotons of hydrogen per year (5 %). Nowadays the Spanish legislation does not allow a hydrogen penetration of 10 % into the natural gas grid. However, it could be possible a legislation change by 2025 or by 2050 which will be equivalent to 1 062 kilotons of hydrogen per year for 2050. Results for all applications are shown in

Figure 3.

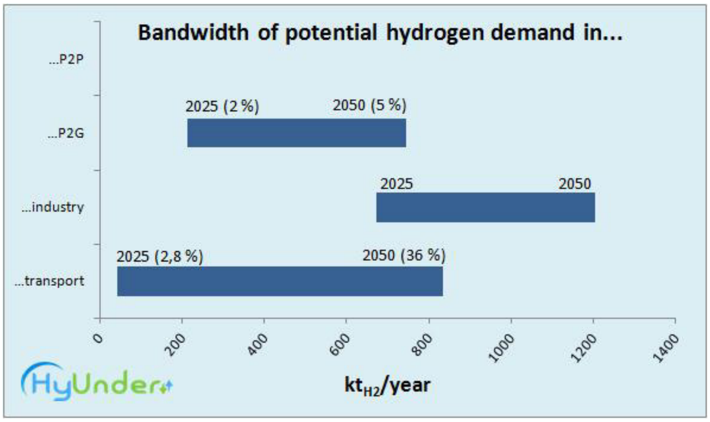

Figure 3. Potential hydrogen demand in the different sectors.

From the financial results details, the transport application appears to be a positive business case with black numbers in all locations; where the achievable market prices for hydrogen sales are based on the general assumption that the fuel cell electric vehicle fuel costs for a given driving range should not exceed the conventional fuel costs. For the industry sector and natural gas sector, the competitive prices do not allow hydrogen from electrolysis being a business case unless incentives against pollution become a reality. Prices took into account for mobility have been (€/kgH2 / year) 6.83/2025 7.63/2050. As it has been said, for industry and natural gas the prices are difficult to be reached for “green” hydrogen at this moment (industry: 2 €/kg H_2 and natural gas (€/kgH_2 / year) 1.66/2025 4.11/2050).

The analysis shows that except for the use of hydrogen from underground storage in the transport application, no other hydrogen use will be a business case due to its negative margins, neither by 2025 nor 2050.

Figure 4 compares the estimated hydrogen production costs with the expected sales price. The total cost is divided in three components: the CAPEX which comprises the equipment and cavern investment (considering a 500 000 m^3 cavern), the OPEX composed by the equipment and cavern operation and maintenances costs, and the OPEX related to the electricity cost (including the stand-by electricity costs).

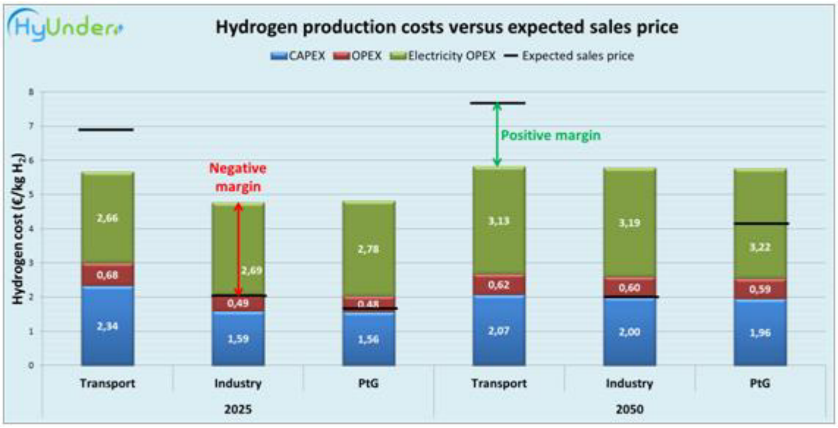

Figure 4. Hydrogen production costs versus expected sales price.

This project has optimized the total hydrogen production costs related to the electricity and equipment costs, thus, threshold price, number of electrolysers and operation hours. The optimized hours of operation for 2025 have been calculated in the order of 6 000 hours, so not all the operation hours are going to be covered by the surplus generation hours. As a consequence, the full load hours for 2050 decreases to 3 800 hours, as surplus electricity does not cover the needed hours of operation in order to cover all the hydrogen demand, the electrolysis plant has to be operated with additional electricity purchased from the pool (with higher prices in 2050 than in 2025) so it will be financially better to introduce more electrolysers in the plant and operating them lower number of hours, so as to reduce the hours of operation at high electricity price.

Regarding the business case assessment, a sensitivity analysis within the mobility application (Figure 5), has been done in order to take care of the influence of the different parameters: electricity price, investment cost in the electrolyser technology, cavern size and annual millage. Mobility sector has been chosen for the sensitivity analysis since it appears at a first state as the nearest application to black numbers in a possible business case.

As a result, it is shown the electricity price and electrolyser investment are the most important factors for the business case, although between both, the electricity price is the most influential one, as a low reduction in the electricity price (expensive electricity, 10 %), has the same influence as the reduction of 25 % the electrolyser investment (expensive technology); furthermore, 30 % of electricity cost reduction implies a reduction in the hydrogen price of 16 %, meanwhile an electrolyser cost reduction of 50 % indicates a 12 % hydrogen price decrease. The other parameters, cavern size and annual millage does not have the same influence as they can make a 6 % and 9 % respectively reduction in the hydrogen price in the best of the cases.

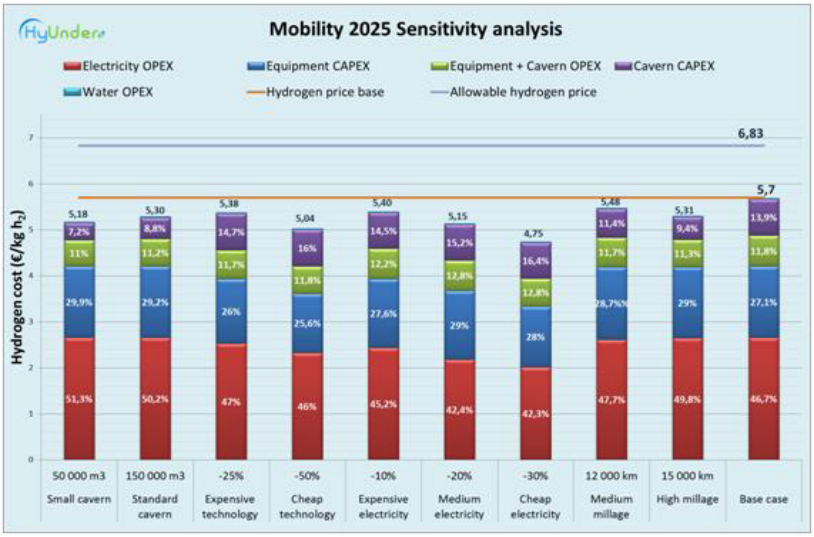

Figure 5. Hydrogen price for the mobility scenario, horizon 2025, sensitivity analysis.

4. Conclusions

To sum up, the Spanish Case Study for hydrogen underground storage at large scale yields the following conclusions:

• High renewable energies sources potential, mainly wind and solar, is available in Spain for electricity production. Currently, the Spanish power system has an overcapacity due to the high capacity installed of wind power and CCGT. An increased in the power systems capacity will lead to high percentages of energy that cannot be consumed internally in the electricity grid (surplus electricity) and to some management problems due to the high intermittency of renewable energy sources, especially wind.

• Hydrogen storage can integrate RES in other sectors which do not have overcapacity and with a high use of fossil fuels as the natural gas sector (power to gas applications), the industry sector with high requirements of hydrogen in refineries, and the transport sector.

• The Spanish geology can provide four technically interesting options for hydrogen underground storage (North, Northeast, East and South of Spain). All locations are extremely good located next to high wind onshore resources, and with certain proximity to estimated hydrogen demands in the time horizons 2025 and 2050, the ones analysed in the report. All Spanish high wind resources could be covered with hydrogen underground storage in cavern sites except Galicia (rock geology – but high PHES potential). All Spanish high hydrogen demand sites estimated for the transport sector in both time horizons could be covered with hydrogen underground storage in cavern sites except Madrid, a different supply system like a pipeline needs to be considered for the centre region of Spain. The locations on the North and Northeast are initially the better options for an early marked business case.

• A financial analysis has been made for all locations and three applications: transport, power to gas and industry. Re-electrification has not been considered due to the presence of high inner flexibility in the power grid in Spain derived from CCGT power plants, the modern power system infrastructure and management of REE and the low efficiency of the cycle of hydrogen for re-electrification.

• It has been found that the investment cost on electrolysis technology is the main parameter to take into account in the CAPEX of the installation. A possible reduction in the cost per MW of electrolysis would improve financial results. Other cost as the cavern construction is not as important and even negligible in comparison to the investment in electrolyser and the OPEX. In the OPEX, the average price of electricity is the main cost (ca. 47 %), as well for the general financial results.

• From the financial results, transport application is the only application that represents a business case in the four locations and time horizons analysed (2025, 2050) since its expected sales price of the hydrogen store are lower than in the industry or natural gas sectors. For these last ones, the competitive prices do not allow hydrogen from electrolysis being a business case unless incentives against pollution become a reality, under the assumptions established for the assessment of the Spanish Case Study.

• Taking into consideration transport as the only application that represent a business case, it has be seen that the complete hourly demand can be covered with one cavern per site, although transport hydrogen demand does not represent enough values in order to justify the creation of the cavern, so a combination of different applications must be needed i.e. mobility + injection into the natural gas grid. Nevertheless, the seasonality of the natural gas demand implies a reduction in the positive financial results also in a work of improving the model the seasonality of the natural gas price must be taking into consideration.

• A comparison between PHES has be done in terms of generation potential and it has be seen that it is not going to be possible to cover all surplus generated in Spain with this technology. Although the hydrological plans of the Spanish rivers are expected to change. As a consequence the minimum environmental flows and maximum ramping rates are going to be reduced, for this reason hydropower operation will become increasingly restrictive.

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