"Assessment of the Potential, the Actors and Relevant Business Cases for Large Scale and Long Term Storage of Renewable Electricity by Hydrogen Underground Storage in Europe"

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R E P O R T

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Contents

List of abbreviations

CO_2	Carbon Dioxide
DE	Germany
EC	European Commission
EU	European Union
EV	Electric Vehicle
FC	Fuel Cell
FCEV	Fuel Cell Electric Vehicle
FR	France
GHG	Green House Gas (es)
H_2	Hydrogen
km	kilometre
MWh	Megawatt-hour
NG	Natural Gas
NL	The Netherlands
NPV	Net Present Value
O&M	Operation and Maintenance
PtG	Power to Gas
RES	Renewable Energy Sources
RO	Romania
SMR	Steam Methane Reforming
SP	Spain
TWh	Terawatt-hour
UK	United Kingdom
vol.%	Volume percent

WP	Work Package

1 Introduction – European context, the need for storage and the case for hydrogen

The European Union has set itself ambitious climate protection targets which call for a fundamental transformation and decarbonisation of the energy system in Europe: the targets for 2020 are a 20 % reduction of greenhouse gas (GHG) emissions, a 20 % share of renewable energy sources in the energy mix and a 20 % reduction in primary energy use; the EU's long-term strategy until 2050 envisages a 80 % to 95 % reduction of GHG emissions compared to 1990 CO_2 emission level.

Achieving these demanding targets will require a fundamental conversion of the energy system, with renewables such as onshore and offshore wind, and photovoltaic (PV) energy playing a crucial role in the electricity generation mix. Unlike the energy sources used in conventional power plants, these renewable sources are not controllable and they fluctuate over time, resulting in intermittent feed-in of electricity into the grid.

As the European energy system decarbonises, there will be a greater reliance on intermittent renewable energy sources, whose growing penetration poses a number of challenges in terms of their large-scale system integration: most importantly, this includes temporary mismatches between supply and demand as well as growing strains on the electricity grid. It will require a mix of different solutions to smooth mismatches and maintain grid stability, including grid expansion, curtailment of generation peaks, demand-side management, flexible generation, and energy storage ('electricity' storage), and conversion of energy for capturing the renewable energy.

At highest level of abstraction, the need for energy storage is driven by the extent to which the electricity system is subject to (temporary) mismatches between supply and demand. In those cases, storage can serve as a buffer which absorbs surplus electricity generated from renewable sources at times when supply exceeds demand on the supply side, and to provide additional capacity in deficit situations when the volatile generation is not sufficient to cover electricity demand on the demand side.

Key parameters which determine supply-demand mismatches and the resulting need for storage include the type (wind, PV) and amount of installed intermittent renewable generation capacity, the wind speed and solar irradiance profiles over time, as well as electricity demand profiles. The most important indicator for surplus electricity in the grid is low electricity prices.

Additionally, the demand for energy storage also depends on the structure of renewable generation capacity by level of grid feed-in i.e. distribution vs. transmission grids and the general availability of grid capacity as well as the geographical distribution of generation and consumption centres.

The electrolysis of water to produce hydrogen in combination with hydrogen underground storage, in those places geologically feasible, is a key technology. It is a readily available and technically feasible option for large-scale (storage capacities >1 TWh), seasonal (chemical) storage of fluctuating renewable electricity, which provides an appealing solution for realizing a high penetration of renewable energy sources. This does not only hold for the European power grid, but also for the wider European energy system as a whole.

The main objective of WP6 is to identify potential business cases for the use of hydrogen storage in future energy markets for six European countries with a potential of storing hydrogen in geologic formations underground: France, Germany, the Netherlands, Romania, Spain and the UK. Based on our assessment, these countries have sufficient geological potential for the underground storage of hydrogen in salt caverns and may be seen as prototypic concerning the introduction of this energy storage concept in their energy markets.

The present report combines the findings and conclusions of all national case studies developed in the HyUnder project and is divided into three chapters: a first chapter to describe the methodology used to assess the technology and the different approaches between countries, a second chapter with a summary of the joint results from the individual case studies and a final chapter with conclusions.

In the development of the report the consortium partners, comprising E.ON Gas Storage, Shell and Solvay as industry partners, has been supported by industry and a wider group of Supporting Partners: Air Liquide, AkzoNobel, Alphéa, BRGM, Bucharest Polytechnic University, ECOIND, Enagas, GasTerra, Gasunie, GDF-Suez, Iberdrola, Linde, National Company of Salt Bucharest, Province of Groningen (NL), Province of Drenthe (NL), Province of Overijssel (NL), S.C. Oltchim, Siemens, Vattenfall, Volkswagen.

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 natural gas (NG) grid, (chemical) industry and re-electrification.

The proposed 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. However, the models provided for the hydrogen storage analysis can be also used at an aggregate level e.g. national level for the evaluation of a number of caverns for overall hydrogen consumption in one specific country. In the HyUnder project it was decided to focus the assessment on two time horizons:

- Early market (2025): This is the period believed to provide first real business opportunities for large scale energy storage by using hydrogen in salt caverns and can be underpinned by data from ample energy studies in each of the Case Study regions, i.e. plant technology is partially in its infancy (large compressors, cavern operation with hydrogen, little experience with plant safety and unknown public acceptance).
- Established market (2050): This will be the period when hydrogen salt cavern storage is believed to provide a business-as-usual technology for large scale energy and electricity storage, i.e. component cost will have come down, safety issues will be solved and full public acceptance will be reached through sound operational records such as with large scale natural gas storage today.

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 refuelling stations).

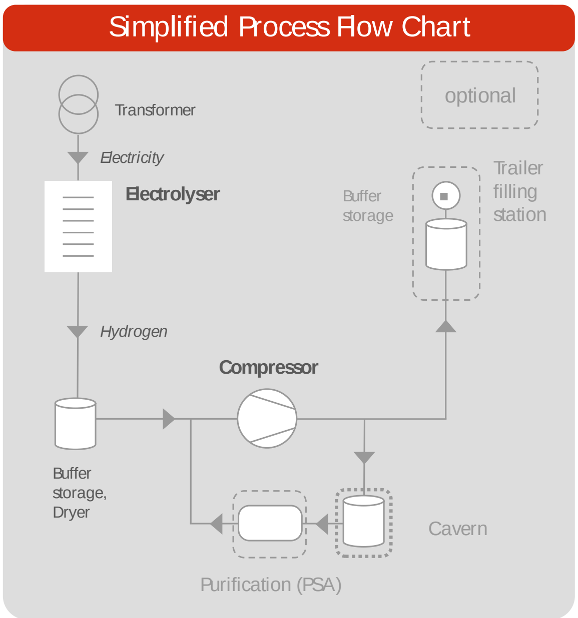

Figure 1. Cavern plant operation. Source: Shell

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[1] 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. For a more detailed description of the joint methodology refer to WP 6.1[2].

[1] Note that some countries used the model to conduct the techno-economic analysis not for a single cavern but for a whole area or entire country. However, the specific hydrogen costs remain comparable regardless the approach selected by the case study.
[2] HyUnder deliverable D6.1: Assessment of the potential, the actors and relevant business cases for large scale and seasonal storage of renewable electricity by hydrogen underground storage in Europe. Joint Methodology for Case Studies, compiled by LBST, 2013.

Based on this common approach country differences have appeared between the national case studies. The different approaches are summarized in Annex1.

3 Summary of Joint Results from individual Case Studies

How to manage the expected increase in the penetration of intermittent renewable sources in the energy mix and how to absorb the intermittent generation in the energy system is one of the challenges of decarbonising the European energy system. Hydrogen production through water electrolysis in combination with hydrogen underground storage in salt caverns in Europe is presented as one of the solutions to the challenge. Business cases for hydrogen underground storage have been assessed in the HyUnder project.

3.1 *Size and timing of the challenge*

The specific set-ups of the energy systems and national energy policy approaches vary significantly across European countries. Hence the manifestation of the challenges of integrating renewables and the role of any particular solution will vary by country and location, and will depend among others on the respective share of fluctuating renewables. In any case, these developments are expected to create an increased demand for energy storage technologies.

The unique aspect of hydrogen as electricity storage medium is its use as 'energy vector', i.e. its versatility with regard to a range of end-use applications, not only for re-electrification i.e. "classical" electricity storage, but also for use as vehicle fuel, in industry or for admixture to the natural gas grid, thereby offering the possibility to integrate wind and solar energy into the energy system beyond the electricity system and bridge into sectors such as transport, natural gas and industry.

It has been assumed that underground storage of hydrogen will initially be driven by an increase in "surplus" renewable electricity, being defined to occur when the difference between the electricity generation from renewable sources and conventional (must-run) power plants exceeds the overall electricity demand at any given point in time. Obviously, the moment, extent and location of the occurrence of this surplus depend on the speed, scale, and type of renewable electricity rollout. Basic assessment of supply-demand mismatches, assuming an ideal "copper plate" electricity transmission system, and thus neglecting any possible network congestions, have been carried out on a national level to provide an indication of the maximum potential for storage of surplus. Locally or regionally, however, the occurrence of specific grid bottlenecks may increase the need for storage.

The following table provides a high-level overview of the country case study estimates on annual surplus electricity, and – assuming 100% conversion to hydrogen – the hydrogen supply potential for different applications as well as rough estimates of the potential number of caverns, installed electrolyser capacity and related investments.[3] The numbers are of hypothetical nature and meant only to give an indication about the potential market size for underground hydrogen storage and subsequent hydrogen applications; as other storage technologies and flexibility measures are being put in place, actual numbers are expected to be lower.

Table 1. Overview of country case study assessments.

	Germany		Netherlands		Spain		UK		Romania	
	2025	2050	2025	2050	2025	2050	2025	2050	2025	2050
Surplus/a [TWh_{el}]	15	75	1	43	8	24	6	21	1	1
% intermittent RES of total electricity demand	30%	70%	31%	80%	32%	65%	42%	62%	13%	14%
% surplus of intermittent RES generation	9%	19%	3%	30%	3%	6%	8%	11%	9%	10%
H_2 equivalent [kt][4]	297	1,485	26	844	162	471	113	416	19	28
#FCEV (million)[5]	3.7	18.3	0.3	10.5	2.0	5.8	1.4	5.1	0.2	0.3
% passenger car fleet	8%	42%	4%	133%	8%	24%	4%	16%	5%	7%
% natural gas use	3%	15%	<1%	9%	2%	5%	1%	4%	<1%	<1%
% H_2 demand industry	8%	41%	3%	93%	24%	88%	16%	59%	16%	19%
No. of caverns[6]	15	74	1	43	8	24	6	21	1	1
Electrolyser capacity [GW][7]	5	25	0.5	14	3	8	2	7	0.3	0.5
Investment in electrolysis [B€][8]	5.6	18.7	0.5	10.7	3.0	6.0	2.1	5.2	0.3	0.3

[3] Numbers in the table may slightly deviate from case study results, due to differences in assumptions. Data from the French case study are not included due to differences in the approach.
[4] Assumes 100% conversion to hydrogen, 66% efficiency.
[5] Based on 0.54 kg H_2/100 km and 15,000 km per year.
[6] 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).
[7] Based on 2,000 full load hours.
[8] Assumes investment of 700 €/kW_{el} for electrolysis in 2025 and 500 €/kW_{el} in 2050.

In Table 1, the annual estimated surplus electricity has been converted into the theoretical amount of hydrogen that could be made available for use in different applications (which are mutually exclusive in this case). In principle, end use options for this hydrogen are its use as a fuel in the potentially emerging mobility sector, selling it to industrial hydrogen customers, admixing it to the natural gas grid, and for re-electrification. In the case of industry this would largely be a substitution of today's fossil-based hydrogen production, whereas the other sectors would generate new demand and new markets for hydrogen. With FCEVs on the verge of market introduction, hydrogen as vehicle fuel currently receives considerable attention. However, in the short to medium term, potential hydrogen demand for mobility will be small compared to what could be fed into the natural gas grid or the existing substitution potential in the industry sector.

Clearly, the results illustrate that the estimated amount of surplus, if converted entirely to hydrogen, could fuel a significant number of FCEVs in some cases, such as in Germany. Also, it could replace a large share of industrial hydrogen which is currently produced mainly from natural gas. Building such an infrastructure of integrated hydrogen electrolysis and underground storage sites would require significant multi-billion Euro investments, with installed electrolyser capacities of several GWs.

3.2 *Location analysis*

In this section the most promising geological sites for hydrogen underground storage in salt caverns are analysed, specifically from a market perspective. It was decided to only consider sites where salt caverns are operated under feasible geological conditions to develop underground gas storage caverns and necessary infrastructure and apply standard procedures for brine disposal (brown field sites).

A common methodology has been developed to present comparable results of the most attractive geological locations for hydrogen underground storage in Europe (See Figure 2). To assess cavern sites the following parameters have been used:

- Quality of the geology to build the cavern

- Vicinity to transport needs
- Vicinity to fluctuating energy sources (sufficient voltage level)
- Vicinity to H_2 pipelines
- Vicinity to NG consumptions and industrial consumptions
- Vicinity to high voltage power grid
- Vicinity to NG grid nodes
- Number of locations.

The quality of the geology is one of the main parameters to determine the feasibility of building a hydrogen cavern. The percentage of insolubles in the salt structure and the useful application of brine (industry, salt production) or access to brine disposal options like the sea are key factors. Besides the quality of the geology, other location factors have been taken into account in order determine promising site locations, most importantly the availability of cheap electricity, e.g. by eliminating grid fees, as well as the access to potential future hydrogen markets. With respect to these aspects the decision for an optimum site will follow a trade-off between the location's vicinity to renewable electricity hubs versus its vicinity to existing hydrogen infrastructure and hydrogen demand centres. Where possible, brown field natural gas storage sites (initially) are preferred locations for developing hydrogen caverns for a number of reasons like lower expected development costs compared to green field sites, e.g. due to existing brine disposal infrastructure, rapid extension of permits, or public acceptance.

The results obtained in each of the case studies are presented in Figure 2.

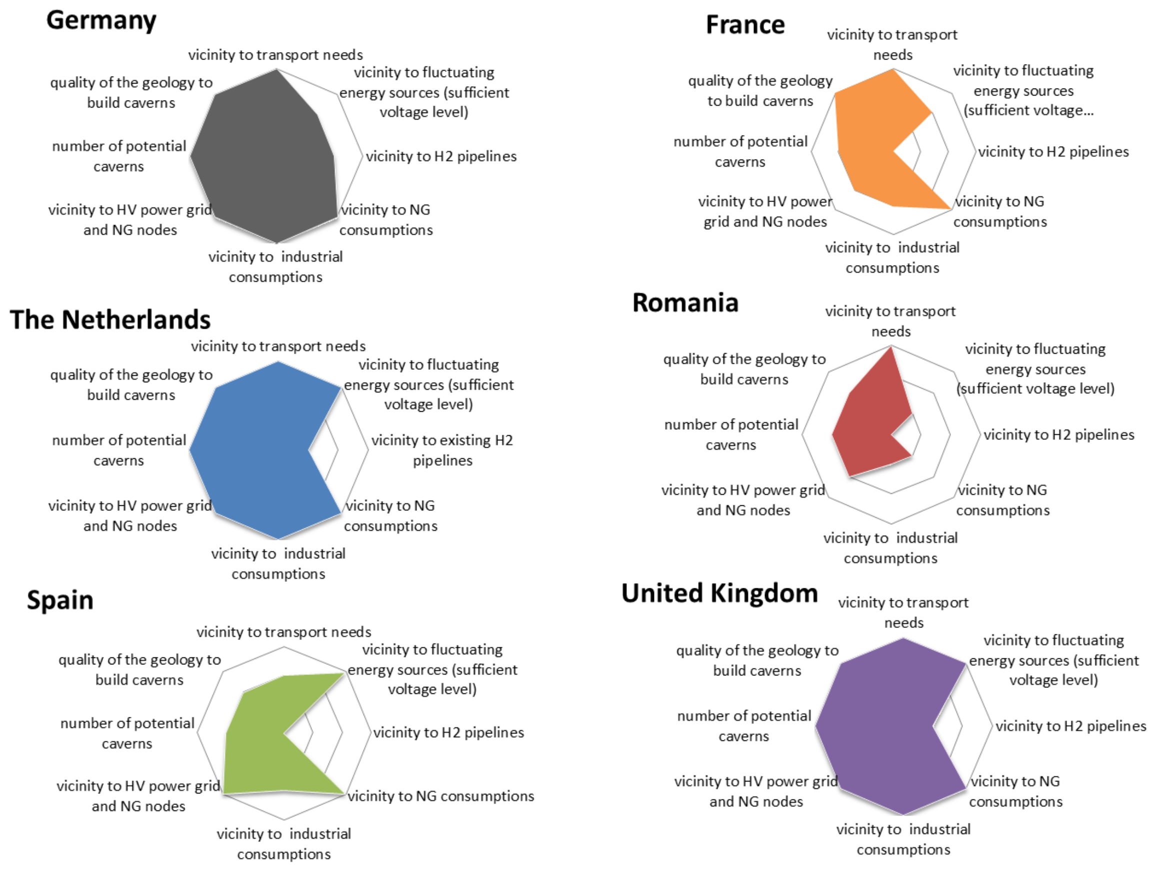

Figure 2. Summary geological conditions for hydrogen underground storage in Europe (Germany, France, Romania, Spain, The Netherlands and the United Kingdom). Source: HyUnder project.

It can be summarized that hydrogen underground storage is geologically feasible in Europe (DE, NL, FR, SP, RO, UK) in principle. Also we have observed a sound match of electricity supply and user specific criteria for some of the locations, such as in Germany, The Netherlands and the UK.

In the following map, Figure 3 the areas are highlighted where hydrogen underground storage in salt caverns in Europe would be generally feasible.

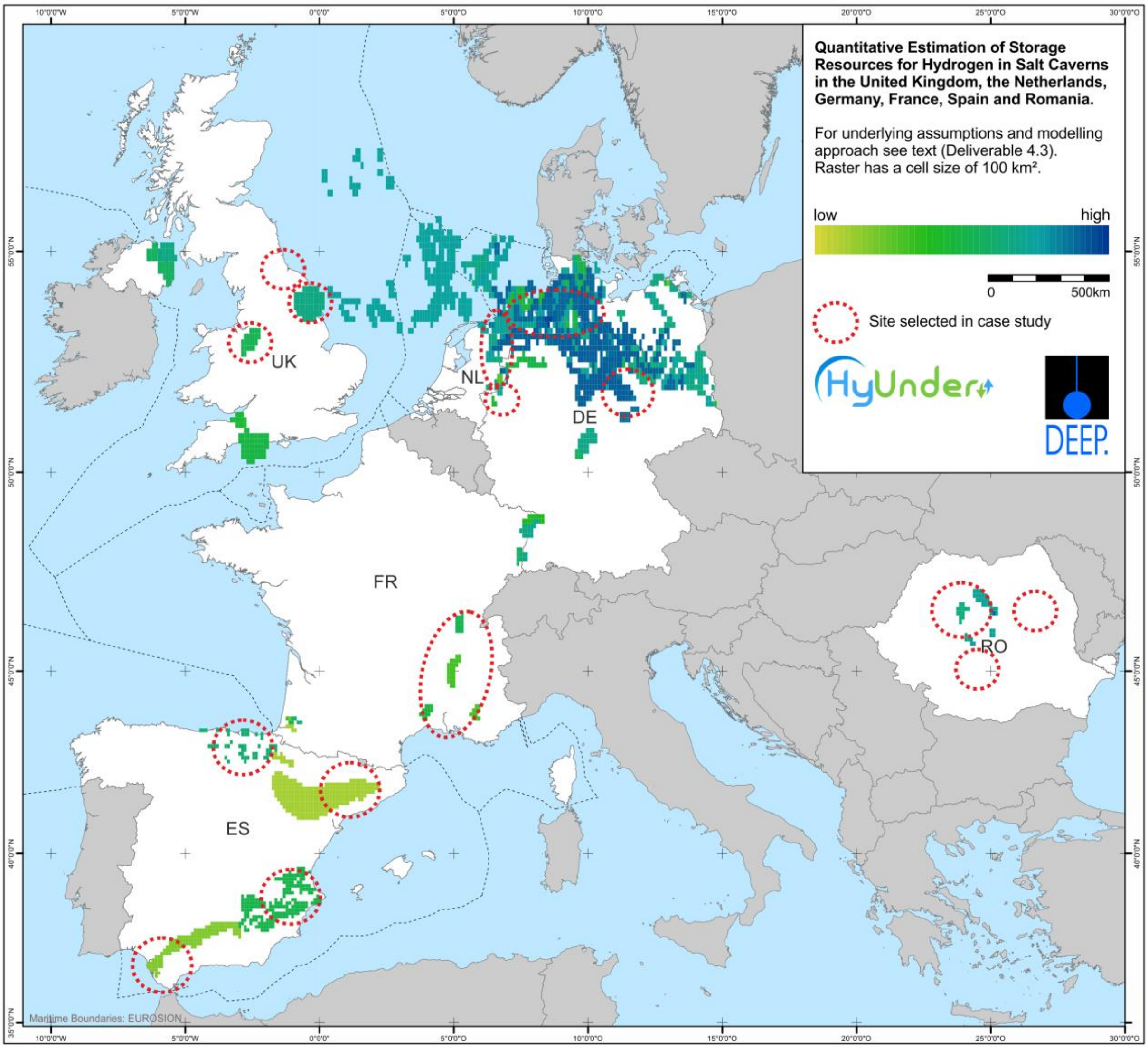

Figure 3. Geological mapping of salt formations and selected storage sites[9]

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[9] The assessment of the salt deposits was made based on an approach to design model caverns, on the available geological information and common cavern construction limitations. However, salt deposits in some locations were assessed directly by the case study participants, based on different parameters or with additional data available. Thus for the UK and Romania, sites have been selected for the case study assessment that show no significant potential based on the cavern model.

Potential business cases for hydrogen underground storage have been analysed as part of the project. The economic assessment of the hydrogen storage technology comprises both the supply side of the technology, plant CAPEX and OPEX (based on electrolysis cost mainly) as well as the hydrogen utilization, and from the demand side, under certain assumptions of hydrogen demand in 2025 and 2050.

3.2.1 Supply side

Result of the studies carried out for each country, clearly indicate that, apart from future electricity prices, electrolyser investment costs and electrolyser utilization are the most important factors for the potential business cases. Therefore, four general cases have been incorporated, based on data and results from all Case Studies. The final results are presented in Figure 4, where the economic assessment results are depicted as CAPEX (cavern, electrolyser and topside equipment), O&M costs for the cavern, electrolyser and topside equipment and expressed as “fixed OPEX” as well as costs for electricity OPEX.

Four scenarios have been analyzed in order to compare the relation between high and low utilization related to hydrogen demand. First, low and high utilization have been quantified as 500 hours for the first one and 5 000 hours for the second one, this is to say respectively an utilization by 6 % and 60 %, which is justified due to high renewable energy penetration (13 % - 42 % for 2025 for the different case studies).

Throughout the project, a standard cavern size of 500 000 m^3 has been considered, except for low hydrogen demand (400 tons), where the size chosen it has been 50 000 m^3 in order to study the initial expansion state.

Related to hydrogen demand 400 tons were considered for low utilization and low cavern size implying a full annual load cycleone fulfilled cavern/year (Case A). The same condition for a large cavern in low utilization has been calculated (4 000 tons and cavern size 500 000 m^3 for 500 hours, Case B). Finally, 12 000 (Case C) and 28 000 (Case D) tons have been considered for the case of high utilization, implying three and seven full cavern load cycles, respectively.

Furthermore, the electricity price is believed to be harmonized across Europe in the future (2050) as markets become more integrated. Here, we present the lowest and the highest prices assumed by all Case Studies taking into account the 2025 scenario with average prices of 32 €/MWh (low electricity price estimated in the European countries involved in the HyUnder project) and 78 €/MWh (high electricity price estimated in the European countries involved in the HyUnder project) for both levels. As a general conclusion it is shown that for low utilization (A and B), high equipment cost represents 97 % of the total cost while the electricity cost is negligible, since as lower the utilization is, higher is the number of electrolysers to be include in order to cover all the hydrogen demand. Besides, special attention is required in Case A where very low hydrogen demand has been considered which implies significantly increases of the cavern CAPEX, reaching 16 % of the total costs. Also for low utilization, hydrogen prices have no case for being competitive in any possible business case (32 €/kg H2 and 26 €/kg H2). For high utilization levels (C and D), the situation changes completely, most of the cost are represented by electricity cost (54 % and 56 %). As well, cavern CAPEX participation became insignificant in both cases. It is very important the difference between high and low electricity price which in fact represents 35 % and 37 % of the total costs.

In conclusion, high utilization cases are the ones which lead to positive business cases; low utilization does not lead to a positive investment case because of high number of electrolysers that there must be installed. As a consequence, hydrogen price is competitive for cases C and D (from ~ 4 €/kg H2 to 6 €/kg H_2 depending on high or low electricity price).

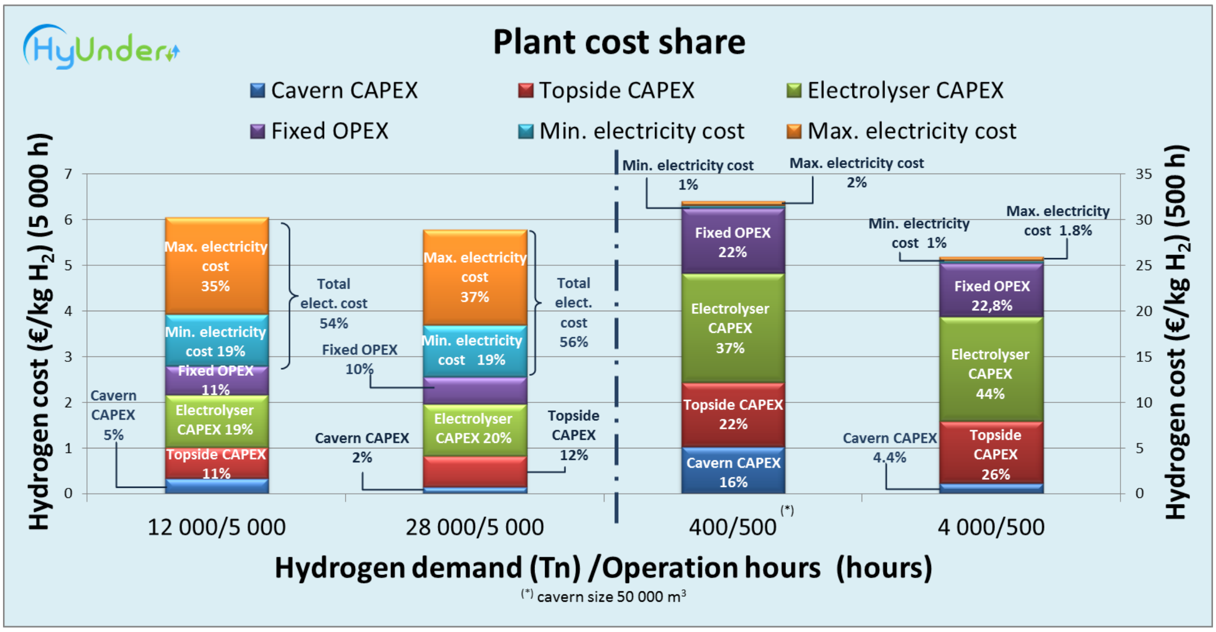

Figure 4. Hydrogen underground storage plant cost share. Source: HyUnder project.

The importance of the utilization of the plant could be seen as well in Figure 5. The figure compares the cost of hydrogen for electrolysis with the allowable cost of hydrogen for a number of applications at different full load hours of plant operation (FLH). The left-hand side of the figure shows the cost window which is formed by the 2013-case including cost of storage, and the 2050-case without cost of storage. The allowable cost of hydrogen on the right are derived from current and projected future cost of energy carriers for the reference case, taking into account differences in efficiency for hydrogen and reference conversion technologies if needed.

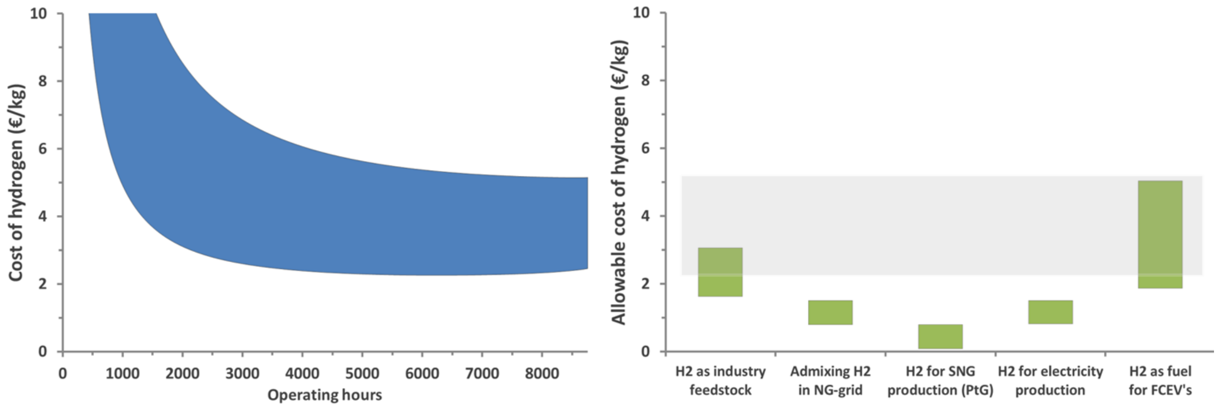

Figure 5. Comparison of cost of hydrogen for electrolysis with the allowable cost of hydrogen for various applications. Source: HyUnder project.

3.2.2 Demand side

The economic assessment of the technology requires the estimation of the hydrogen demand in each of the case studies of the HyUnder project in both time horizons established for the assessment, 2025 and 2050. In order to understand the order of magnitude of the hydrogen 'supply side', i.e. the estimated hydrogen storage demand, vs. the hydrogen demand in different end-use sectors, potential (future) markets for hydrogen in every country have been studied (see Table 2). Whereas for industry this would largely be a substitution of part of today's fossil-based hydrogen production, the other sectors could generate an additional hydrogen demand. For Power-to-Gas applications, also the technical limits of the injection of hydrogen in the NG grid need to be considered.

The estimation of the future hydrogen demand for the transport sector and for Power- to-Gas applications is based on external references, assumptions and regulations regarding the maximum admixture of H_2 to the NG grid i.e. level of methanation to be injected into the NG grid directly as synthetic methane gas, in the different countries of the Case Studies.

Table 2. Estimates of FCEV penetration and hydrogen maximum admixture in the NG grid in 2025 and 2050. Source: external references and national regulations. (*Values referenced to potential additional demand of injection of H_2 in the NG grid, not estimated actual demand).

	Estimated H_2 share in the NG network (% .vol)[10]		Penetration of FCEVs[11] (%)		
	2025	2050	2025	2050	Reference
DE	2 %	10 %	4 %	5% - 50 %	[NOW 2013-2] (data for 2030 instead of 2025); 2050 : [McKinsey 2011]
FR	0 %	10 %	1,4 %	16 %	Assumptions; PROTEC H_2 project
RO	5 %	5 %	5 %	5 %	Assumptions (No official targets)
SP	2 %	5 %	2,8 %	36 %	HyWays - Spain
NL	-	-	0,2 %	26 %	Assumptions (No official targets)
UK	Up to 3 %	Up to 10 %	<1 % (up to 5 % in 2030)	Up to 50 %	UK H_2 MOBILITY

[10] Based on maximum legal percentages of injection into the natural gas grid.
[11] Percentage based on the total passenger car fleet.

The country specific estimated hydrogen demands and the potential demands of hydrogen generation based in renewable electricity surplus are shown in Figure 6:

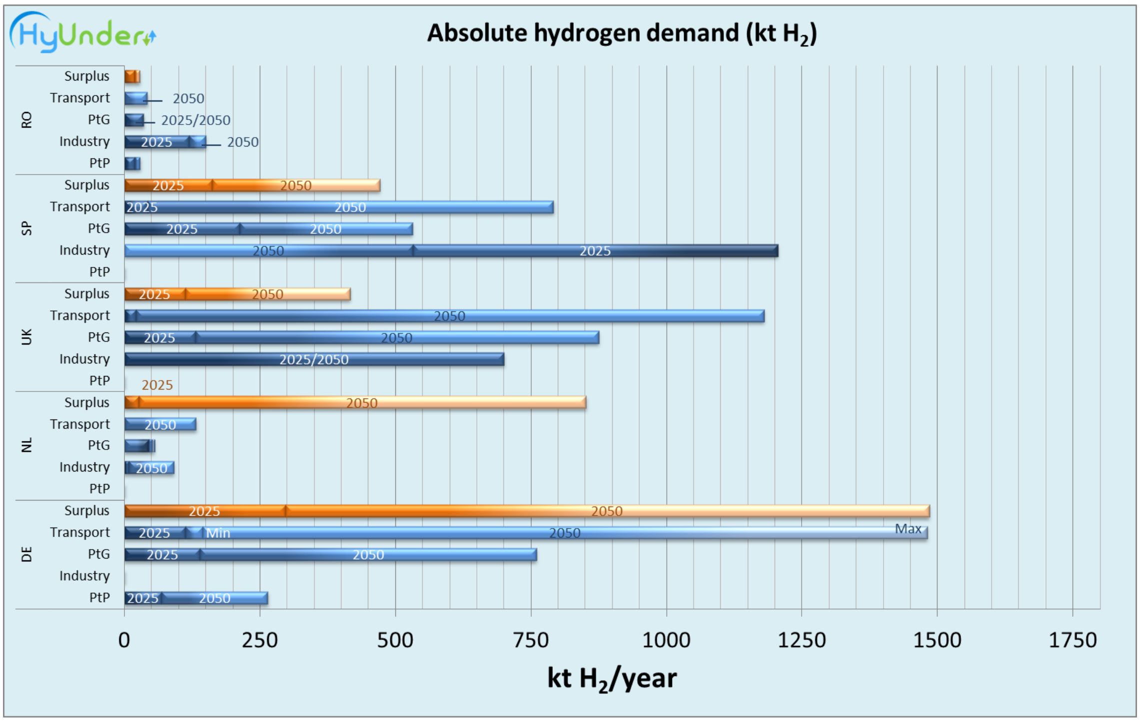

Figure 6. Assumed absolute hydrogen demand for each Case Study and each application (Germany, Romania, Spain, The Netherlands and the United Kingdom); (In the French Case Study, only regional demands in potential regions were calculated, see Annex I). Source: HyUnder project.

Each Case Study has analysed the potential hydrogen demand in four different applications: transport, injection into the NG grid, (chemical) industry and re-electrification. As it is shown in Figure 6, absolute hydrogen demand in kilotons per year has been studied for 2025 and 2050 (blue bars). After that it has been compared with the hydrogen that could be produced with the surplus renewable electricity (orange bars) in order to better understand the share of hydrogen demand to be covered with it.

Special cases are the re-electrification application in The Netherlands and Spain, where it has not been considered in the first case and it does not make sense due to overcapacity in the second; the industry application in Spain where the hydrogen consumption will decrease because of fuel cell electric vehicles penetration, and in Germany where in a short to medium term increase and in a long term decrease can be expected but it has not been quantified. For transport application in the United

Kingdom in 2050 minimum and maximum values were calculated depending on the FCEV penetration.

3.2.3 Economic synthesis

The financial results of all Case Studies analysed under the framework of the HyUnder project has arrived to similar results that could be established at European level as common conclusions of the economic assessment of hydrogen underground storage in Europe.

The German Case Study had been defined to serve as potential blueprint for the other Case Studies of France, the Netherlands, Romania, Spain and the UK. In this subchapter economic results from the German Case Study are presented.

The German Case Study firstly analysed the reference scenarios for the 4 applications or end – use established as framework study in the HyUnder project: the transport sector, injection into de NG grid, re-electrification and the use of hydrogen in industry.

From the baseline scenarios and based on today's understanding of the development of the future energy markets only the mobility application offers positive economic results as it could be seen in Figure 7. Production Cost and Average Sales Price per kg H2 in the reference cases for Germany. Source: German Case Study; HyUnder project.

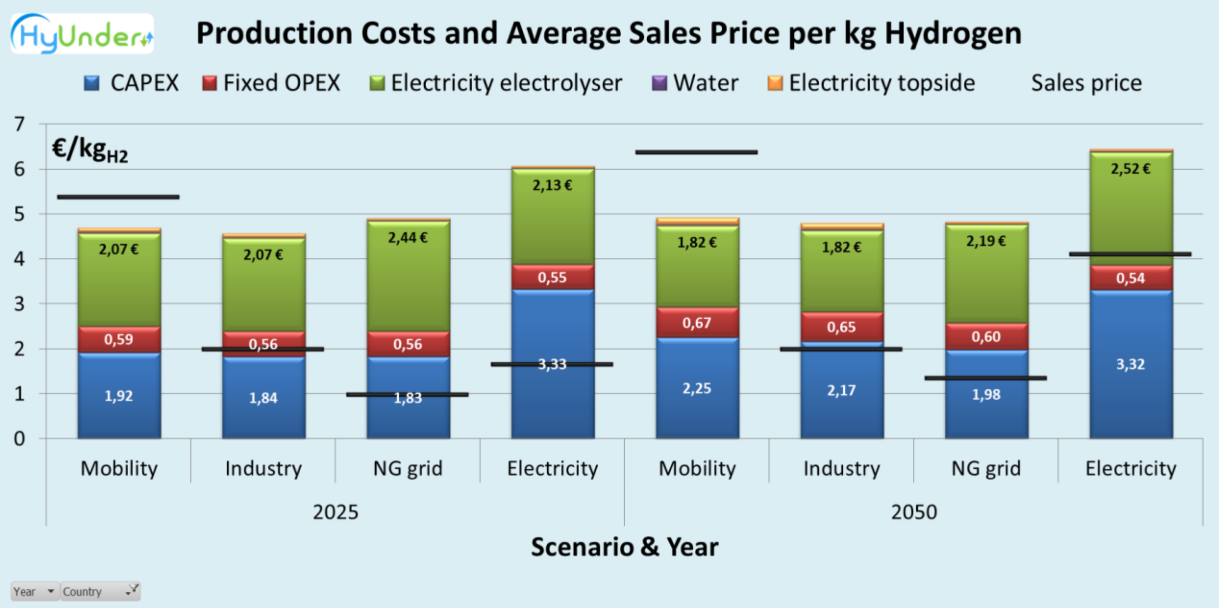

Figure 7. Production Cost and Average Sales Price per kg H2 in the reference cases for Germany. Source: German Case Study; HyUnder project.

A sensitivity analysis of the German Case Study for the transport sector application was implemented. The scenario “Mobility 2025” was used as a reference case for the variation of the following parameters:

- Smaller facility size (smaller cavern of 50 000 Nm³).
- Inclusion of grid transport fee.
- Investment costs electrolysis technology.
- Average electricity price.
- Electricity price volatility.

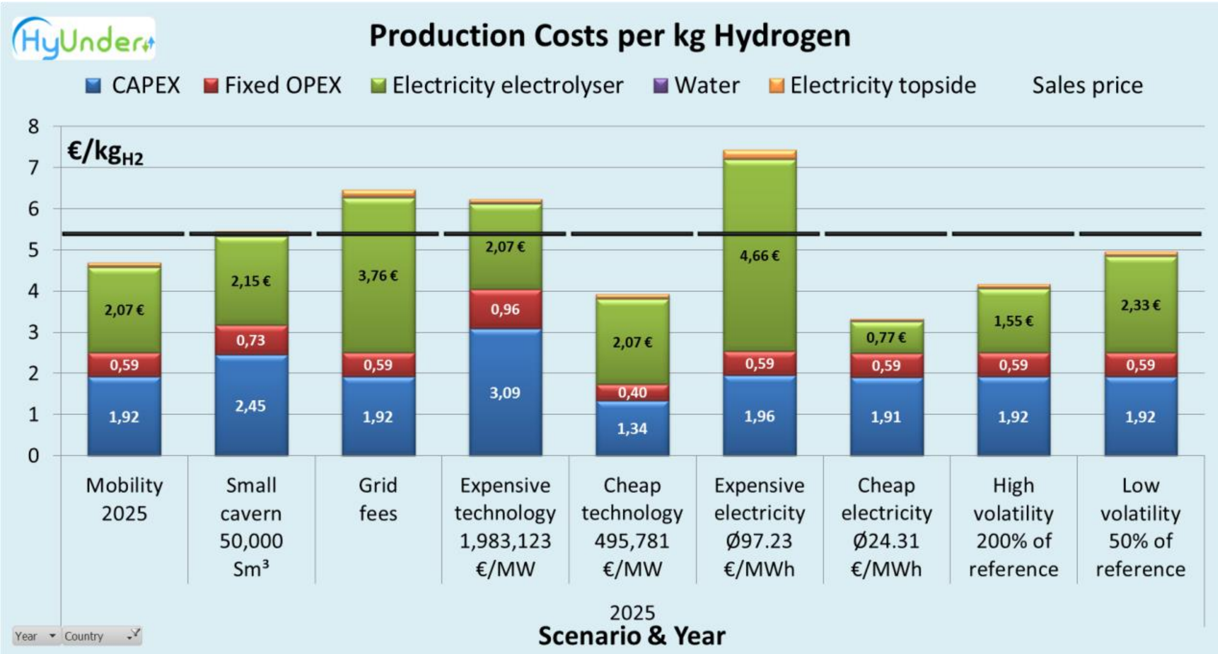

Figure 8. Production Cost and Average Sales Price per kg H2 in the sensitivity analysis for the German Case Study. Source: German Case Study; HyUnder project.

Positive values of NPV are obtained for the reference scenario of mobility in 2025 and in the scenarios of low cost of the technology and electricity. It seems as well as the volatility affects the financial results.

In all case studies, hydrogen for mobility offers the most valuable business case. The analysis has demonstrated that hydrogen produced by electrolysis, salt caverns and distributed to vehicles has the potential to be an economically-competitive fuel, but that the business case is critically dependent on the achievable price of hydrogen and the cost of the electrolyzer technology and the electricity prices among others.

4 Conclusions

In summary, the analysis of all Case Studies for hydrogen underground storage arrives at the following high-level conclusions:

• A share of intermittent renewables which covers about 30-40 % of the national electricity demand already could result in some TWh´s of so-called surplus electricity that needs to be accommodated in the energy system. Higher shares of 60-80 %, and more, could result in tens of TWh´s of surplus electricity, annually, in countries such as Germany, the Netherlands, Spain and UK.

• Underground storage of hydrogen in salt caverns is a technically feasible option for large-scale storage of electricity, but requires a suitable geology as well as public acceptance.

• Electrolysis dominates the total costs of an integrated production and underground hydrogen storage facility with over 80 % (at some 50 % utilization), 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 H_2.

• Besides electrolyser CAPEX and electricity purchase prices, the costs of hydrogen from electrolysis strongly depend on the electrolyser utilization. At less than about 2,000 hours the capital costs start to dominate the production costs, making hydrogen from electrolysis increasingly expensive. Because simulations indicate that it may take quite some time before situations with significantly more than 2,000 hours of surplus are reached, storage of surplus electricity as hydrogen does not seem to represent a near-term economically viable case. Improving the utilization and therefore the economics of electrolysis would require the purchase of additional electricity from the grid.

• Hydrogen energy storage as a means to store renewable electricity via electrolysis and underground storage is economically very challenging. In the short term, under the assumptions taken, the transport sector is the only market expected to allow a hydrogen sales price that may enable a commercial operation of an integrated hydrogen electrolysis and storage facility.

• Where hydrogen from water electrolysis has to compete on a heating value basis with natural gas, i.e. where the benchmark for the hydrogen sales price is set by the price of natural gas, such as in the case of admixture to the natural gas grid, when used as feedstock in industry or for re-electrification, it is not economic. Therefore, potential business cases for other sectors depend on the “willingness-to-pay a premium” by the end-user, or a very favourable policy support. Specifically, the use of ‘low-CO_2’ hydrogen (from electrolysis) in industry depends on its cost-competitiveness against natural gas reforming (SMR). It is questionable whether this will happen in the absence of a regulation that allows monetizing its potential CO_2 benefits.

• Not any single industry sector alone will create a viable business case for underground hydrogen storage. Initially, hydrogen energy storage would need a combined pull from the power balancing market and the mobility sector, as it is otherwise unlikely to be implemented widely. Over time other markets would have to fully develop to leverage the economic synergies with hydrogen energy storage.

• Sensitivity analysis indicates that the most important factors for a potential business case are both low electrolyser CAPEX and significant periods of low electricity prices, which in the case of re-electrification should be accompanied by a very high volatility, i.e a very high spread in electricity prices. The future development of electricity prices, and more generally electricity market designs, and the actual pricing of ‘surplus’ electricity are among the biggest uncertainties. Other factors that could contribute to a positive business case include favourable feed-in tariffs for ‘green’ fuels , reduced grid fees and a significant increase of CO_2 certificate prices to a level of 100 €/t.

- Despite the higher specific costs of a small cavern of some 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 small caverns.

In other words, underground hydrogen storage may become a viable option for large-scale, seasonal electricity storage and make economic sense in places with (i) the suitable geology, (ii) significant amounts (TWhs) of intermittent REN and surplus (over extended periods), (iii) low electricity cost (over a reasonable utilization of >40-50%) and (iv) a CO_2 price and/or emergence of a hydrogen mobility market (the right policy support).

It is important to mention that in the analysis provided by the HyUnder project the subsequent hydrogen infrastructure is not included and the corresponding barriers and cost may vary substantially for different applications (e.g. the refuelling station infrastructure for the mobility sector may be more costly and difficult to build-up than the infrastructure required for the hydrogen use in the industry sector). Moreover, the results presented in the project do not include revenues from explicit load management within the electricity grid, like the provision of balancing power.

Annex I. Highlights from National Approaches

Case Study

France

Companies and authorities involved

Hinicio (partner), CEA (partner), Air Liquide, GDF-Suez, BRGM (Bureau de Recherches Géologiques et Minières), Alphéa.

Methodology approach for the economic assessment:

The approach used in the French case study slightly differs from other countries, in the sense that no national aggregate data (renewable energy production, renewable energy surplus, hydrogen demand) have been calculated. Only local data were considered, in the vicinity of potential storage sites. In a first step, potential regions for locating the storage cavity were assessed against a list of objective criteria relating to the geology, as well as the anticipated hydrogen demand and renewable energy developments in the nearby-region:

- First, a geological mapping of salt formations across the country was carried out. 6 candidate regions were shortlisted and thoroughly assessed: depth of the salt layer, thickness, amount of insoluble matters, etc.
- Second, estimates of hydrogen demand from the mobility, natural gas and industry sectors were calculated for the years 2025 and 2050. Re-electrification was discarded upfront, after intense discussions among the team for costs and low efficiency reasons.
- Last, the renewable energy potential of each of the potential regions were assessed based on the political objectives published in recent years at the regional level.

The site chosen for modelling and further analysis was selected combining each of those criteria.

The second step consisted in the static modelling of the selected cavity in 2025 and 2050, based on the model previously developed in WP6.2 and applied in each national case study.

Finally, a dynamic modelling has been performed on the hourly operation of the very same cavity, using a publicly available software named HOMER and relying on the same technical and economic assumptions as with the static model but considering only considering the mobility sector, which appears to be the most attractive downstream market, price-wise.

Case Study

Germany

Companies and authorities involved

Shell, Eon Gas Storage, Volkswagen, Siemens, KBB, DEEP, Linde, Vattenfall, Solvay

Methodology approach for the economic assessment

We have undertaken a regional and national approach in parallel. For scaling at national level the energy storage requirement has been identified, starting from nationally accepted Leitstudie-scenarios (assumptions on renewable energy and energy demand development, grid extension, etc.) and compared with the potential hydrogen demand development (2025/2050). These numbers were then translated into a maximum possible hydrogen storage demand. It was found that the geologic storage potential is sufficient to cover all of Germany's future large scale storage needs. At regional level we have studied the cavern location sites from a market and infrastructure perspective (energy supply, energy infrastructure and H2 demand development by market segment). Out of 25 caverns scrutinized, 6 single sites in 3 regions have been identified as being specifically well suited. The cavern specific business case development built on a single project based approach for one prototype cavern and for 4 market segments (fuel for transport, chemical, re-electrification, injection to gas grid). For this purpose, that part of the infrastructure close to the cavern (e.g. power plant for re-electrification) have been taken into consideration. As electricity prices the following numbers (avg. price/volatility in €) have been assumed: 49/25 (2025) and 101/72 (2050). For the business case analysis (case: fuel for transport) sensitivity analysis has considered cavern size (minor impact), electricity price (average price level, volatility) (very high impact), grid fees (high impact) and electrolyser investment (very high impact). For a national extension this analysis would have to be extended by just multiplying the prototypic case respecting the required storage capacity of one cavern and the national demand.

Case Study

The Netherlands

Companies and authorities involved

AKZONOBEL, Gasunie, GasTerra, Air Liquide, Province of Groningen, Province of Drenthe, Province of Overijssel.

Methodology approach for the economic assessment

The potential of hydrogen production from so-called “surplus” renewable electricity has been estimated for national level through simulations on hourly basis using “best guesses” for the development of installed wind and solar production capacity, and electricity demand in end-use applications. The analysis shows good comparison with estimated future potential hydrogen demands from industry, transport, replacement of natural gas, and electricity production. On a regional level, cavern locations sites have been evaluated from a market, infrastructure and regional government perspective. In total 8 locations, out of 27, have been identified as potentially suitable for underground hydrogen storage, which offer ample capacity for potential future needs for buffering and storage of renewable hydrogen. The economics of electrolytic renewable hydrogen production combined with buffering of hydrogen in underground storages have been considered for a single cavern project in the light of the different hydrogen applications. Cost of production and storage [12] have been compared with allowable cost of hydrogen which result from the reference systems with which hydrogen is in competition. In the analysis, electricity prices of 22 €/MWh and 35 €/MWh [13] have been used for 2025 and 2050, respectively. These prices result from hourly spot market electricity prices for recent years and are taken in correspondence with the estimated number of future “surplus” hours. A sensitivity analysis is carried out for a number of parameters including electrolyser investment cost, full load hours, electricity price, oil and natural gas price and price of carbon dioxide.

[12] Including cavern top-side facilities (drying and PSA), but excluding hydrogen application specific facilities such as re-electrification plant and facilities for natural gas grid injection.
[13] Derived from 2009 - 2012 day ahead prices on the APX Power Spot Exchange

Case Study

Romania

Companies and authorities involved

The Romanian Case Study results from the involvement of important Romanian stakeholders under coordination of NCHFC. The results do not necessarily express the views of any one singular contributing company, but instead the voice of a group of diversely acting specialists, all individuals being experts in their specific application area of hydrogen energy or the use of underground caverns for other industrial purposes in general.

Methodology approach for the economic assessment

In Romania was identified four potential sites for hydrogen storage and three of them were selected for in-depth analysis, located in: Central, South and East. The analysis was conducted according with project's criteria, which refer to the evaluation of a set of locations, like: good geological conditions, cavern field in conservation. These sites were compared to each other with respect to strategic and financial aspects. In analysing potential business cases, actors interest, it was found that there is not a regional differentiation across Romania, locations are somewhat distributed proportionally across the country. Roughly we can affirm that from the three sites, two have a slight advantage, this advantage is considerable increased if it is also considered the storage of hydrogen as by-product from chemical industry. For renewable hydrogen was proposed six scenarios, three for 2025 and other three for 2050. Scenarios refer to maintaining the same maximum amount of renewable hydrogen, but its use in various sectors: transport, gas and power. Additionally was realized the sensitivity scenarios, the prices is 1/3 from main scenario (study case), and the size of caverns is ten times smaller. The number of caverns was three for horizon of time 2025 and 2050. The ideal scenarios providing a comparison of hydrogen costs and its economic value for the major hydrogen application areas: mobility, gas supply and power, for 2025 and 2050. The Romanian electricity prices (€/MWh/year) were 45/2025, 82/2050 and it is assumed to align to the Western Europe.

Case Study

Spain

Companies and authorities involved

Enagás, Iberdrola, Solvay.

Methodology approach for the economic assessment

The complete analysis has been done for the national case also regionals ones, considering same methodology. First of all, geological aspects have been analysed, thus, four regional cases were selected. For each one, hydrogen demand was calculated, taking into consideration three possible business cases: transport, industry and injection in the NG grid. Re-electrification does not make sense in the Spanish case due to high power overcapacity installed. In transport sector, medium consumption of 0.54 kg h2/100 km, 9 500 km/y and penetration by (%/year) 2.8/2025, 36/2050 were the parameters take into account. Sensitivity analysis was included in this case; therefore, cavern size, electrolyzer cost, electricity price and annual millage were varied. As the electricity price is the most representative value, surplus electricity (8/2025, 23/2050 (TWh/year)) and volatility were included in the calculation. Based on 2013 electricity prices and demand increase by 34% (2025, total: 331 TWh) and 45% (2050, total: 357 TWh) the average prices obtained (€/year) were 75 in 2025, 153 in 2050. Also it has been considered the electrolyzer operator pays pool electricity price, thus, the same values applies both for national and for regional cases.

Case Study

The United Kingdom

Companies and authorities involved

A number of industrial stakeholders were consulted on a confidential basis**.**

Methodology approach for the economic assessment

Future (2025/2050) renewable energy penetration has been estimated at a national level for a number of scenarios, based on a combination of the National Grid Future Energy Scenarios and DECC Pathways; corresponding possible energy storage requirements (2025/2050) have been identified based on these scenarios and other sources. The potential future (2025/2050) hydrogen market demand from mobility, industry, re-electrification and gas grid injection was estimated from public sources (e.g., UKH2Mobility) and consultation with industry stakeholders.

At a regional cavern location sites were studied from a geological (salt cavern location), market (proximity to current and potential future H2 demand) and infrastructure perspective (proximity to renewable energy sources and energy infrastructure). Three regions which are currently used for underground gas storage are also suited for addressing early hydrogen markets, but, all salt-bearing locations offer potential for hydrogen storage to meet future demand.

The cavern-specific business case development was built on a single project based approach for one prototype cavern. A number of electricity price scenarios were considered; for example APX market prices adjusted for inflation: €60/MWh and €100/MWh (2025 and 2050 respectively). Sensitivity analysis for the mobility business case, which appears the most promising based on potential allowable hydrogen prices, considered the variation of: cavern size (minor impact); electricity price (very high impact); electrolyser investment and usage levels (very high impact); and grid fees (high impact). Factors such as premium electricity pricing for grid balancing services, which would enhance the business case for re-electrification, were not considered within the scope of the project for compatibility across the case studies.