Sensitivity analysis of techno-economic assessment in WP5

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Authors:

Jan MICHALSKI, Christopher KUTZ[1]

[1] **Ludwig-Bölkow-Systemtechnik GmbH, Germany**

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Approved by:

Name	Institute	Date
Christopher KUTZ WP5 Leader	Ludwig-Bölkow-Systemtechnik GmbH	29.09.2022
Arnaud REVEILLERE Project Coordinator	Geostock	29.09.2022

TABLE OF CONTENT

1. Definitions

The following sensitivity analysis is based on the energy system modelling exercises from Task 5.5 (D5.5 "Major results of techno-economic assessment of future scenarios for deployment of underground renewable hydrogen storages"). It allows for testing the robustness of the modelling results in respect to predefined input parameters. Following input parameters have been identified in a close cooperation with the project's Advisory Board:

- **Availability of volume capacities for porous media:** different levels of geological potential for underground H_2 storage in porous media based on the results from Work Package (WP) 1 and 2 as limiting factor for developing new H_2 storage sites,
- **Storage efficiency for porous media:** different values for roundtrip efficiency of H_2 storage in porous media to examine the impact of microbiological activities,
- **Storage cost:** variation of overall storage cost taking into account both capital expenditures (CAPEX) calculated as annualised investment outlays and operating expenditures (OPEX) including variable and fixed operations and maintenance (O&M) cost such as energy or repair cost during a prototypical year separately for porous media storage and salt caverns,
- **Hydrogen transport cost:** different values for overall H_2 pipelines cost to account for uncertainties regarding the availability and cost of dedicated interconnectors for hydrogen between the grid nodes/countries within the system.

The first two parameters represent technical issues/constraints related to underground H_2 storage in porous media whereas the remaining ones test the impact of economic boundary conditions on optimal system design. For the sake of compatibility, all sensitivities are carried out for Scenario B in 2050, i.e., including salt caverns and porous media for a large-scale domestic renewable H_2 production in the long-term. To allow for unambiguous interpretation of the results, only the selected input parameters are varied within one sensitivity analysis while all other input values remain unchanged. Major output parameters used for the comparison of individual sensitivity analyses include expected volume and flow rate capacities for both salt caverns and porous media storage. The results are described and discussed in more detail in the next chapter.

2. Sensitivity analysis results

2.1. Availability of volume capacities for porous

According to the results from WP2, the geological potential for underground H_2 storage might be a limiting factor for the build-up of new storage facilities. As a default value, the analysis assumes a theoretical maximum of 12,000 TWh for porous media storage capacity in countries which might have suitable geological conditions (see also D5.4 for underlying assumptions and input data). This figure is orders of magnitude higher that what could be needed in any of the scenarios. Consequently, in the "Default Value" case, the porous media storage potential is not limiting except when geology is known to be unsuitable, i.e. in Cyprus, Estonia, Finland, Luxemburg, Malta, Portugal and Sweden. To challenge this assumption the sensitivity analysis in this chapter includes also in a first step the overall potential for onshore and offshore sites as estimated in WP2 ("WP2 capacity constraints (onshore & offshore)"). In the second step storage availability is further restricted by excluding all offshore sites and limiting the model run only to onshore sites provided by WP2 ("WP2 capacity constraints (onshore only)"), as offshore storage facilities might become challenging for technical realisation and thus comparatively expensive.

The results of the sensitivity analysis reveals that the estimated geological potential for hydrogen storage in porous media has a very limited effect on overall system level of EU27&UK with almost constant value for the overall storage capacities (Figure 1).

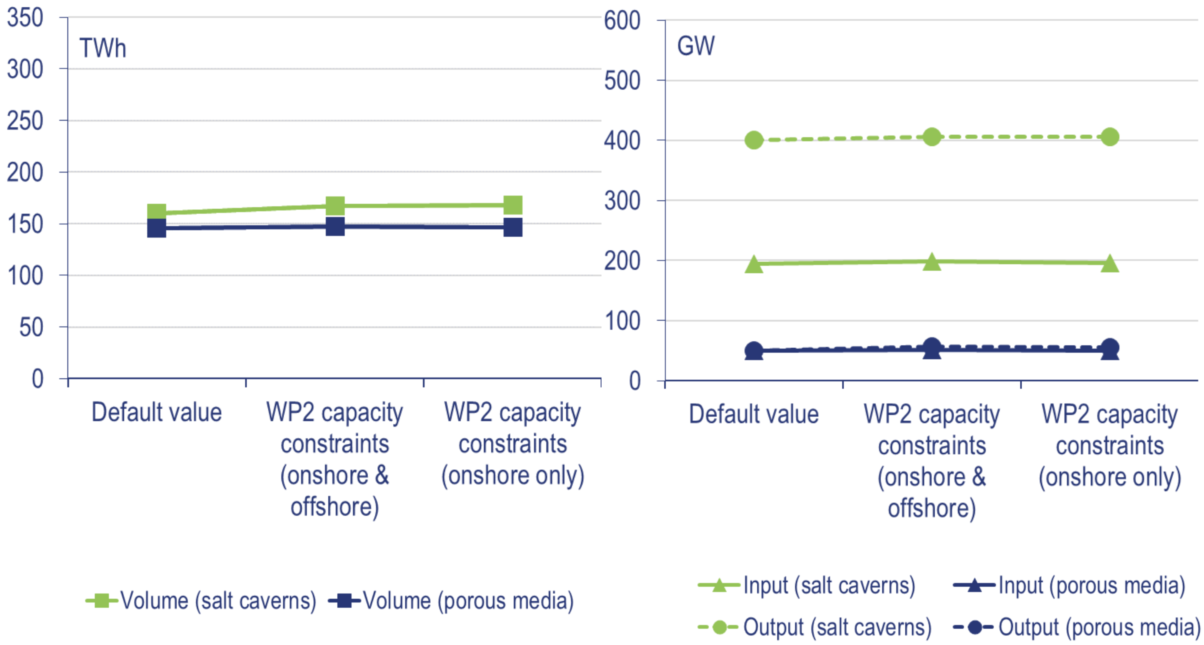

Figure 1: Volume capacity (left) and flowrate capacity (right) for underground H_2 storage based on different levels of availability of porous media capacities

The main reason is that with constraining the storage potential for porous media storages in all Member States, a reallocation of storage capacity in salt caverns and storage media can be observed. Figure 2 and Figure 3 show the country-specific volume capacities for salt caverns and porous media, respectively, for the different cases. One key result is that imposing country-specific capacity constraints, porous media storage capacity is significantly reduced in Italy and – to a lower extent – in Czech Republic, while additional capacities in porous media are used in France and Germany. In addition, significant reallocations in salt cavern volumes are observed in France, Germany, the Netherlands, Spain and UK. In contrast to that, nearly no effect can be observed when only onshore storage potentials for porous media are allowed, indicating that onshore storage potentials are sufficient.

In addition, further impact of limited storage capacities in porous media can be summarized as follows: also it also leads to slightly higher electrolysis capacities and stronger focus on domestic green hydrogen supply, i.e., H_2 production via domestic electrolysis increases and the amount of hydrogen imported from outside the EU decreases. In this context, the system requires larger intermittent power supply from domestic wind and solar. Although the installed capacity of H_2 gas turbines remains unchanged to balance out short-term fluctuations from wind and solar, the overall power generation from hydrogen (H_2 re-electrification) goes down as intermittent feed-in profiles complement each other and reduce the energy demand from other sources.

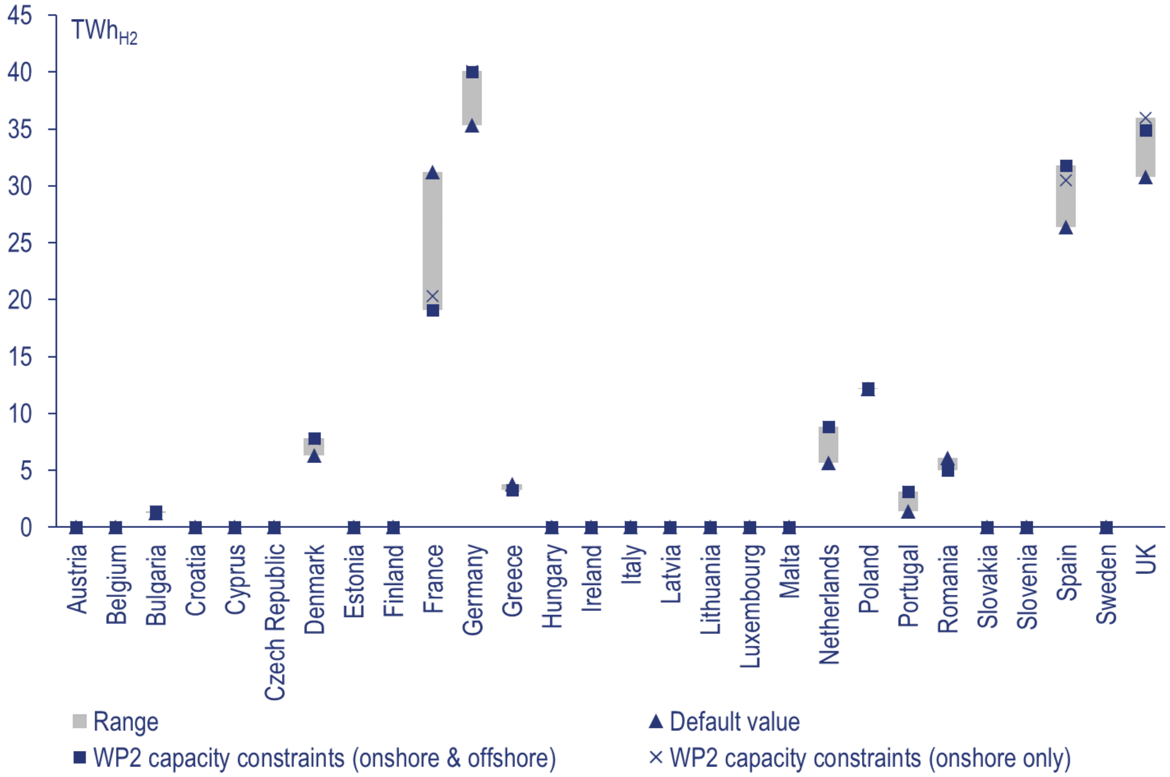

Figure 2: Country-specific optimal volume capacity for salt caverns in scenarios with different capacity constraints for porous media

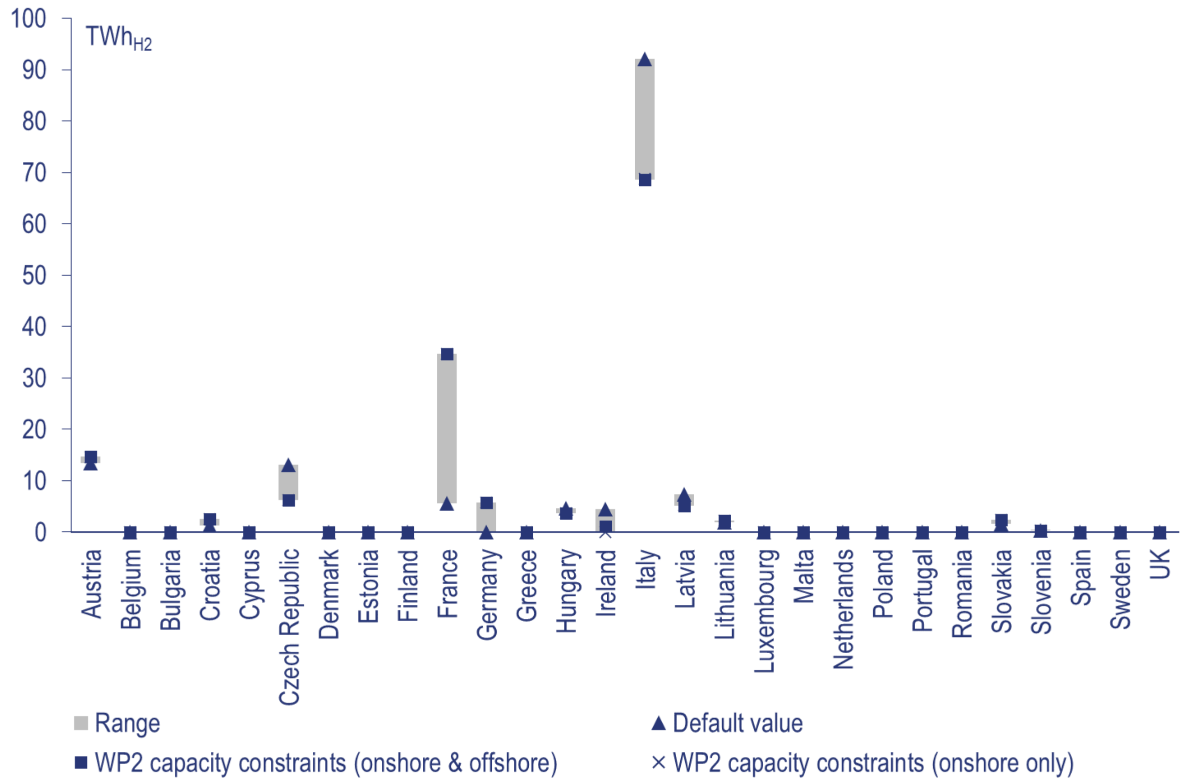

Figure 3: Country-specific optimal volume capacity for porous media in scenarios with different capacity constraints for porous media

The sensitivities show nearly no impact of limiting porous media storage capacities from onshore & offshore to onshore only. The main reason is that, although the overall capacity constraints for EU27+UK decreases from 18,737 TWh to 7,362 TWh, these limitations are still way above the actual capacities installed (145.7 to 147.5 TWh). In total, there are only three countries, where optimal volume capacities are reduced compared to the reference case ("Default value") where no effective limit is in place: Czech Republic, Ireland and Italy (see Figure 10).

In general, however, some sensitivity results for storage capacities show the complex relationships between the different parameters. On the one hand, there is a non-linear country-specific potential which in some cases is large enough and has no impact on optimal storage size. On the other hand, the optimal energy exchange between countries and thus local storage needs depend on a complex cost trade-off between different energy supply and transport technologies which can substitute each other. Hence, in some cases the model makes disrupted decisions based on country-specific supply and demand trajectories and grid topologies.

2.2. Storage efficiency for porous media

Another important parameter for optimal design of H_2 storage in porous media is its efficiency. The capability to store hydrogen and thus efficiency strongly depends on site-specific conditions related to microbiological activities (see also WP4). To test the impact of this uncertainty, the storage output efficiency in porous media is varied as follows: 95%, 98.5% (default) and 100% (see Figure 4).

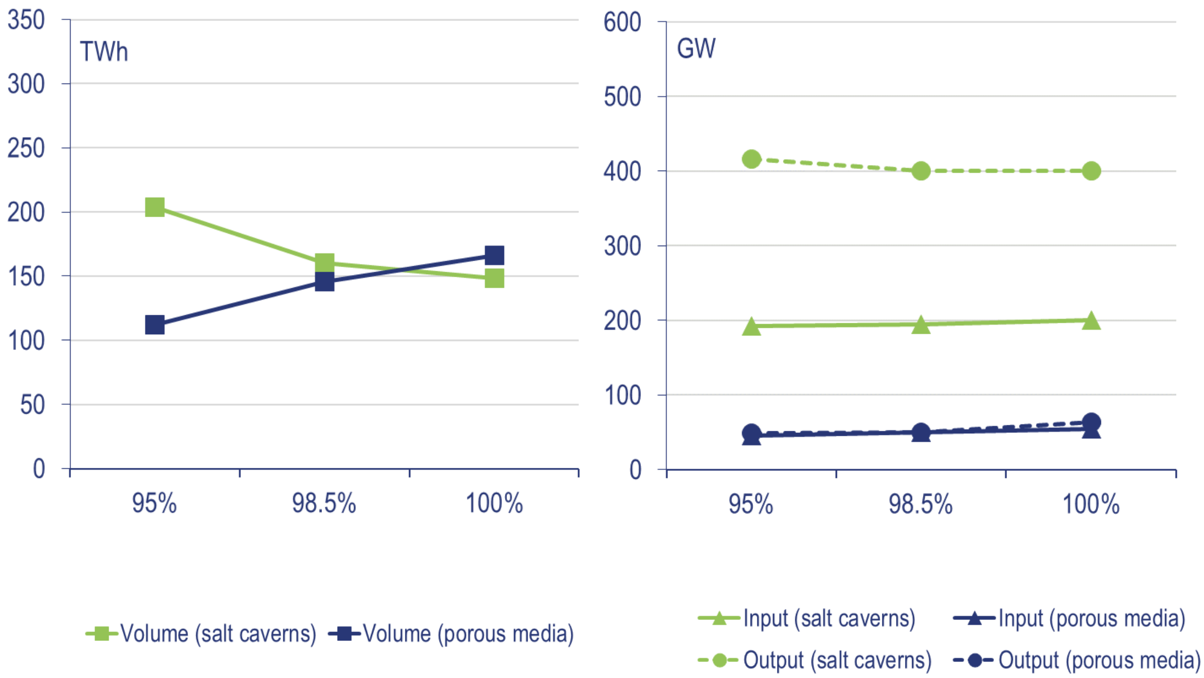

Figure 4: Volume capacity (left) and flowrate capacity (right) for underground H_2 storage based on different levels of efficiency for porous media storage

The higher the efficiency of porous media storage the more cost-competitive the technology and, hence, the higher the installed capacities. The volume capacity varies significantly between 110 TWh (95% efficiency) and 170 TWh (100% efficiency) on EU27+UK level, whereas only slight changes can be observed for the flow rate capacities. This is due to the fact that while the efficiency indirectly affects the volume-related storage cost (the lower the ratio between storage input and output, the higher the cost will be), it has no impact on the injection and withdrawal cost. Hence, the flow rate capacities for injection (input) and withdrawal (output) still follow the same system requirements having an adequate impact on the optimal storage design (e.g. in respect to volume to flow rate ratio) and on the optional way of operation (e.g. in terms of full cycle equivalents per year). In contrast, the volume capacities of salt caverns decrease strongly with rising efficiency of the porous media technology within a range of 150 TWh (95% efficiency) and 200 TWh (100% efficiency) such that the overall volume capacity of underground H_2 storage remains at a comparable level. Interestingly for salt caverns, decreasing volume capacities are accompanied by slightly increasing input flow rate capacities as salt caverns are utilised more frequently to buffer also short-term fluctuations in H_2 supply and demand.

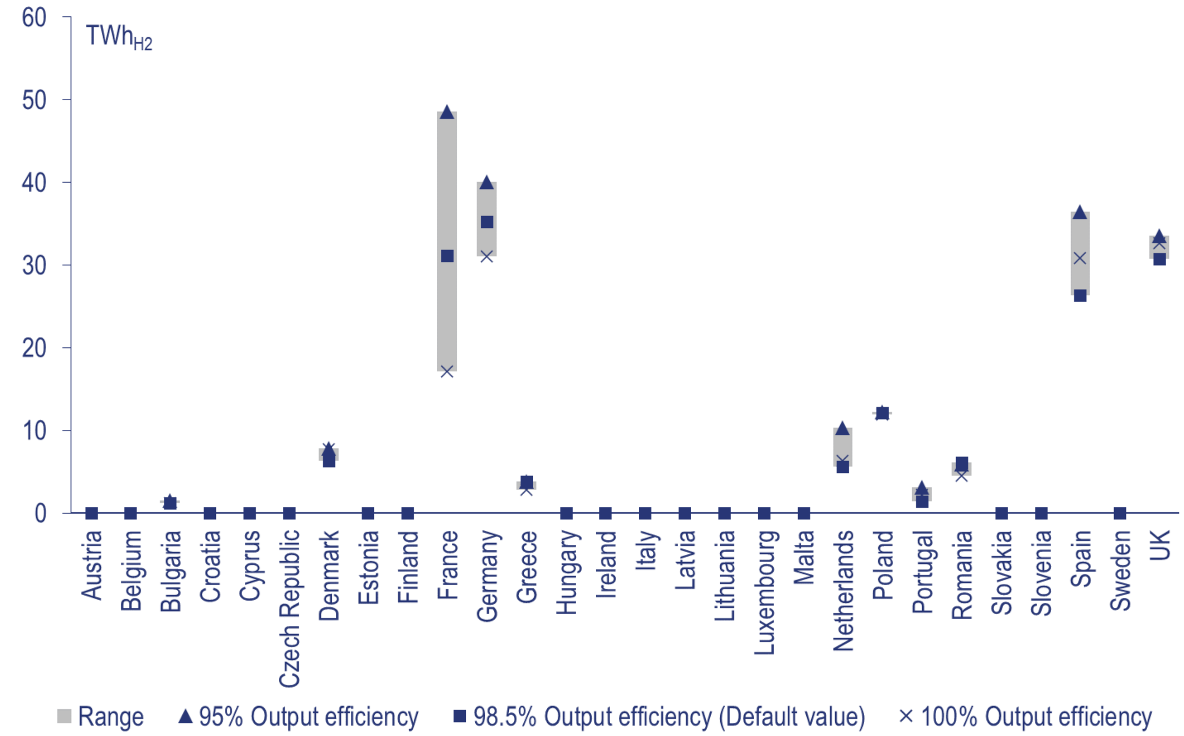

Figure 5: Country-specific optimal volume capacity for salt caverns in scenarios with different levels of output efficiency for porous media

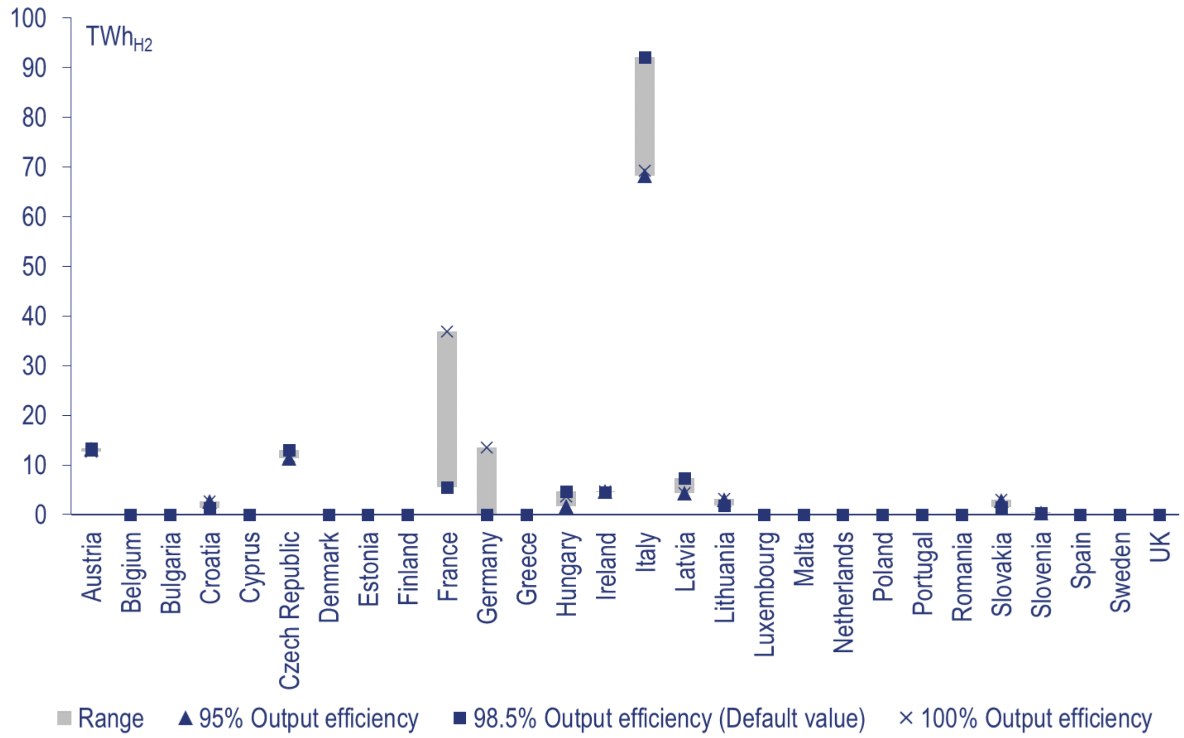

Figure 6: Country-specific optimal volume capacity for porous media in scenarios with different levels of output efficiency for porous media

A detailed look on country level reveals, where the main reallocations are performed in the optimal model solution. The results for salt cavern and porous media capacities are shown in Figure 5 and Figure 6, respectively. In general, two trends can be observed. Increasing the output efficiency for hydrogen storage in porous media from 98.5% to 100% leads to a partly reallocation of storage capacities for porous media from Italy to France and Germany (see Figure 6). At the same time, storage capacities in salt caverns decrease in those two countries. Due to the increased competitiveness of storage media, those countries where both storage technologies directly compete are the main drivers for any reallocations. Conversely, when the storage output efficiency is decreased to 95%, additional salt cavern capacity is needed, mainly located in France and Germany.

2.3. Storage cost

Storage cost is a crucial parameter for investment decision in new underground storage capacities. However, it is also a rather uncertain parameter as the actual storage cost strongly depend on site-specific conditions. Therefore, Figure 7 and Figure 8 illustrate the results from a sensitivity analysis of the overall storage cost for porous media storage and for salt caverns, respectively. In this context the default values for storage cost including CAPEX (i.e., initial investment cost) as well as OPEX (i.e., fixed cost and variable cost) for both volume and flow rate capacities are multiplied by following factors 50% (low storage cost), 100% (default value) and 150% (high storage cost).

The analysis reveals strong sensitivity of installed capacities in respect to storage cost. As salt cavern and porous media technologies are competing the increase in cost of one technology leads to capacity reduction of the affected technology and capacity growth of the other technology. In case of variation of storage cost for porous media the volume capacities vary between 40-270 TWh and 90-260 TWh for porous media and salt cavern, respectively. In case of variations of cost for salt caverns the ranges are similar with 40-210 TWh for porous media and 100-300 TWh for salt caverns. As a rule of thumbs a 50% increase (decrease) of storage costs translates into ca. 50% reduction (growth) of affected technology and ca. 50% growth (reduction) of the competing technology. Nevertheless, the cumulative volume capacity is slightly larger for low storage cost (i.e. at 50% of default values): 350 TWh for variation of porous media cost and 340 TWh for variation of salt cavern cost. The additional storage capacities are helpful to balance out renewable energy supply and demand and decrease overall system cost. However, for greater storage cost (i.e. at 150% of default values) the cumulative volume capacity remains almost unchanged at ca. 310 TWh for both sensitivities. This indicates that there is no room for further reduction of cumulative volume capacities due to physical requirements of the underlying energy system. Hence, increasing storage cost are directly translated into higher total system cost.

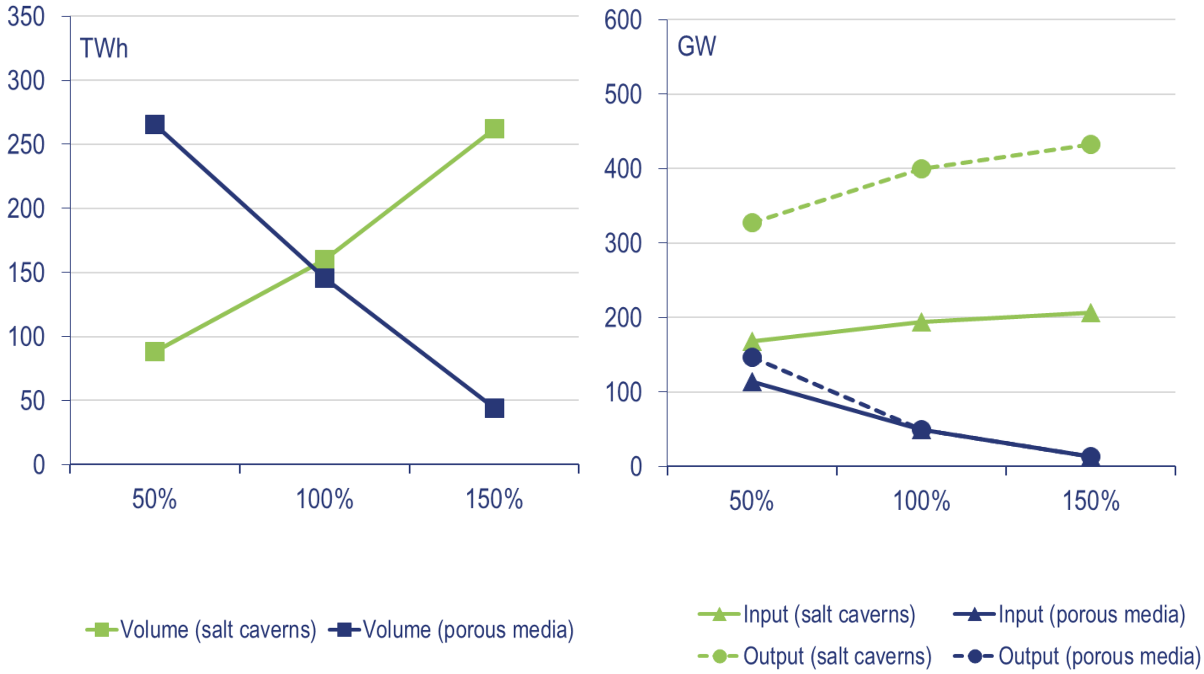

Figure 7: Volume capacity (left) and flowrate capacity (right) for underground H_2 storage based on different levels of technology cost of porous media storage

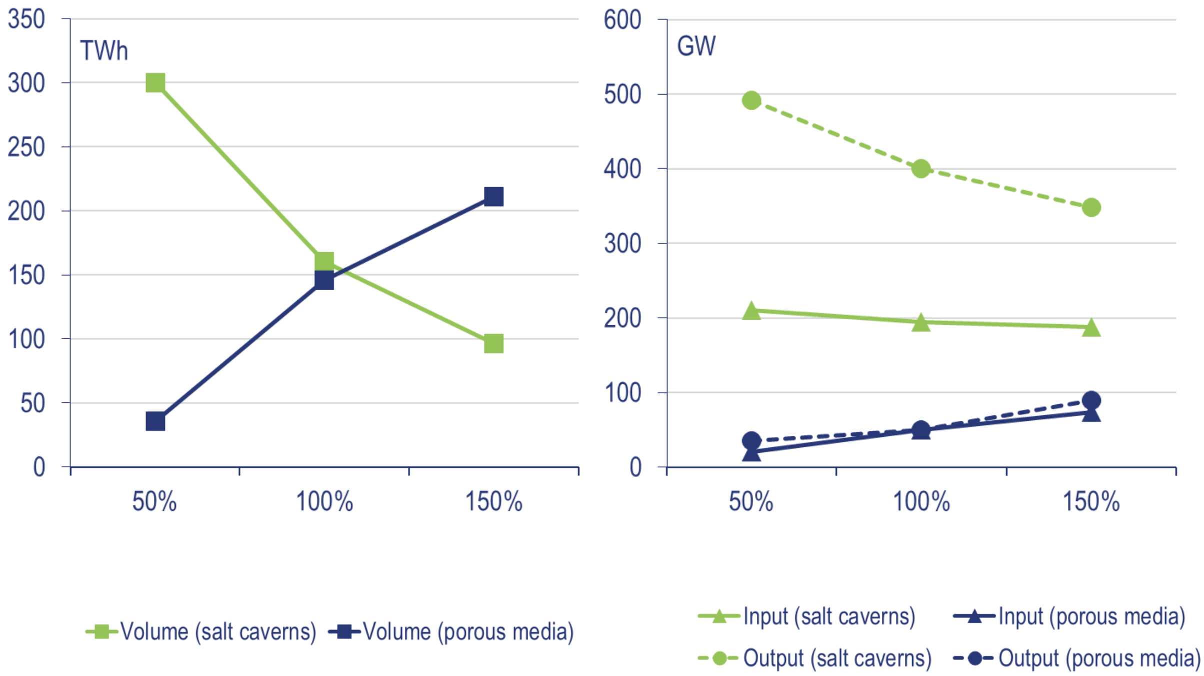

Figure 8: Volume capacity (left) and flowrate capacity (right) for underground H_2 storage based on different levels of technology cost of salt caverns

The flow rate capacities change with the same pattern as volume capacities. The lower the technology cost the higher the corresponding flow rate capacity of the affected technology and vice versa. However, salt caverns are characterised by limited sensitivity between flow rate capacity and storage costs. This means that a 50% decrease (increase) of storage costs for salt caverns (porous media) results in a much smaller change in flow rate capacities of salt caverns. It indicates that the ability of salt caverns to inject and withdraw large quantities of hydrogen in a short time remains an important measure for system flexibility in all cases. In other words, there is only limited possibility/need to reduce/increase the corresponding capacities due to the physical constrains of the underlying energy system. The change in spatial distribution of the storage capacities (both volume and flow rate capacities for both technologies) is non-linear as it depends on a complex cost trade-off between different system elements including individual power plants, electrolysis capacities, power lines, hydrogen pipelines.

On country-level, the observed results are similar compared to the reallocation effects described in chapter 2.2: Main changes are seen in France and Germany, but also e.g. Spain where hydrogen storage in salt caverns directly competes with porous media. Here, the increase in technology costs for one technology results in a decrease of storage capacities in that country which is compensated by higher deployment of the other technology. On special situation is observed for Italy, where only porous media storages are present and the need for storage media capacities largely depends on the installed capacities in France and Germany. The storage volumes for both storage technologies for variations in technology-specific costs can be found in the Appendix (Figure 11 and Figure 12 for variation in technology costs for storage in porous media and Figure 13 and Figure 14 for variation in technology costs for salt cavern storage).

2.4. Hydrogen transport cost

The possibility to transport hydrogen from one node to another in an economic way has also an impact on optimal H_2 storage design. To account for this parameter the overall cost of H_2 pipelines is varied by multiplying the default values by following factors: 75%, 100%, 125%, 150% (default in Scenario B), 175% and 200%.

However, according to analysis results the overall impact of H_2 transport cost on storage capacities and technology mix is very limited and ambiguous – at least on the system level for EU27+UK. As expected, high transport cost reduce overall H_2 flows and pipeline capacities between the grid nodes. Moreover, hydrogen transport is also used more efficiently at higher utilisation rates.

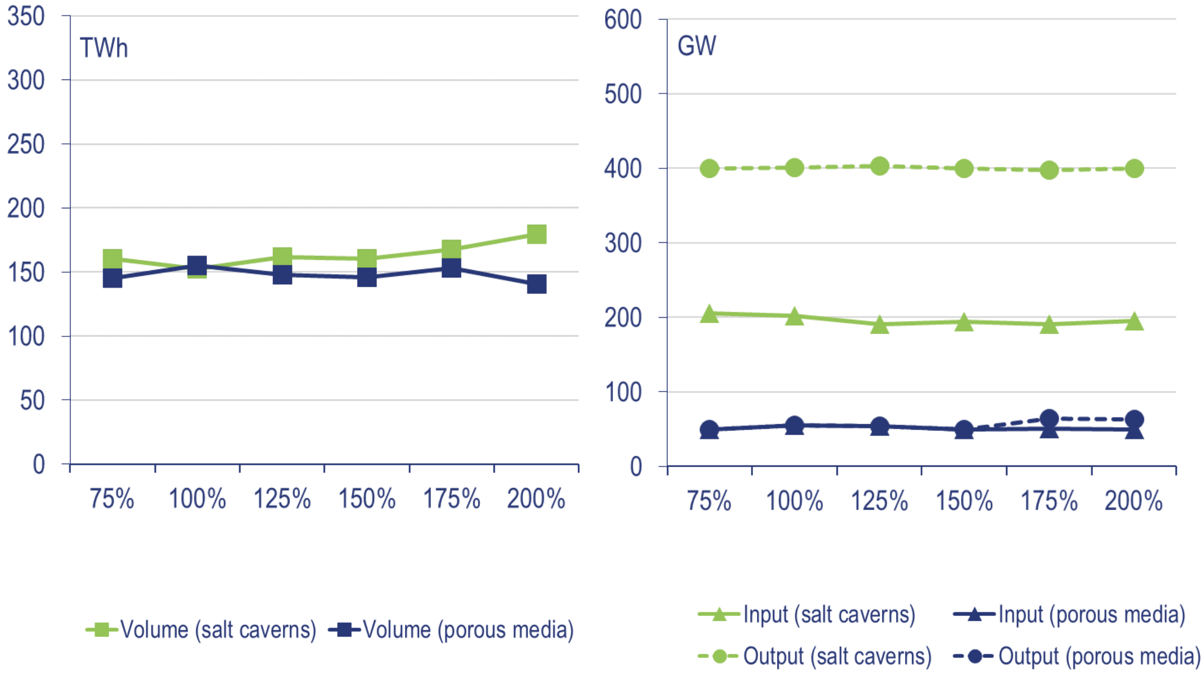

Figure 9: Volume capacity (left) and flowrate capacity (right) for underground H_2 storage based on different levels of H_2 pipeline cost

As a more general observation, the cumulative volume capacities and withdrawal flow rate capacities are larger for high transport cost to compensate the reduced energy exchange between the nodes by additional local storage services. However, for cumulative injection flow rate capacity the opposite is true. This is due to a more distributed electrolysis production and limited renewables peakshaving and H_2 export from countries with large and cheap intermittent power sources. In addition, under the assumptions of scenario B salt caverns tend to be more favourable in comparison to porous media and have slightly higher volume capacities ranging between 160 TWh (lowest H_2 transport cost) and 180 TWh (highest H_2 transport cost). The volume capacity for porous media slightly decreases from 145 TWh (lowest H_2 transport cost) to 141 TWh (highest H_2 transport cost).

The high complexity of the impact of storage costs on optimal storage capacities in each node (e.g. country) is underlined by the country-specific results in the Appendix (Figure 15 and Figure 16). Depending on the actual transport costs, high changes in optimal installed storage volumes is observed for selected countries. While storage costs mainly change optimal capacities of salt caverns in France, Germany, the Netherlands and Spain, the impact on porous media capacities is dominant in France, Ireland and Italy. There is, however, no linear trend to be observed for most of the countries, indicating complex interdependencies caused by different trade-offs.

3. Appendix

Appendix to 2.1: Impact of availability of porous media capacities

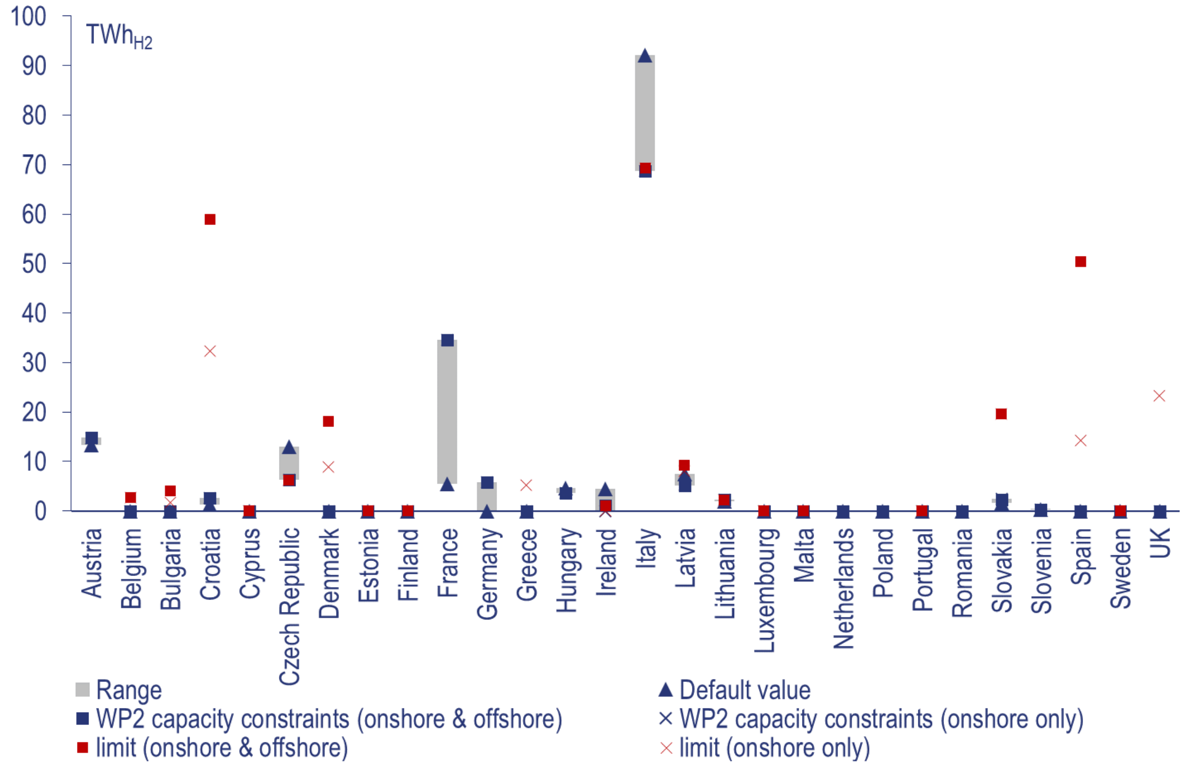

Figure 10: Country-specific optimal volume capacity for porous media in scenarios with different capacity constraints for porous media. In red: capacity constraints for different scenarios.

Appendix to 2.3.1: Variation in technology costs for porous media hydrogen storage

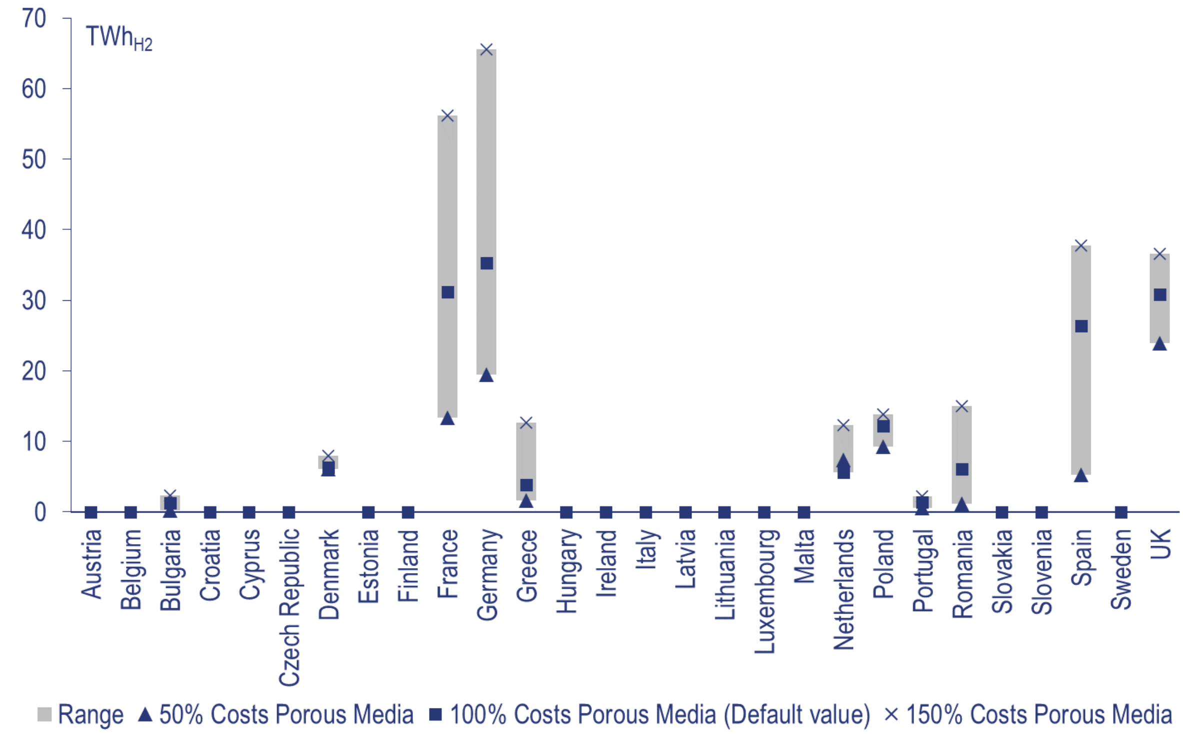

Figure 11: Country-specific volume capacities for salt caverns based on different levels of technology cost of porous media

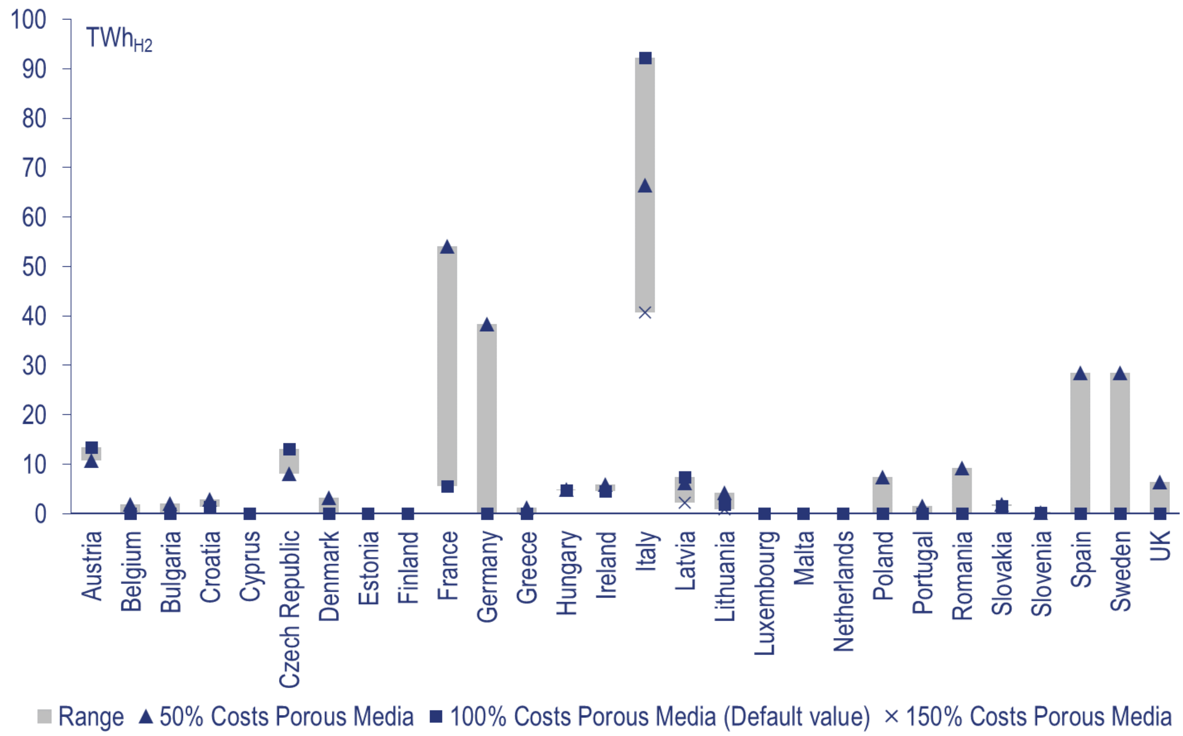

Figure 12: Country-specific volume capacities for porous media based on different levels of technology cost of porous media

Appendix to 2.3.2: Variation in technology costs for hydrogen storage in salt caverns

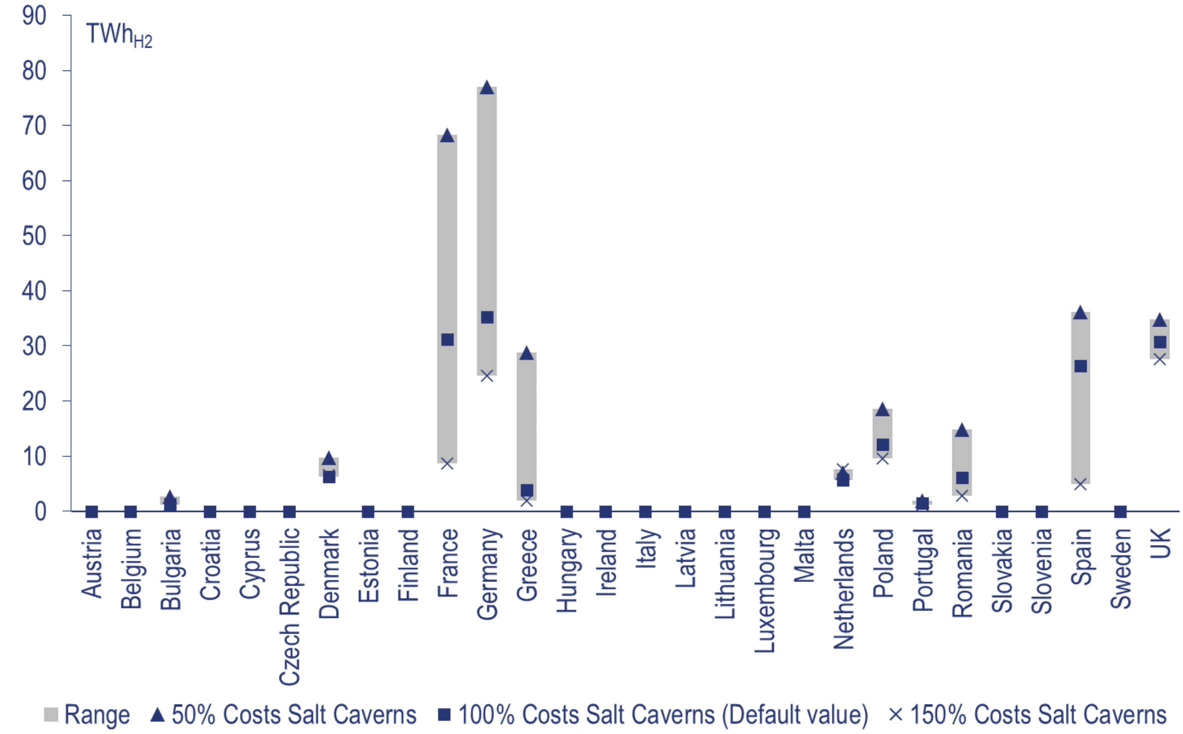

Figure 13: Country-specific volume capacities for salt caverns based on different levels of technology cost of salt caverns

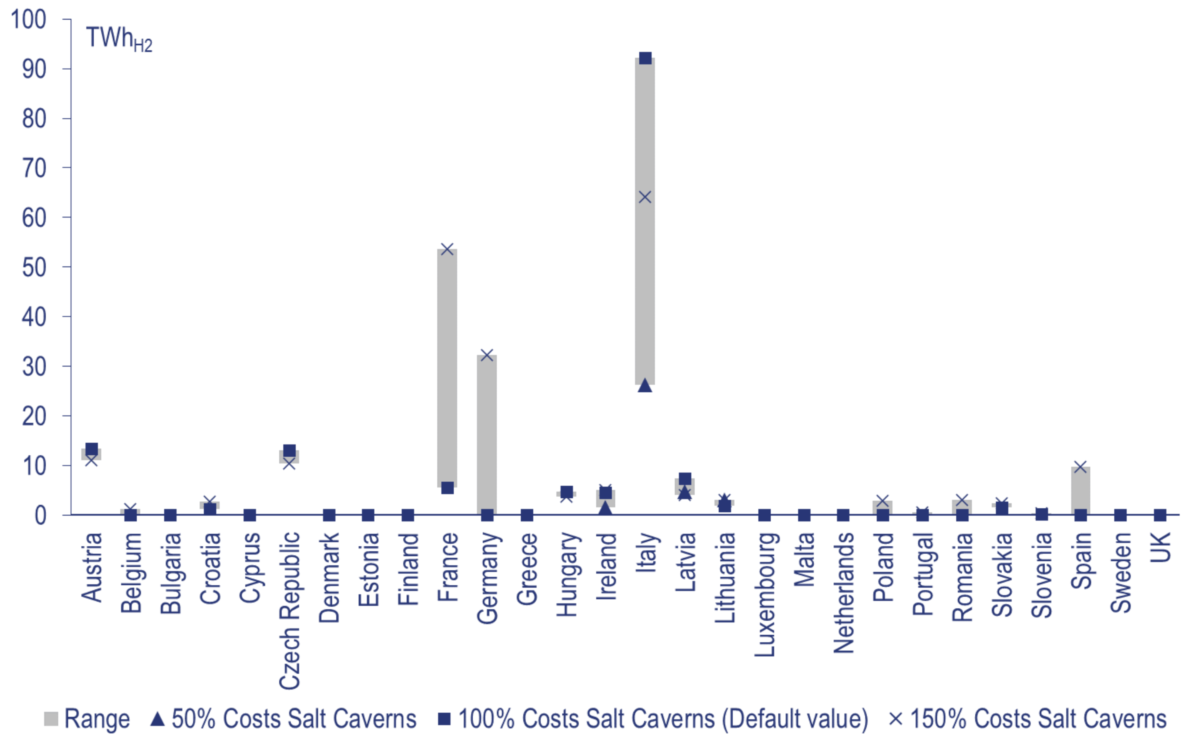

Figure 14: Country-specific volume capacities for porous media based on different levels of technology cost of salt caverns

Appendix to 2.4: Variation in technology costs for different levels of H_2 pipeline cost

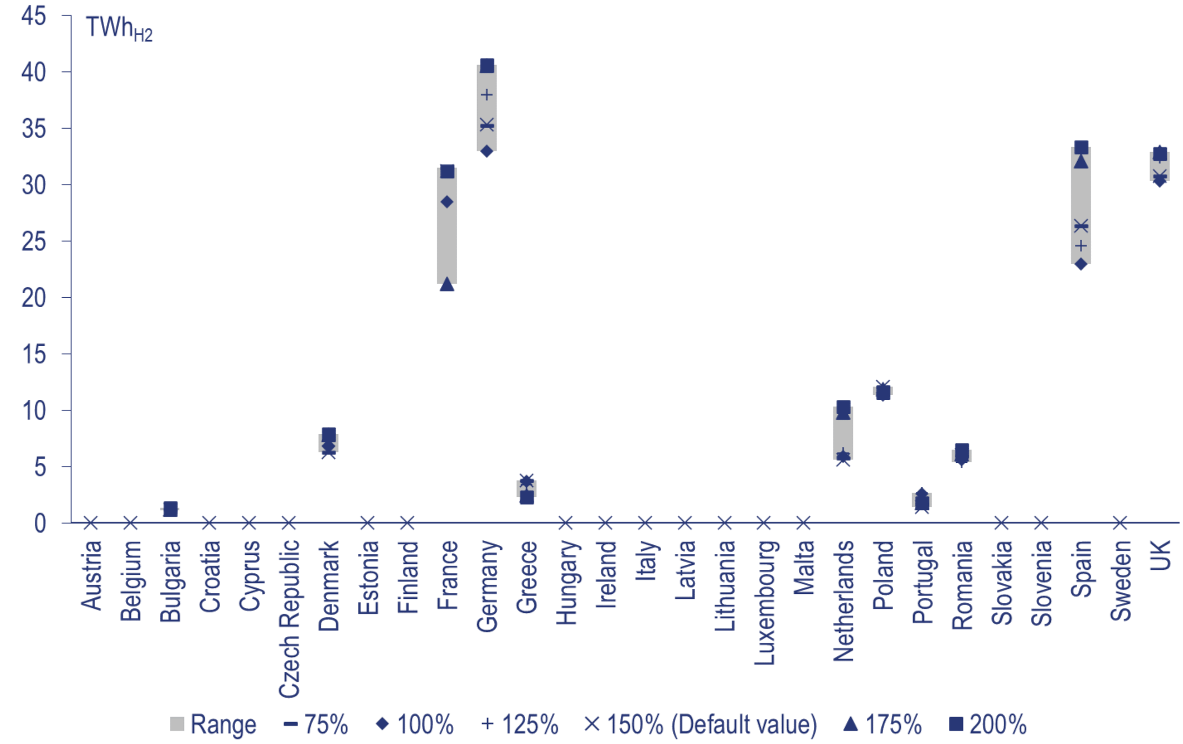

Figure 15: Volume capacity for salt caverns based on different levels of H_2 pipeline cost

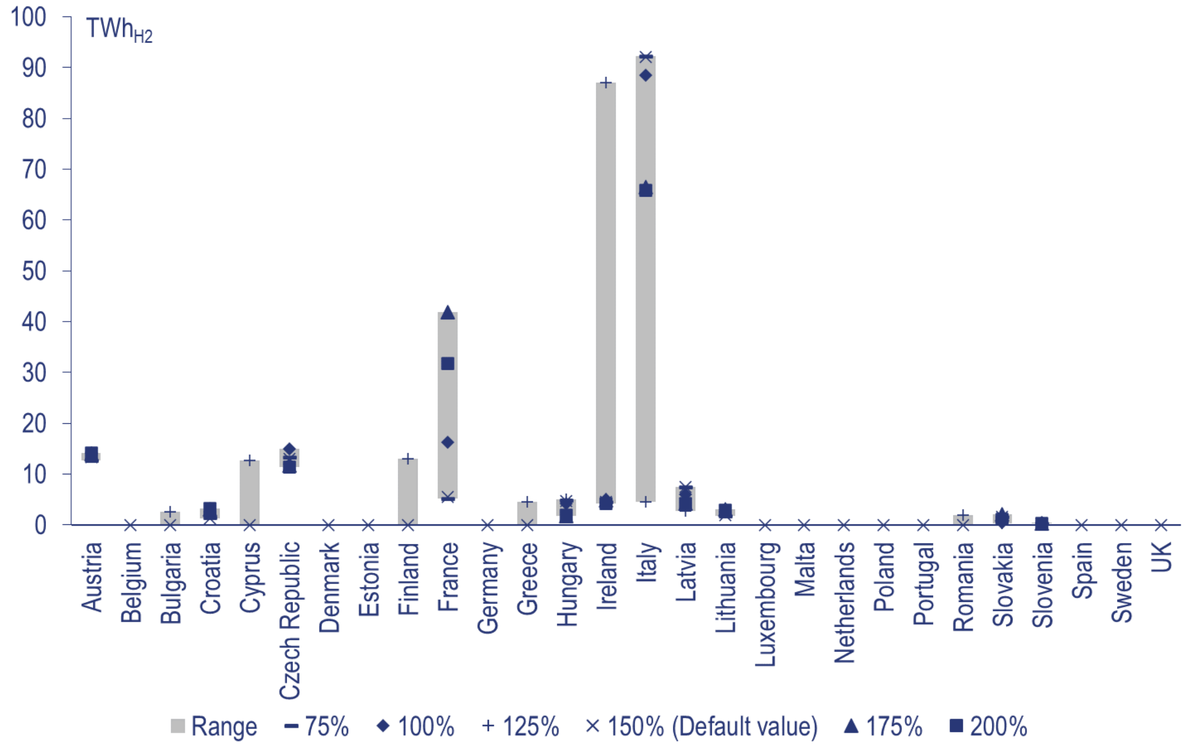

Figure 16: Volume capacity for porous media based on different levels of H_2 pipeline cost

4. Abbreviations

CAPEX	Capital expenditures
EU	European Union
H_2	Hydrogen
O&M	Operation and maintenance
OPEX	Operating expenditures
UK	United Kingdom
WP	Work Package

Hystories project consortium

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