Major results of techno-economic assessment of future scenarios for deployment of underground renewable hydrogen storages

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Revision History

Revision	Revision date	Summary of changes
0	23.05.2022	Initial version
1	01.09.2022	Country-specific results were added in Appendix 7.2 and 7.3.
2	28.09.2022	Additional country-specific data for key parameters for all scenarios added as Appendix 7.4.

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1. Introduction

This deliverable documents main results of the energy system modelling exercise in WP5. Building upon the assumptions and input data from Task 5.4 (D5.4 “Assumptions and input parameters for modelling of the European energy system”) the model as adapted and described in Task 5.3 (D5.3 “European energy system model description”) provides the outcomes for the four scenarios as defined in Task 5.1 (D5.1 “Scenario definition for modelling of the European energy system”). As a reminder, following scenarios are considered for the detailed analysis:

- **Scenario A:** mainly domestic H_2 production with limited H_2 imports from outside the EU taking only salt caverns for underground H_2 storage into account.
- **Scenario B:** as Scenario A but additionally including porous media for H_2 storage.
- **Scenario C:** smaller share of domestic H_2 production in comparison to Scenarios A and B and therefore with larger share of H_2 imports to Europe. As in Scenario A, only salt caverns for underground H_2 storage are taken into account.
- **Scenario D:** like scenario C but including porous media storage.

For the sake of comparability, all scenarios assume same hydrogen and power end user consumption as well as CO_2 emission caps. The calculations are carried out for the time horizons in 2030, 2040 and 2050. One model run is carried out for Scenario A in 2025 to provide the results also for a short-term scenario as a reference. The geographical scope focuses on EU-27 and the UK as a large economy directly connected to the European energy system. In this context each country is represented by one node within the power and hydrogen grids. Additional countries such as Switzerland, Western Balkan, Norway, Ukraine etc. are included in a simplified way, i.e., mainly only as an additional node in the grid without dedicated power or hydrogen production and consumption. The modelling exercise is carried on an hourly basis for one prototypical weather year (see also model description in D5.3).

The remaining of the deliverable is structured as follows. Chapter 2 describes the optimal design for power and hydrogen supply. Chapter 3 focuses on underground hydrogen storage providing the results on required storage capacities and H_2 infrastructure needs as well as corresponding optimal way of operation. Chapter 4 describes expected energy transport infrastructure in more detail. Economic and environmental evaluation is included in Chapter 5. Finally, Chapter 6 draws overarching conclusion.

2. Expected structure of energy supply

2.1. Optimal power supply in EU27 & UK

In the following, key elements of the overall power supply and demand as well as the installed capacity by technology are described. The optimal power supply follows in general the assumed power and H_2 consumption.[1] According to the analysis results, the power supply für EU27 & UK increases from ca. 3,000 TWh/a in 2025 to 5,600-6,300 TWh/a by 2050. The differences in the overall power consumption and supply between the scenarios A to D are caused by different shares of domestic H_2 production via electrolysis. In all scenarios, electrolysis is responsible for more than 25% of the total power consumption by 2050 (see Figure 1, lower graph). Since scenarios C and D assume larger H_2 imports from outside the EU and therefore less domestic H_2 production, the overall power demand and consequently also the power supply is lower than in scenarios A and B. Energy losses due to power storage are negligible with less than 1% of total power supply.

The overall structure of power supply in terms of technology split is similar among the analysed scenarios (see Figure 1, upper graph). Intermittent renewable power supply from wind onshore, wind offshore and photovoltaics/solar (PV) is the major primary source in the future power system with ca. 2,000 TWh/a by 2030 and 4,300-5,000 TWh/a by 2050. Its share increases from less than 40% in 2025 to more than 75% in 2050. Among the renewable power supply, wind onshore and PV play the major role as the most cost-competitive technologies. Power production from run-of-river power plants (“hydro”) remains at a constant level of ca. 380 TWh/a (6%-12% of total power supply) among all scenario and time steps.

Nuclear power plants represent baseload supply with more than 7,000 operating hours per year (Table 1) also in the long-term as a dispatchable CO_2-free technology. However, according to the scenario assumptions the overall installed nuclear capacities decrease slightly from 80 GW in 2025 down to 70 GW in 2050 (Figure 2) and, hence, the corresponding power production is also falling from 700 TWh/a or 20% of total supply by 2025/2030 to ca. 550 TWh/a or 10% by 2050. Similarly, biofuel power plants can be considered as a base to medium load technology operated at 5,000-8,000 h/a. With constant installed capacities of 40 GW the technology plays only limited role in the power system providing 200-300 TWh/a (or 3%-8% of total supply).

In contrast, gas-fired power plants (methane and hydrogen) are one of the major pillars for system stability in all scenarios and time steps. With a constant overall installed capacity of 170-230 GW they are responsible for 40%-70% of the overall dispatchable capacities substantially contributing to system flexibility. In the short- to medium-term (i.e., 2025 to 2040) most gas-fired power plant are based on methane typically from fossil sources as the overall CO_2-emssion caps still allow for some power production from clean sources such natural gas. Within this timeframe, power production from natural gas accounts for ca.

[1] See D5.4 “Assumptions and input parameters for modelling of the European energy system”

150 TWh/a (2040) to 500 TWh/a (2025) or 3% (2040) to 16% (2025) of total power supply whereas H_2-based power supply is very limited. In the long-term (i.e., after 2040), however, natural gas cannot be used for power production due climate neutrality target. Hence, only gas turbines based on renewable hydrogen provide electricity of ca. 100-200 TWh/a required to balance out intermittent power plants.

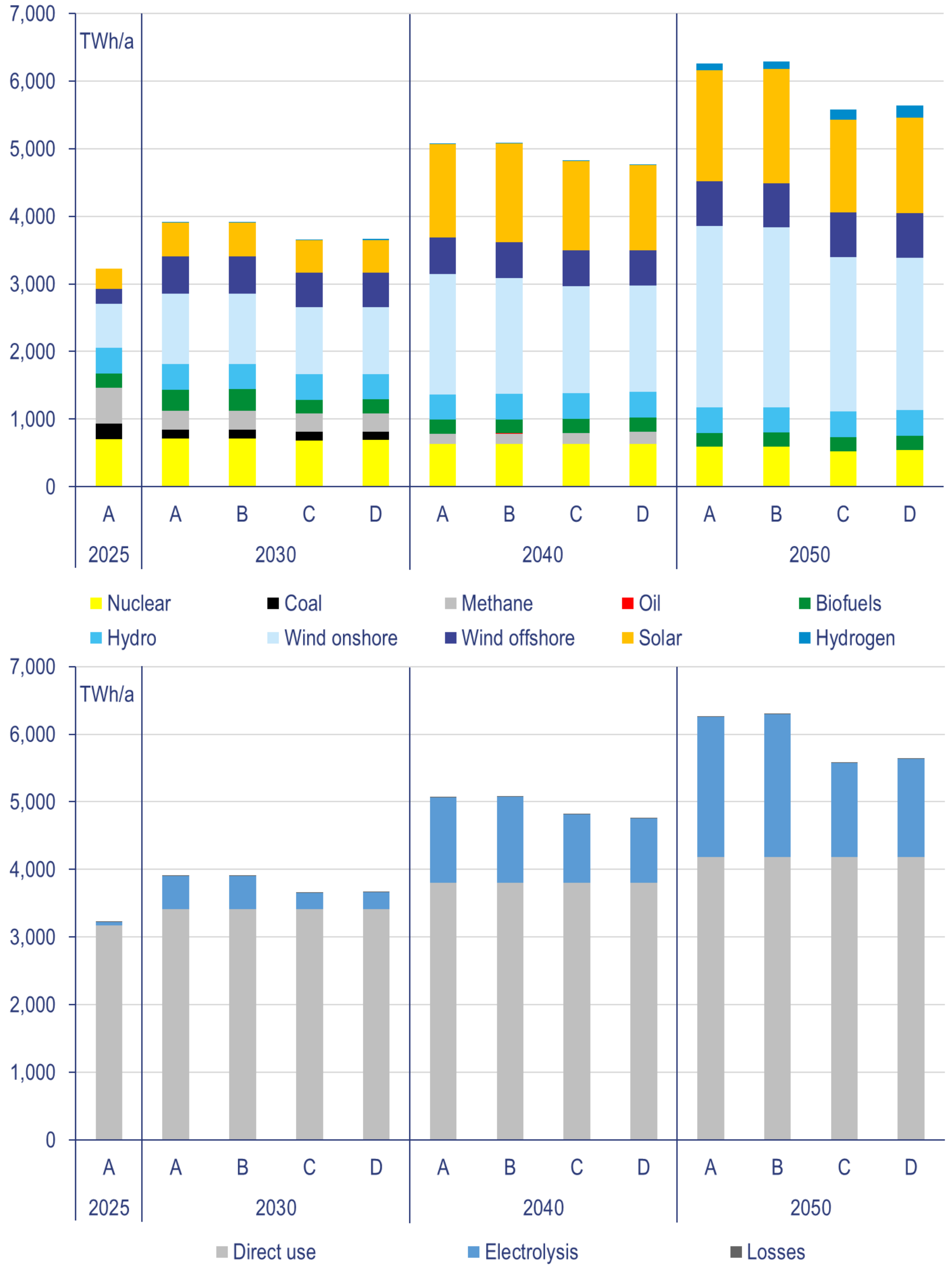


Figure 1: Power supply (top) and use (bottom) in EU-27 & UK in selected scenarios

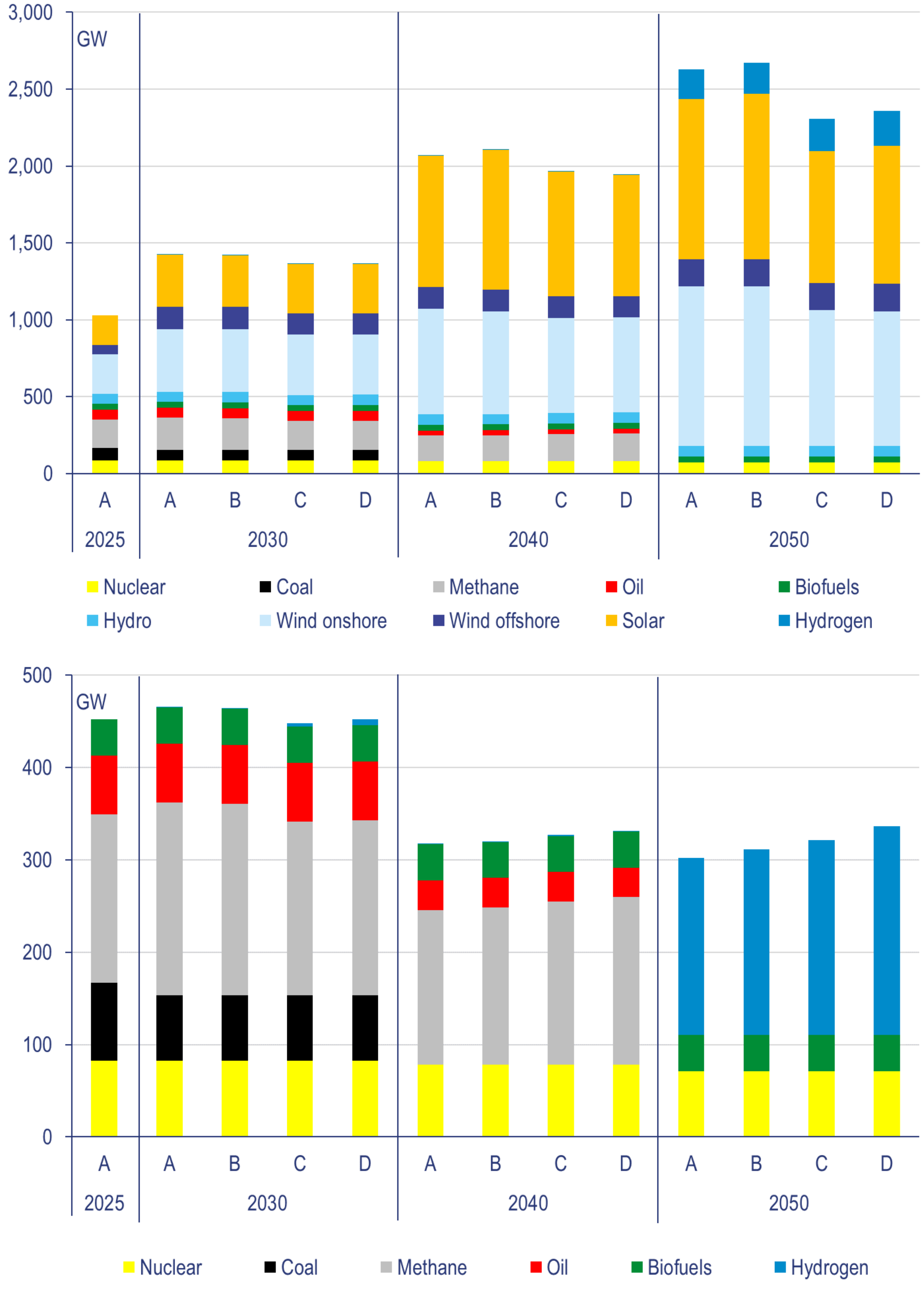


Figure 2: Total installed power plant capacities (top) and dispatchable power plant capacities (bottom) in EU-27 & UK in selected scenarios

It has to be noted, that in scenarios with porous media storage (scenario B and D) the production and capacities in 2040 and 2050 are higher in comparison to their counterparts without porous media (scenario A and C, respectively). This is caused by the higher amount of local energy production and use. Moreover, larger H_2 imports (scenario C and D) require higher gas-fired capacities and, consequently, higher dispatchable power plant capacities due to limited compensation potential between different intermittent technologies. As a peakload technology, the corresponding utilisation rate of gas-fired power plants is comparatively low with ca. 3,000 h/a in the short-term decreasing to less than 1,000 h/a by 2040 and 2050.

Other dispatchable technologies include coal and oil-fired power plants. As an energy carrier with comparatively high specific CO_2-emissions, coal is gradually being phased out until 2040 with ca. 230 TWh/a of produced electricity or less than 10% of total power supply in 2025 and ca. 120 TWh/a or less than 5% by 2030. Interestingly, the utilisation rates are also relatively low with 2,000-3,000 h/a. This indicates the limited role of coal power plants in the future energy system with increasing share of renewable energy. The contribution of oil power plants to power supply is negligible due to its comparatively high variable cost and specific CO_2 emission.

Table 1 summarizes the average utilisation of different power supply technologies for EU27 & UK as a result of the modelling exercise.

Table 1: Average utilisation of power supply units in EU-27 & UK in selected scenarios (full load hours)

	2025	2030				2040				2050			
Scenario	**A**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
Nuclear	8,498	8,694	8,695	8,343	8,375	8,102	8,142	8,064	8,104	8,312	8,360	7,406	7,666
Coal	2,785	1,761	1,763	1,772	1,773								
Methane	2,911	1,358	1,372	1,425	1,409	889	887	930	991				
Oil						62	60	62	61				
Biofuels	5,256	7,994	7,989	5,280	5,282	5,283	5,283	5,284	5,285	5,299	5,298	5,301	5,297
Hydro	5,685	5,688	5,689	5,681	5,680	5,670	5,672	5,668	5,671	5,665	5,672	5,661	5,663
Onshore wind	2,535	2,547	2,548	2,533	2,533	2,594	2,559	2,562	2,557	2,577	2,549	2,587	2,572
Offshore wind	3,727	3,754	3,753	3,712	3,713	3,725	3,725	3,720	3,723	3,728	3,740	3,726	3,733
Solar	1,526	1,488	1,488	1,487	1,487	1,624	1,610	1,628	1,595	1,577	1,572	1,602	1,566
H_2 turbines		599	3,199	3,033	3,428	370	146	285	146	496	556	705	800

Figure 3 depicts curtailment of intermittent power supply in EU-27 & UK. In 2025 as well as for Scenarios A and B in 2030 renewable energy curtailment is very limited at ca. 1 TWh/a, indicating an efficient use of intermittent power plants. In scenarios B and D with larger share of cheap hydrogen imports from outside the EU, however, the required curtailment is already ca. 7 TWh/a in 2030. This is due to the fact that in some cases it is cheaper to produce additional power from hydrogen than to re-distribute electricity from intermittent sources between different grid nodes within the power grid with constrained capacities. After 2030 the curtailment levels increase substantially up to 7-16 TWh/a according to rising shares of intermittent power supply in the system. Still, the curtailed energy amount in all cases corresponds to less than 2% of total intermittent power supply.

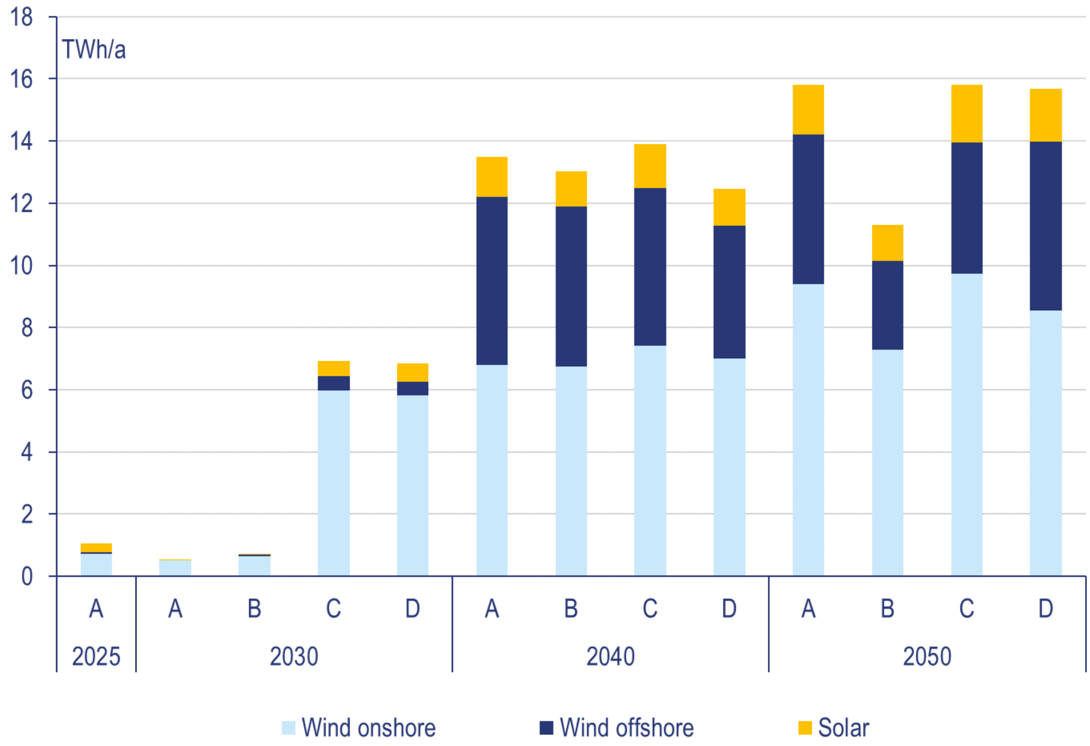


Figure 3: Curtailment of intermittent power supply in EU-27 & UK

Typically, additional use of underground H_2 storage in porous media reduces the curtailment. Due to wider geographical distribution of its potential across European Member States, porous media storage is characterised by a better proximity with existing and future onshore and offshore wind and solar capacities at Member State level in comparison to salt caverns. The limited spatial resolution of the model, however, does not allow for further conclusions on the actual regional distribution within a country. In any case, these results already indicate that hydrogen and its storage in porous media help to integrate renewable energy supply into the overall system. Hence, the curtailment levels are typically lower in scenario B and D in comparison to scenarios A and C without porous media, respectively. As mentioned before, the model design does not consider regional distribution within a country but rather depends on differences in capacity factors and energy demand patterns. Most of intermittent power curtailment occurs for wind onshore. It is followed by wind offshore with disportional values in comparison to its share in total power supply. In contrast, solar energy has disproportionately low curtailment levels due to a better match between power production and use during daytime.

2.2. Hydrogen supply in EU27 & UK

Similar to the power sector, overall hydrogen supply follows again the predefined demand. In all scenarios the demand increases strongly from ca. 350 TWh/a by 2025 up to 1,700-1,900 TWh/a by 2050 (Figure 4)[2]. Hydrogen is mainly used directly in the different end user sectors including industry, heating, mobility sectors as defined in Task 5.4 (D5.4 "Assumptions and input parameters for modelling of the European energy system"). The differences in H_2 consumption between the scenarios are due to its re-electrification in dedicated H_2-based power plants. In line with the corresponding power production scenarios B and D with porous media storage require larger H_2 quantities for the power sector than scenarios A and B without porous media, respectively, due to more distributed energy production and use. In addition, scenarios C and D with larger H_2 imports are characterised by higher H_2 consumption than scenarios A and B with mainly domestic H_2 production, respectively.

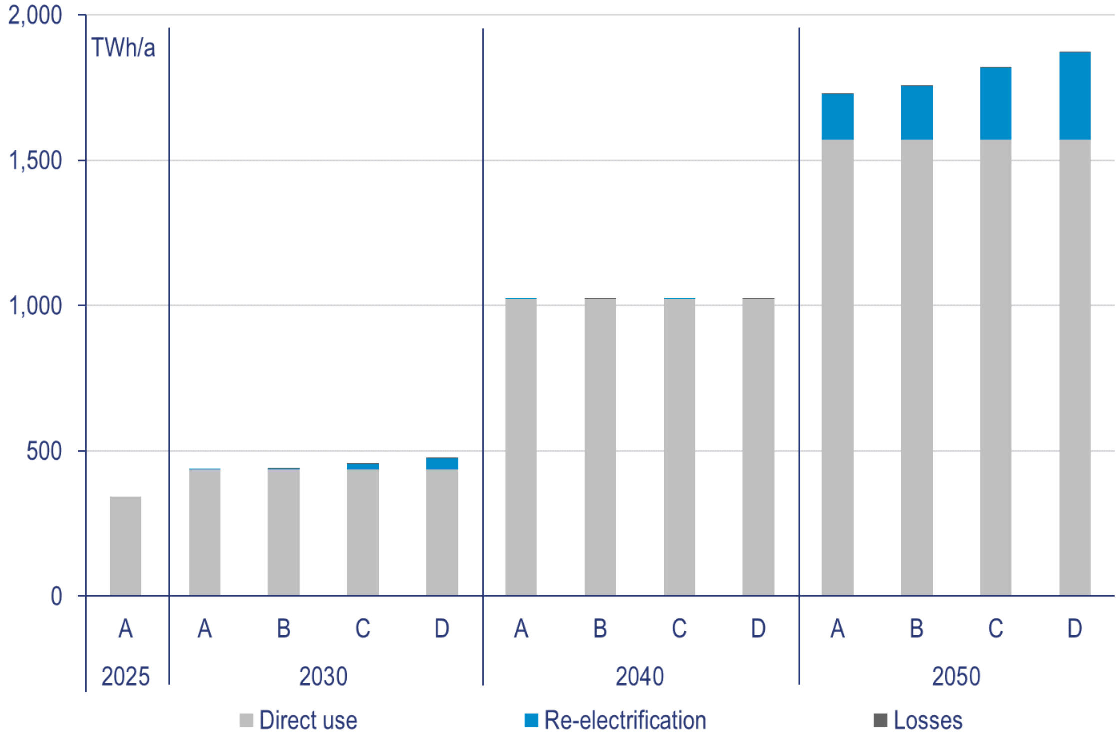


Figure 4: Hydrogen use in EU-27 & UK in selected scenarios

[2] Detailed results on MS level for scenario B in 2050 are shown in Appendix 7.3. Further data for all scenarios are provided in Appendix 7.4.

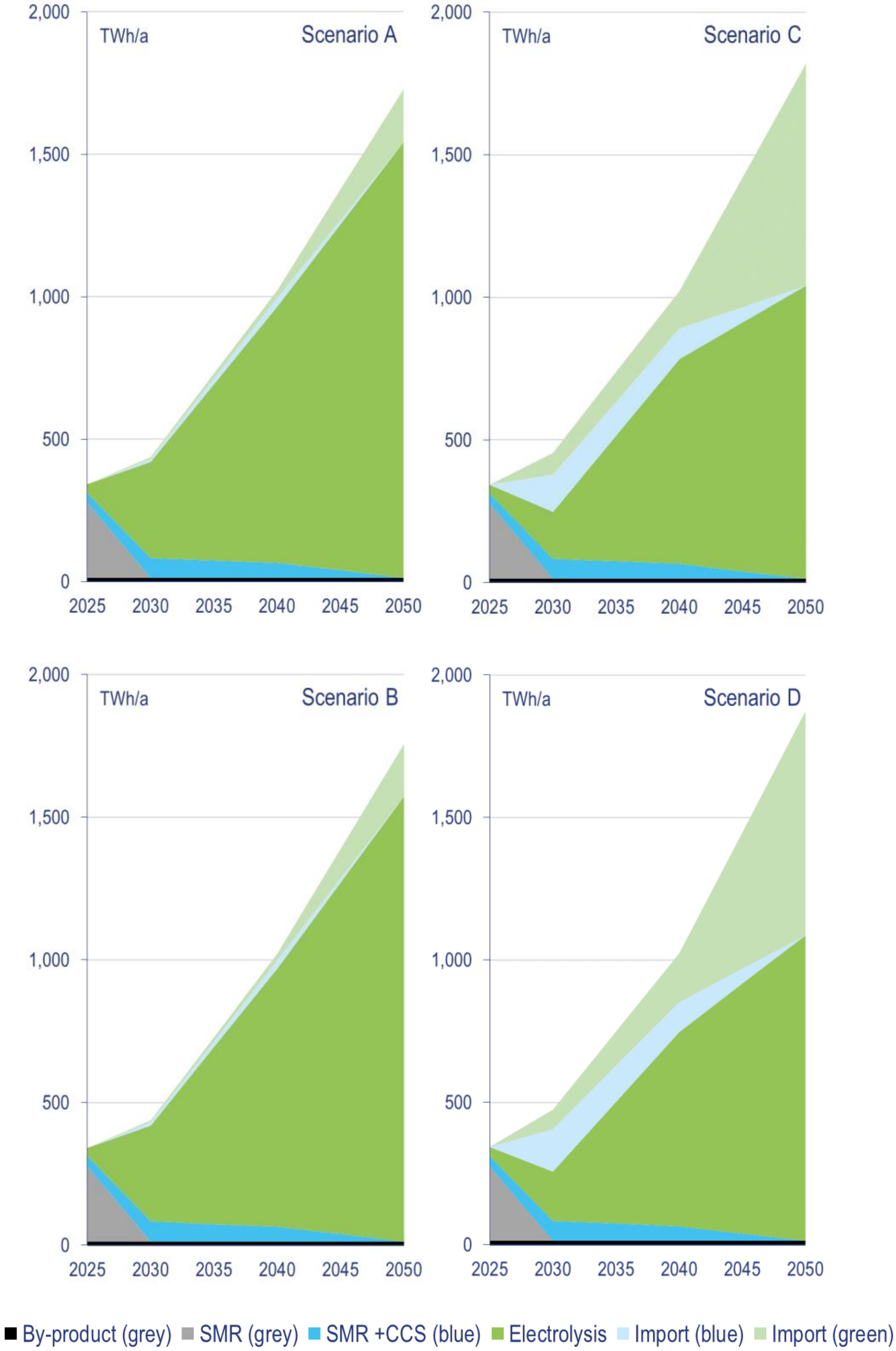


Figure 5: Expected hydrogen supply in EU-27 & UK

In respect to the structure of hydrogen supply all scenarios have in common that grey hydrogen production via steam methane reforming (SMR) without carbon capture and storage (CCS) as today's major technology with ca. 260 TWh/a is replaced by clean H_2 production technologies after 2025 (Figure 5).

Moreover, in all scenarios blue hydrogen (SMR with CCS) is provided in the transition phase prior to 2050 to a limited extent of 35-220 TWh/a. Supply of by-product hydrogen is also limited and remains at a constant level of 13 TWh/a. Hydrogen production via electrolysis becomes the major technology already in the short-term after 2025 in line with the REPowerEU plans by the European Commission [EC 2022]. It increases from 31 TWh/a in 2025 by a factor of ca. 6 up to 1,700-1,900 TWh/a by 2050. In fact, domestic H_2 production via electrolysis from renewable power and green H_2 imports from outside the EU are the only H_2 sources in 2050 in line with the climate neutrality target. The domestic electrolysis capacities increase from 5 GW by 2025 to 370-490 GW by 2050 (Figure 6). In this context, domestic H_2 production in large quantities in scenarios A and B requires greater electrolysis capacities in comparison to scenarios with substantial hydrogen imports in scenarios C and D. In addition, scenarios B and D with H_2 storage in porous media are characterised by higher electrolysis capacities in line with H_2 consumption figures.

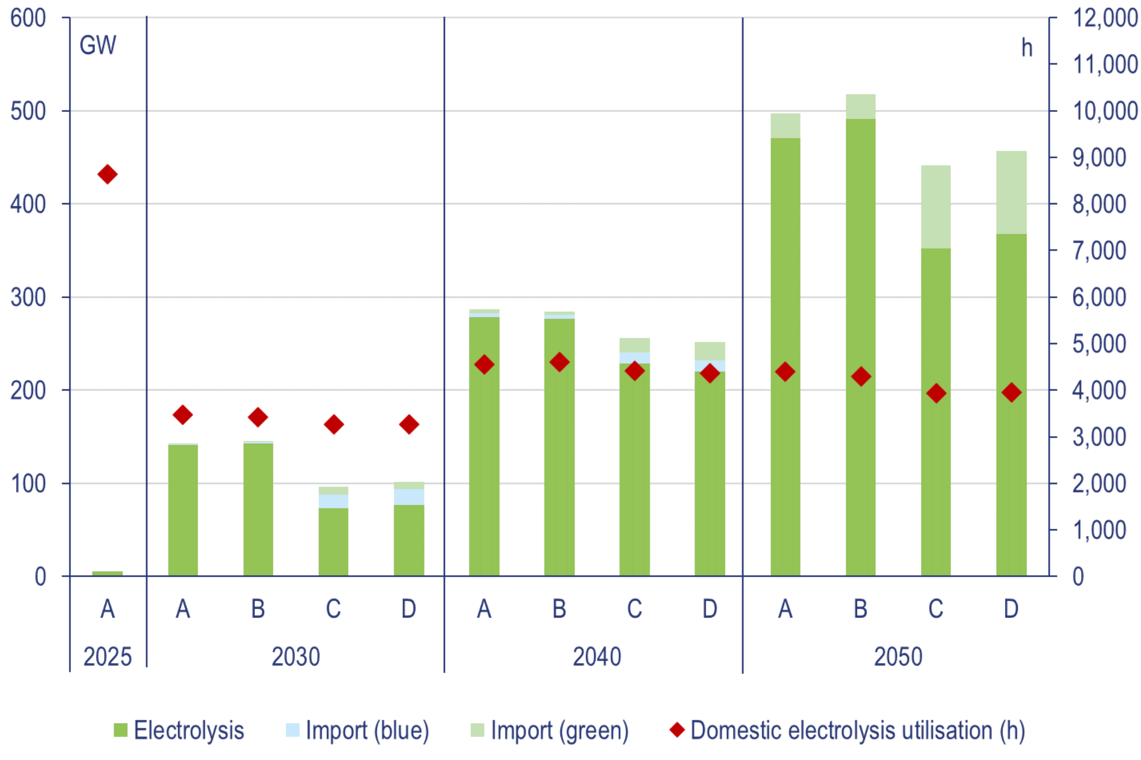


Figure 6: Installed power hydrogen supply capacities (electrolysis and H_2 import pipelines) and utilisation of domestic electrolysis in EU-27 & UK

The utilisation rate for electrolysis varies over time. In 2025 it is very high with more than 8,600 h/a due to comparatively high specific investment outlays and low demand for flexibility measures in the energy system. Then in 2030, intermittent power supply and electrolytic H_2

production become much higher while specific electrolysis cost decrease. Hence, electrolysis is used as a flexible load more frequently and the utilization rate decreases to less than 3,500 h/a. Interestingly, after 2030 the utilisation rate goes up again slightly to more than 3,900 h/a as the increase in H_2 production via electrolysis is stronger than the additional need for flexibility measures due to rising share of intermittent power supply. Generally, for each time horizon the level of utilisation rate is comparable for all scenarios, although it is slightly lower in scenarios C and D (with large H_2 imports) than in the scenarios A and B, respectively. This is due to the fact that scenarios C and D require similar level of system flexibility while the installed electrolysis capacities are lower than in scenarios A and B.

3. Future needs for underground H_2 storage

3.1. Expected storage capacities

Underground hydrogen storage plays an important role in the future energy system as it allows to store large quantities of energy at a seasonal basis. As depicted in Figure 7, underground H_2 storage is expected already by 2030 with storage volume capacities of 20 - 40 TWh or 7 - 14 billion m³.[3] Increasing consumption of hydrogen and share of intermittent energy supply in the system leads to strong growth in storage capacities up to 140-160 TWh or 47-53 billion m³ by 2040 and 280-325 TWh or 93-110 billion m³ by 2050. The required capacities correspond to ca. 5% (scenario C and D in 2030) to 18% (scenarios B and D in 2050) of the overall hydrogen demand (Figure 8). Results on country level are shown in Figure 26 and Figure 27, respectively. Further country-specific results for key parameters are provided in Appendix 7.4.

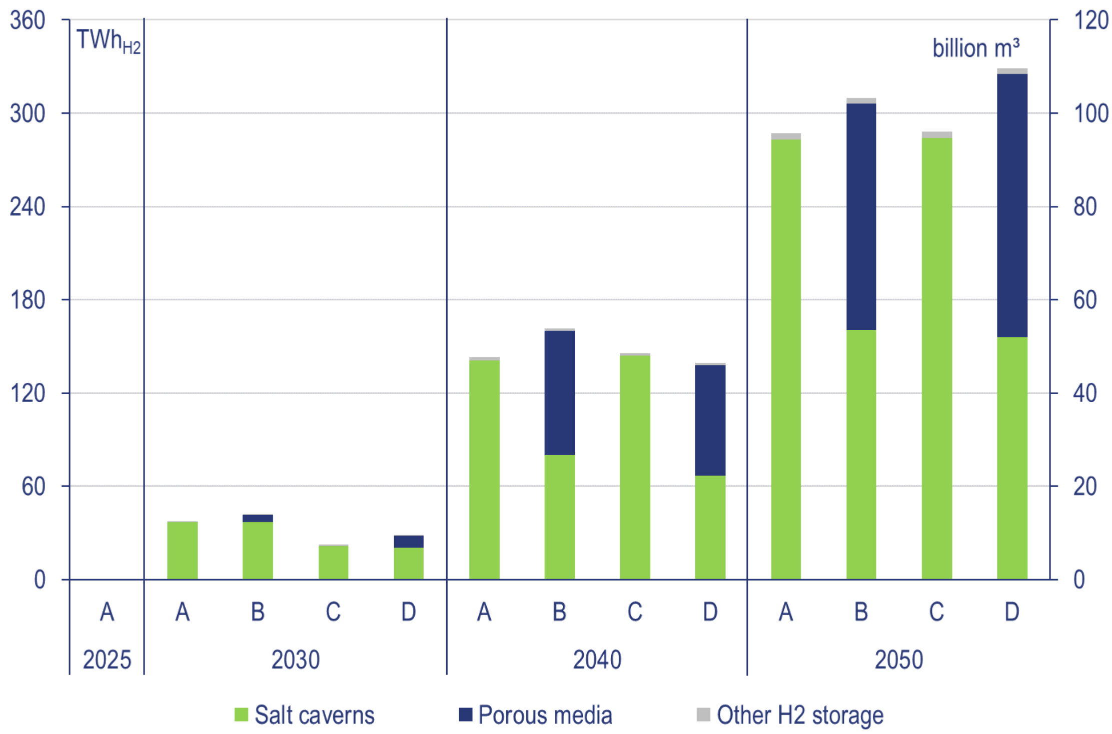


Figure 7: Optimal volume capacity for hydrogen storage in EU-27 & UK

The comparatively low values in 2030 can be explained by comparatively low H_2 demand and rather constant supply (in scenarios C and D including already substantial share of H_2 imports from outside the EU) which limit the need to store large quantities of hydrogen. However, the

[3] Based on volumetric density for hydrogen of 3 kWh/m³.

values increase strongly after 2030 due to large H_2 demand and substantial share of intermittent power and hydrogen generation and thus large requirements for system flexibility.

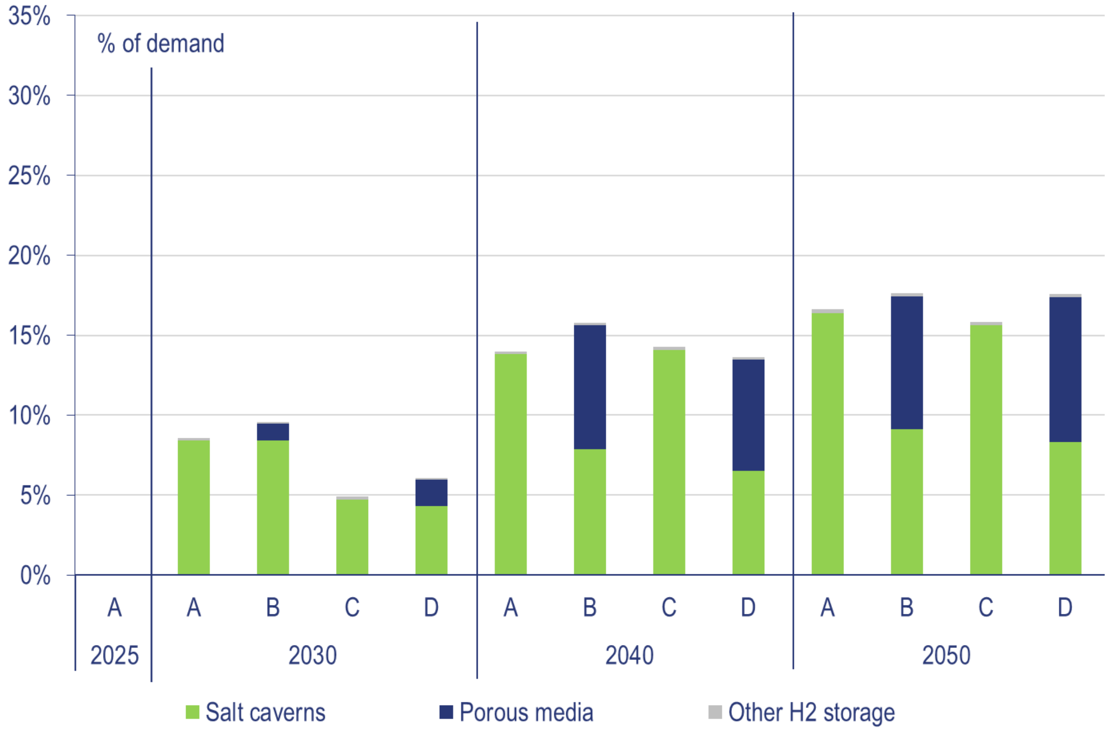


Figure 8: Optimal storage volume capacity as percentage of overall hydrogen demand in EU-27 & UK

In addition, the cost and available capacities for hydrogen transport also influence the overall storage requirements and corresponding technology mix. In fact, the better the spatial distribution of storage potential and the higher the transport cost the more energy is used and stored in local facilities. Hence, the volume capacities in scenarios B and D are higher in comparison to scenarios A and C, respectively. This is confirmed by the relationship between the change in intermittent power curtailment and underground H_2 storage volume capacities between the scenarios with and without porous media technology. The results in Figure 9 reveal that the H_2 storage in porous media limits the curtailment and allows for a better use of intermittent power due to proximity of suitable underground stores with existing and future onshore and offshore wind/solar farms at Member State (MS) level.[4]

There are only two exceptions. First, in scenario B in 2030 both storage capacity and curtailment increase in comparison to scenario A as for this time horizon in each Member State the CO_2 emission cap is still comparatively high and the use of fossil fuel- based power plants cost-competitive. Nevertheless, the overall H_2 storage capacity is higher than in scenario A as local storage facilities are more advantageous from the system perspective than centralised use of salt caverns, especially, given the limited availability of dedicated H_2

[4] For more details on geographical distribution of H_2 storage facilities and transport infrastructure see Chapter 4.

pipelines in this early time horizon. Second, the use of porous media technology leads to lower overall volume capacity (but also lower curtailments) in scenario D in 2040 (in comparison to scenario C) as in system optimum the substantial H_2 imports can be better stored and used efficiently in porous media facilities along the import routes.

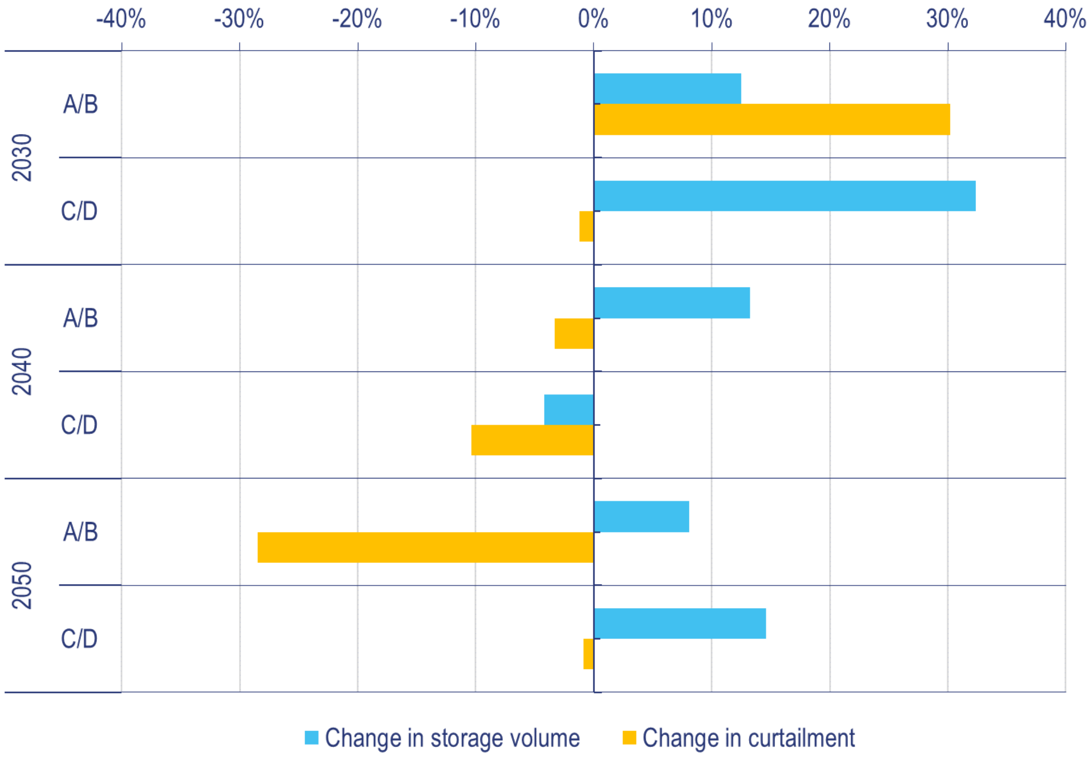


Figure 9: Average change in underground H_2 storage volume capacity and intermittent power supply curtailment caused by the introduction of H_2 storage in porous media in scenarios B and D compared to scenarios A and C (no porous media) for EU-27 & UK

Generally, the constant H_2 supply through imports from outside the EU does not necessarily lead to lower storage requirements and optimal volume capacities. It is rather a unique trade-off between the different supply and demand time patters in each Member State, including the hourly profile for H_2 re-electrification. In 2030 and for scenarios B and D in 2040 and A and C in 2050, the effect of constant H_2 supply in combination with storage possibilities along the import routes is stronger than the effect from local for H_2 re-electrification to balance out intermittent power supply (see Figure 7). In all other cases the latter effect in combination with increasing share of variable H_2 supply from intermittent power sources is stronger than the former effect.

In terms of technology split porous media facilities account for 10%-30% of total H_2 storage volume capacities at a first stage until 2030 and their share achieve ca. 50% at a later stage after 2030 within the corresponding scenarios B and D. In terms of storage volume capacity other above-ground pressurized H_2 storages play only a limited role with capacities of less than 1 TWh (300 million Sm^3) in 2040 or 5 TWh (1.5 billion Sm^3) in 2050.

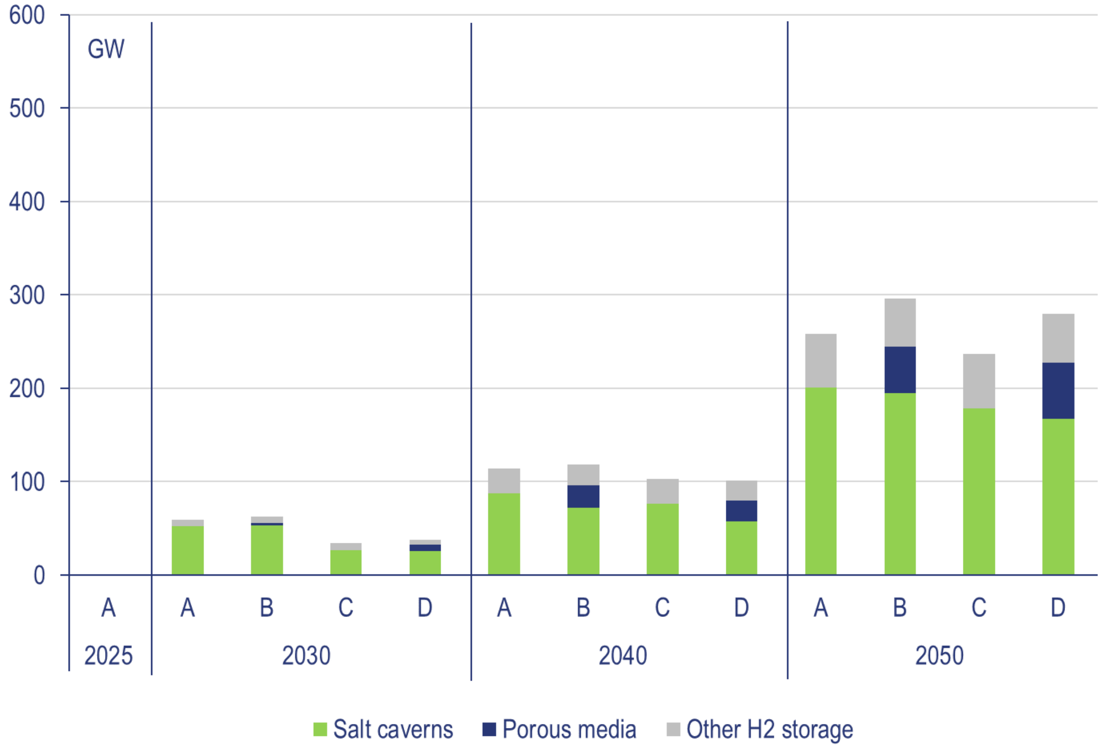


Figure 10: Optimal injection flow rate capacity for hydrogen storage in EU-27 & UK (in GW or GWh/h)

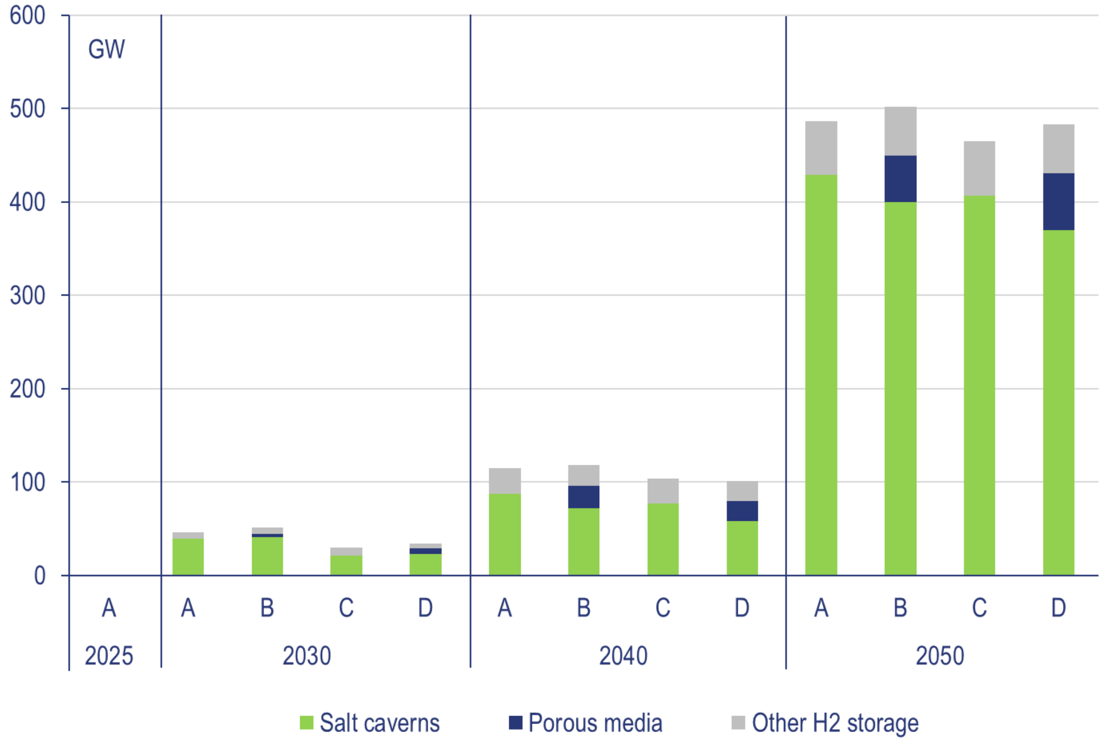


Figure 11: Optimal withdrawal flow rate capacity for hydrogen storage in EU-27 & UK

Figure 10 and Figure 11 show the expected injection and withdrawal flow rate capacities, respectively, for different H_2 storage technologies. In general, until 2030 the injection and withdrawal capacities are comparable to each other for each time horizon, scenario and technology indicating a balance between the changes in H_2 production and demand profiles. This relationship changes substantially in 2050 as the withdrawal capacities are higher (almost by a factor of two) in comparison to injection capacities. This is due to a more variable demand pattern mainly following large H_2-based power plants serving as peak load technologies to balance out the intermittent power generation. Moreover, overall flow rate capacities typically follow the volume capacities: i.e. the greater the storage needs in the system the larger the flow rate capacities. In 2030, the flow rate capacities achieve ca. 35-65 GW and increase strongly up to 240-300 GW for injection and 460-500 GW for withdrawal until 2050. Results on country level are shown in Figure 28 and Figure 29, respectively.

However, the technology split of flow rate capacities does not correspond to the mix of volume capacities. In fact, salt caverns account for the biggest share of the flow rate capacities with a small volume to withdrawal ratio of 400-2,000 indicating a faster response of this technology in storage operation (Table 2). In addition, other above-ground pressurized H_2 storages are characterised by a significant flow rate capacities (comparable to porous media) and, hence, very low average volume over withdrawal flow rate ratios below 100. Hydrogen storage in porous media has the highest ratio between volume and withdrawal flow rate capacities with values well between 1,250-3,300.

Table 2: Average volume over withdrawal flow rate ratio in EU-27 & UK

	2025	2030				2040				2050			
Scenario	**A**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
Salt caverns	1,630	932	897	998	902	1,610	1,118	1,860	1,157	660	401	698	421
Porous media			1,286		1,255		3,262		3,243		2,931		2,765
Other H_2 storage	80	88	84	102	90	69	68	69	69	70	70	70	69

3.2. Optimal way of storage operation

As illustrated in Figure 12 and Figure 13 hydrogen, throughput through the underground storage, i.e. the quantity of hydrogen which is injected and withdrawn from the storage within a prototypical year, corresponds again to H_2 demand and storage volume capacities. Over time, the throughput increases from 80-110 TWh/a in 2030 to 450-550 TWh/a in 2050. In this way the amount of hydrogen stored underground corresponds to 15%-30% of the overall hydrogen demand. This relative range remains robust over time indicating the strong dependency of storage throughput from H_2 demand. Most of the hydrogen is stored in salt caverns (55%-90% of the overall throughput in corresponding scenario and time horizon) followed by porous media storage with 6%-35% and other above-ground storage facilities with

8%-20%. Generally, the availability of porous media reservoirs and focus on domestic H_2 production via electrolysis increase the throughput and storage usage. Results on country level are shown in Figure 30 and Figure 31, respectively.

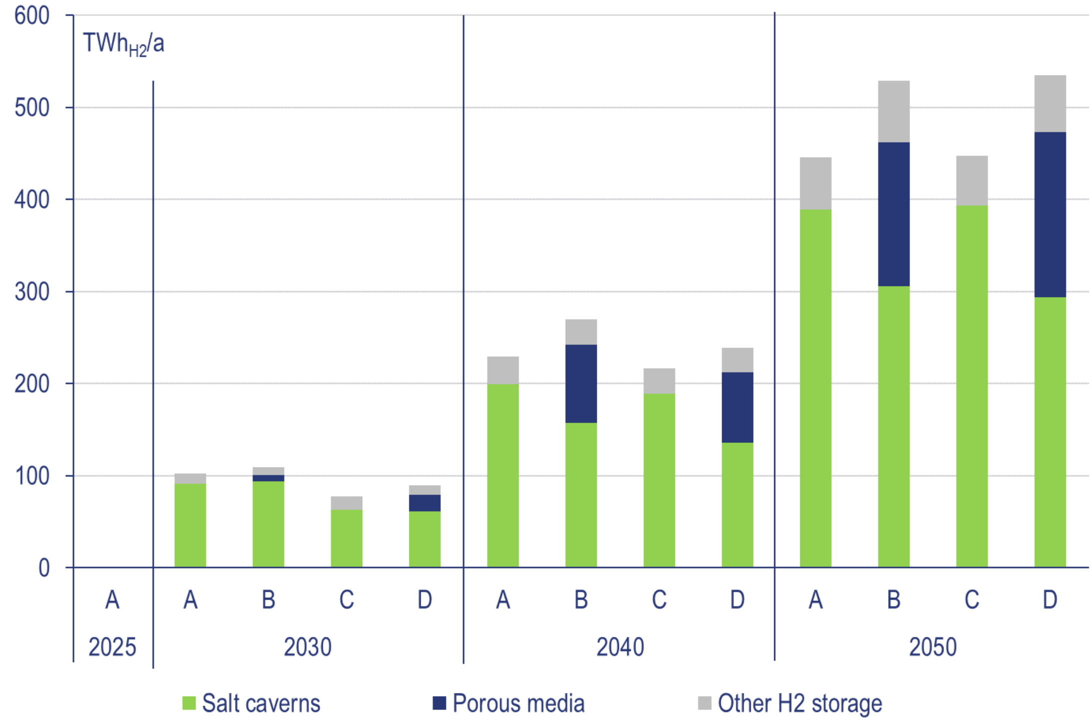


Figure 12: Hydrogen storage throughput in EU-27 & UK

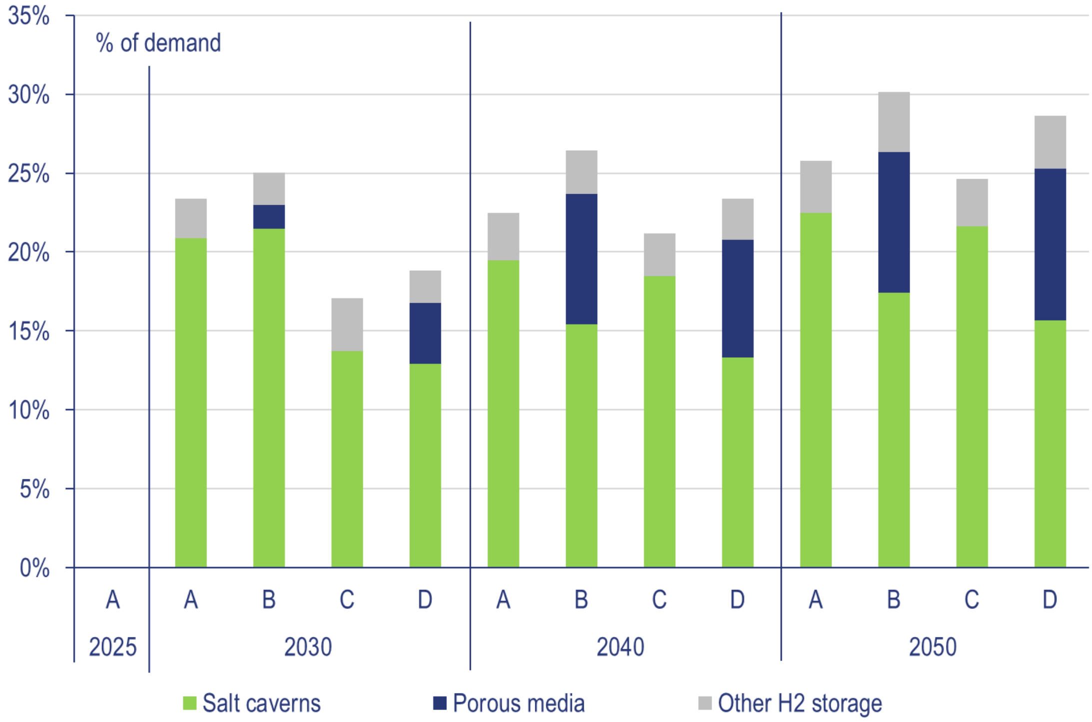


Figure 13: Hydrogen storage throughput as percentage of overall hydrogen demand in EU-27 & UK

As summarized in Table 3 until 2030 salt caverns in EU-27& UK are operated on average on a 4-5 months basis (corresponding to 2.5-3.0 full cycle equivalents per year) and porous media on 5-8 months basis (1.4-2.2 cycles).[5] In the long term after 2030, however, both salt caverns and porous media storage are operated on a more seasonal basis with 6-9 months or 1.4-1.9 cycles and 11-12 months or 1.1 cycle, respectively.

Table 3: Average number of full cycle equivalents in EU-27 & UK

	2025	2030				2040				2050			
Scenario	**A**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**	**A**	**B**	**C**	**D**
Salt caverns	1.2	2.5	2.6	2.9	3.0	1.4	2.0	1.3	2.0	1.4	1.9	1.4	1.9
Porous media			1.4		2.3		1.1		1.1		1.1		1.1
Other H_2 storage	11	17	15	18	20	16	18	15	17	14	18	13	17

As an example, Figure 14 and Figure 15 illustrate the annual pattern of the filling levels of underground H_2 storage facilities in Germany in 2030 and France in 2050, respectively. Each graphs show scenario B and D. Further illustrations for selected countries are included in Appendix 7.5.

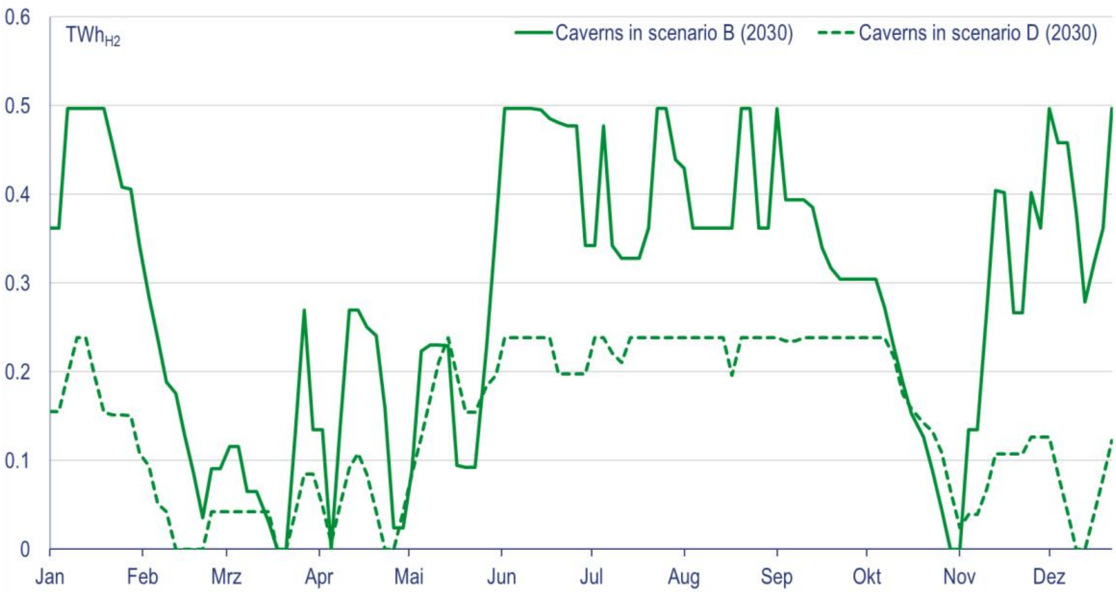


Figure 14:Storage filling level in Germany in 2030 in scenario B & D

[5] Full cycle equivalents per year are calculated as the sum all injections and withdrawals withing the prototypical year divided by storage volume capacity and multiplied by the factor of 0.5. The time basis is calculated by dividing 12 months of a year by the number of cycles per year.

In 2030 only small salt caverns are built up in Germany with a cumulative storage volume capacity between 100-250 GWh in scenario A, C and D and 500 GWh in scenario B. In this context, salt caverns are the most cost-competitive technology in the given grid node and there is no porous media storage. Although in this time horizon the seasonal pattern of storage operation can be already observed, there is still some additional short-term fluctuation in storage filling level to balance out H_2 supply and demand. In addition, the limiting influence of H imports from outside the EU is visible as a difference between scenarios B and D.

In contrast, in 2050 the optimal technology mix in France includes both salt caverns and porous media storage sites with substantial capacities of 27-32 TWh and 5-28 TWh, respectively. Interestingly, the focus on domestic H_2 production in scenario B requires larger salt caverns but smaller porous media capacities whereas in the scenario D with substantial H_2 imports from outside the EU the capacities for both technologies are similar. In terms of optimal way of operation There are still short-term fluctuations for salt caverns but their impact in relation to the overall storage volume capacity and throughput is rather limited. The optimal way of operation for porous media storage is characterised by a strong seasonal pattern – similar to what can be observed for conventional NG storage today – with a minimum level in early spring (March/April) and a peak in early autumn (September/October).

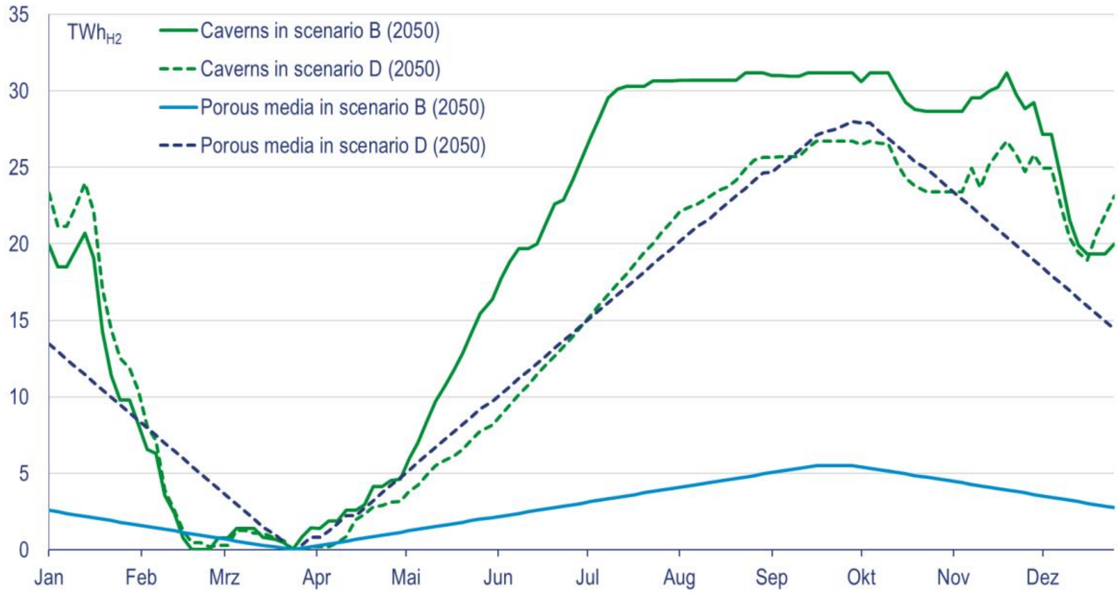


Figure 15:Storage filling level in France in 2050 in scenario B & D

4. Expected energy transport infrastructure

4.1. Overall infrastructure needs

The overall infrastructure needs are strongly linked to results on energy supply on the one hand and assumptions on country-specific energy demand on the other hand. In this chapter the overall development of power and hydrogen infrastructure is summarised in Figure 16, Figure 17 and Figure 18 as total amount of energy flows in TWh/a, installed capacities in GW and resulting infrastructure utilisation in % between all nodes.[6]

As shown in Figure 16 the overall hydrogen flows increase over time mainly due to rising use of hydrogen in all grid nodes. In particular the strong build-up of dedicated cross-border H_2 pipelines between 2030 and 2040 in line with the assumptions on grid topology allows for a substantial grow of transported H_2 volumes. The use of H_2 storage in porous media with its broader geographical distribution across Europe in combinations with higher assumed H_2 transport cost (in scenarios B and D) reduces overall H_2 transport requirements compared to scenarios A and C with salt caverns only, respectively.

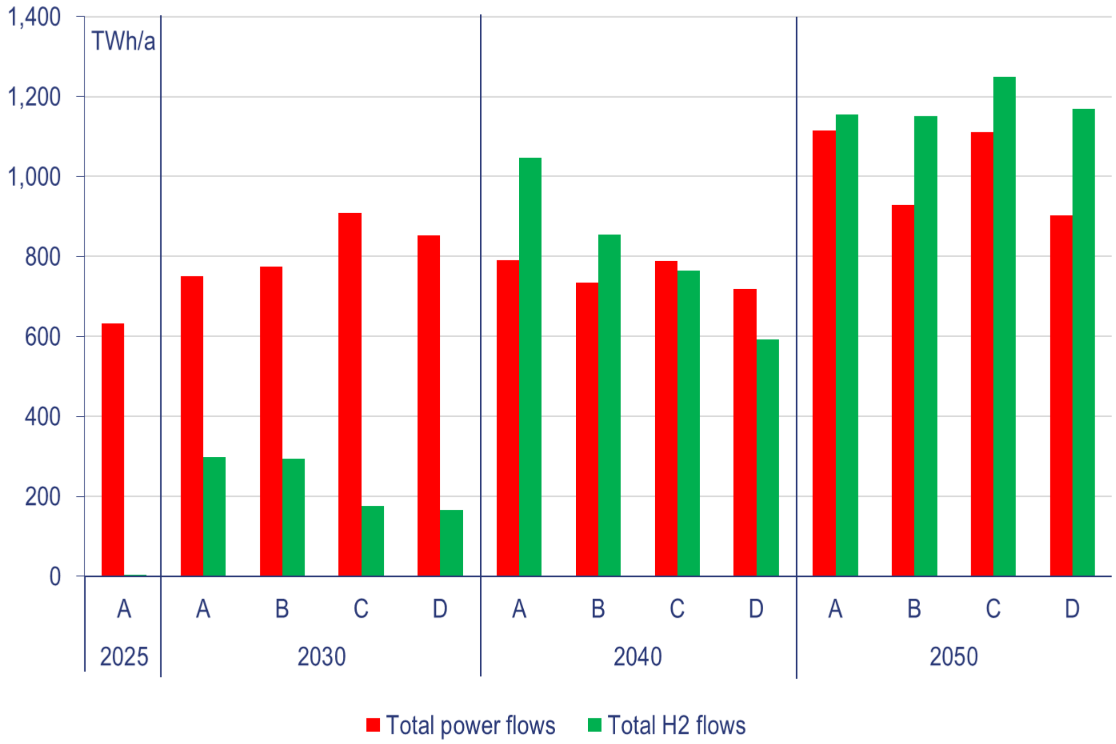


Figure 16: Total energy flows between all grid nodes

[6] Utilisation rate is calculated by dividing actual annual energy flows by overall annual throughput capacity (i.e., installed capacity in GW multiplied by 8760 hours per year). Note that in this chapter the presented results do not take the distances between the grid nodes into account.

Moreover, additional H_2 imports from outside the EU limit total flow volumes (i.e., it is lower in scenarios C and D in comparison to scenarios A and B) as hydrogen can be transported in great quantities directly to large consumers instead of in the case of distributed domestic production. The required cumulative pipeline capacities in different scenarios follow the same patterns for all time horizons. The more homogeneous the geographical distribution of H_2 storage facilities (as in scenarios B and D compared to A and C, respectively) the lower the cumulative capacities between all grid nodes. Moreover, greater H_2 imports from outside the EU (in scenario C and D) help to limit the overall capacities requirements due to a better synergetic use of large backbone pipelines. In most cases the pipeline utilisation decreases over time from 80%-90% in 2030 to 60%-77% in 2050 and is lower in scenarios with salt caverns only (scenarios A and C) than in scenarios with both technologies (scenarios B and D). It is also smaller in scenarios with greater imports from outside the EU (scenario C and D). Only in 2050 the utilisation in scenarios C and D is slightly higher than in scenarios A and B (mainly domestic H_2 supply) in line with the synergy effects of large backbone infrastructure. In 2025 hydrogen flows and pipeline capacities are very low and limited to the interconnector between the Netherlands and Belgium resulting in a very favourable utilisation rate of almost 100%.

Figure 17: Cumulative capacity of energy transport infrastructure between all grid nodes

For the power infrastructure the results are ambiguous as the overall flows and infrastructure needs depend on different, partially opposing effects. On the one hand increasing power consumption due to both direct use in different sectors and domestic hydrogen production via electrolysis requires more power flows and transport capacities. On the other hand, the supply structure also has a large impact on the infrastructure: local intermittent power generation from solar and wind onshore reduces power transport while large centralised dispatchable generation such as nuclear power plants in France increase the transport needs. The overall effect depends on the actual balance between the local demand, size of distributed intermittent and centralized dispatchable generation in the technology mix influenced by country-specific trajectories towards climate neutrality and general technology and fuel cost. Hence, the power flows vary significantly from 600 TWh/a to 1,200 TWh/a between scenarios and time horizons (see Figure 16). The cumulative cross-border capacities follow the power flows and vary between 200 GW and 300 GW (see Figure 17). The utilisation remains stable over time and between scenarios with 50% to 65%.

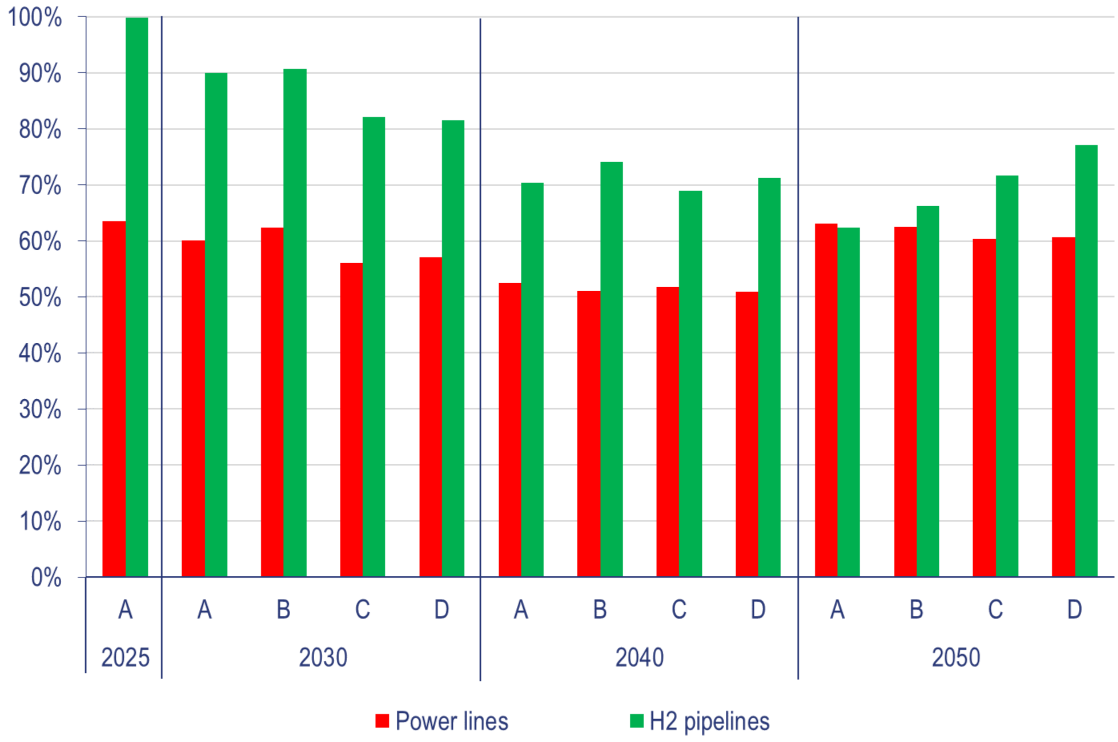


Figure 18: Average utilisation of energy transport infrastructure

4.2. Development of hydrogen infrastructure

The expected hydrogen transport via dedicated pipelines and the development of the corresponding infrastructure depends on the spatial distribution of H_2 supply and demand as well as on assumed topologies of the grid for each time horizon.

In 2030 only rudimental H_2 backbone infrastructure is available allowing for first blue and green H_2 imports from Norway, Ukraine and North Africa (see Figure 19 as an example in scenario B). Only few countries within the EU (Spain, France and Denmark in scenario A and B and Denmark only in scenarios C and D) produce more hydrogen than needed and thus export excess hydrogen to other countries.

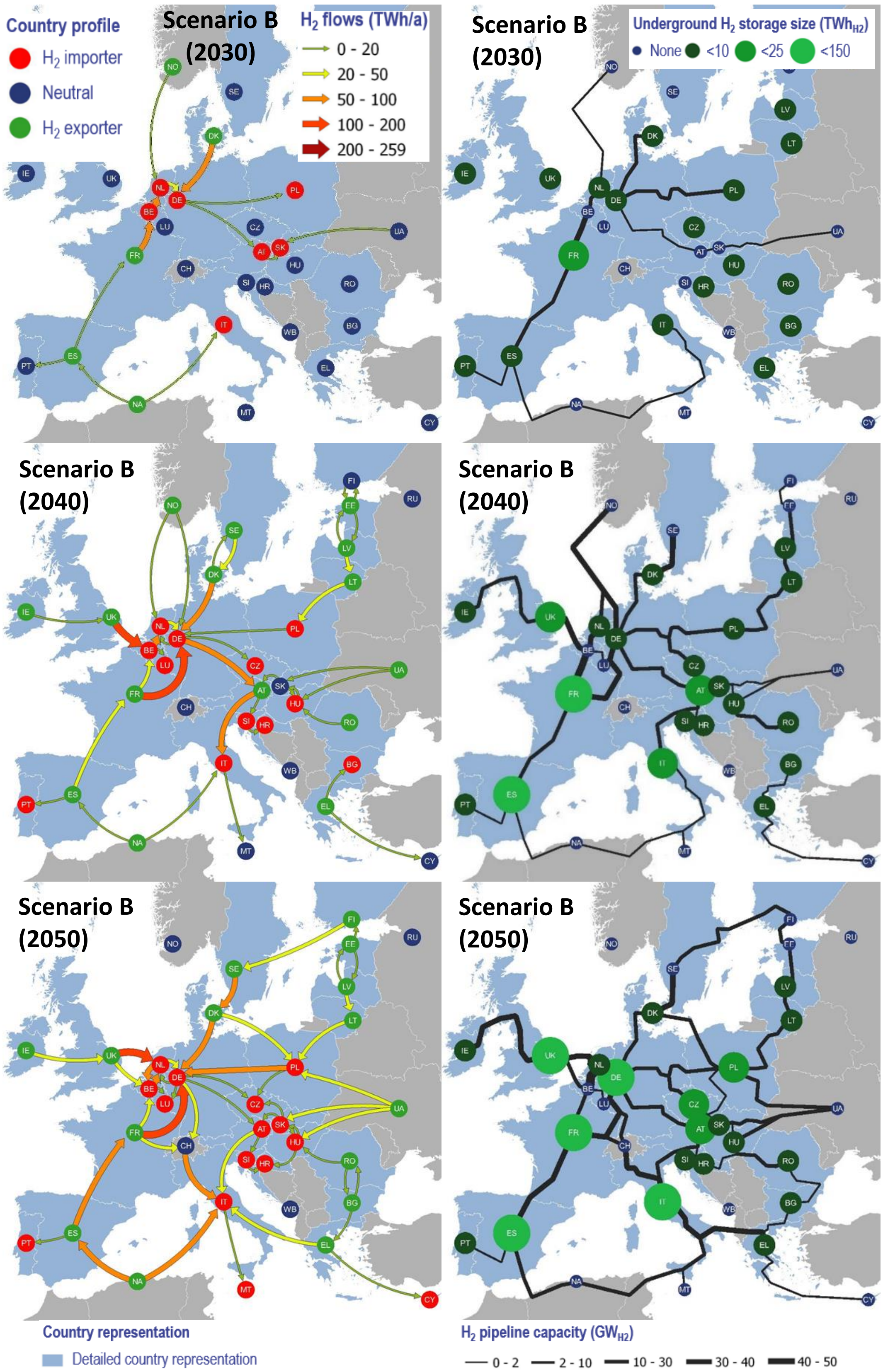


Figure 19: Development of H_2 flows (left) and pipeline capacity (right) in scenario B in 2030 (top), 2040 (middle) and 2050 (bottom)

Most of the Member States either are independent (i.e. supply equals demand) or import H_2 via dedicated pipelines in limited quantities (<100 TWh/a) at small maximum flow rates (<30 GW/h). Small underground hydrogen storage capacities are built up in most countries with corresponding potential. In case underground storage is not possible, e.g. due to geological conditions, other above-ground storage sites are installed to balance out H_2 supply and demand.

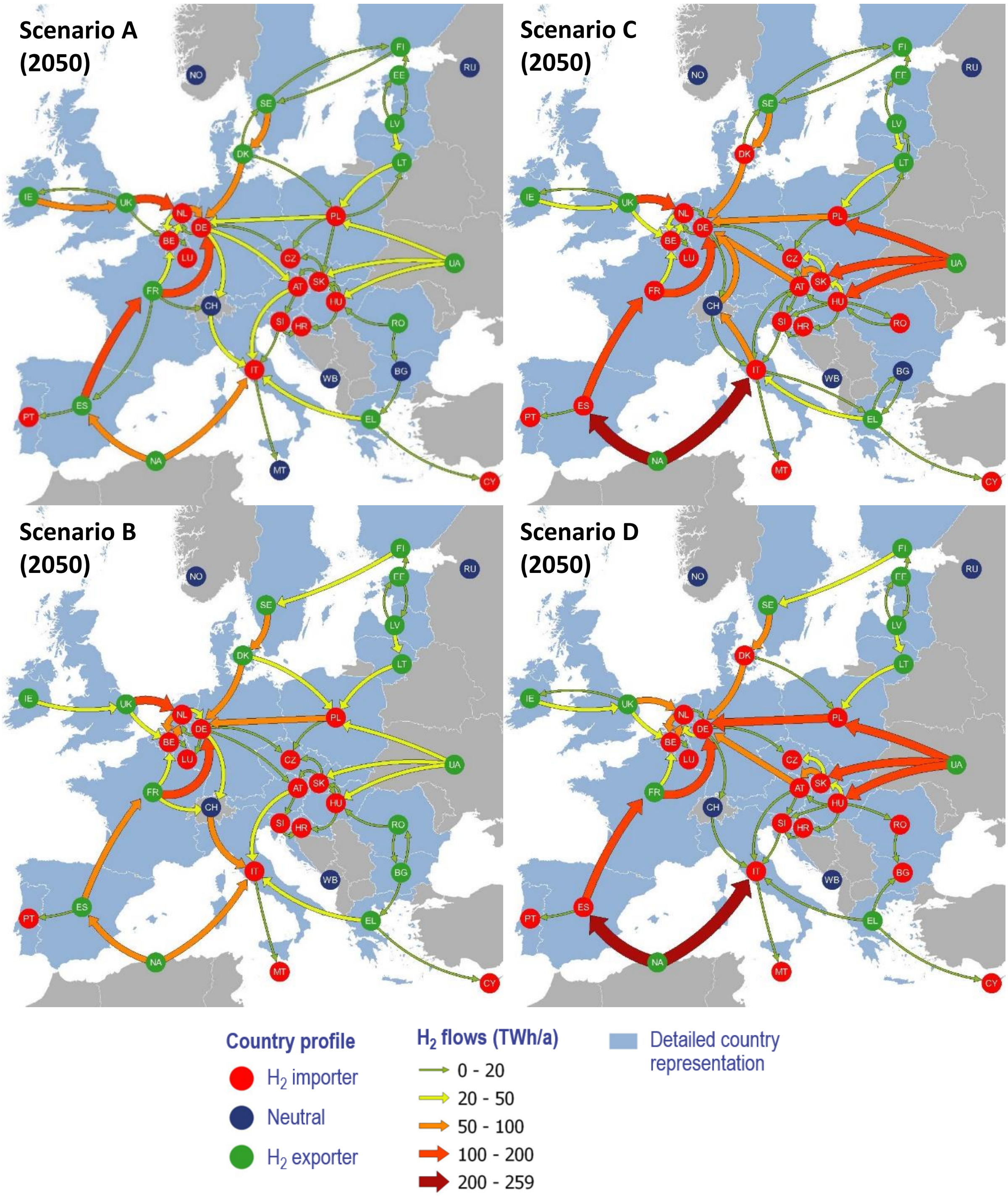


Figure 20: Expected H_2 flows in Europe by 2050

In the long-term after 2030 hydrogen infrastructure is further developed and underground storage capacities grow gradually in each country until the full extent in 2050. At this stage large amounts of energy are transported within the system due to broad spatial distribution of hydrogen consumption and intermittent power generation as major feedstock for green hydrogen, (see Figure 20 and Figure 21 illustrating the scenario differences by 2050).

This is true in particular for scenarios A and B with focus on domestic electrolysis. On the one hand, according to H_2 demand assumptions and expected country-specific trajectories for wind and solar power generation, major net H_2 producers and thus exporters to other Member States are located at peripheries of the European energy system. In fact, more than 95% of net H_2 supply (i.e., residual hydrogen production exceeding country-specific consumption) come from six major regions:

- Northwest incl. Ireland and the UK (responsible for 27% of overall residual H_2 supply),
- Spain (19%),
- France (16%),
- Scandinavia including Sweden, Denmark and Finland (16%),
- Southeast including Greece, Romania and Bulgaria (10%) and
- Baltic countries including Latvia, Lithuania and Estonia (10%).

In addition in scenarios A and B, limited green H_2 imports from outside the EU accounting for less than 200 TWh/a (i.e., ca. 10% of total H_2 use in the system) come from North Africa directly connected via dedicated pipelines to Spain and Italy as well as from Ukraine supplying eastern part of Europe, i.e., directly connected to Poland, Slovakia and Hungary. On the other hand, almost 90% of net H_2 consumption and imports (i.e., country-specific consumption is higher than domestic production) occur in large economies with limited renewable potential (in relation to energy needs) mainly in Central Europe including Germany (responsible for 37% of net H_2 consumption), Italy (24%), the Netherlands (18%), and Belgium (10%).

In terms of H_2 gas flows, France and the Benelux countries become important infrastructure hubs in Western Europe to redistribute hydrogen from Spain, France, the UK and Ireland to Germany, the Netherland and Belgium. In Eastern Europe, major infrastructure hubs are located in Poland to connect Baltic countries with Central Europe as well as in Slovakia and Austria to allow for flows from Ukraine to other countries in the west. Italy can be seen as an infrastructure hub itself as H_2 supply for Italy comes from several directions: via Germany/Switzerland from the west and north, via Austria and Slovakia from the east and north as well as directly from North Africa and Greece. Only in scenario C, net H_2 flow from Italy towards North (Germany/Switzerland) exceed imports from than countries, emphasing its importance for the European import infrastructure.

In scenarios C and D, about half of the hydrogen supply stems from imports from outside the EU with a strong impact on the corresponding hydrogen flows and infrastructure. One the one hand, some of net H_2 production still remains in European peripheries like in the UK, Ireland, Sweden, Finland, Greece and Baltic countries with similar infrastructure needs as in scenarios A and B. On the other hand, green hydrogen imports in large quantities from outside the EU allow for countries with some proximity to North Africa and Ukraine or on the way along major import corridors to Central Europe to switch from domestic H_2 production to H_2 imports. Hence, countries such as Spain, France, Denmark, Romania and Bulgaria stop own H_2 exports to other countries and become net importers. In fact, domestic net H_2 production comes only from eight countries including the UK (32% of total domestic net exports), Sweden (23%), Ireland (15%), Latvia (12%), Greece (8%), Lithuania (4%), Finland (3%) and Estonia (3%). In terms of net H_2 imports Germany alone is responsible for more than 50% of European net imports followed by the Netherlands (17%) and Belgium (9%). Major H_2 imports corridors from North Africa are via Spain and France to Germany as well as directly to Italy (except for scenario C where some hydrogen from North Africa is transported to the North via Italy). For imports from Ukraine the routes to Central Europe go through Poland and Austria/Slovakia.

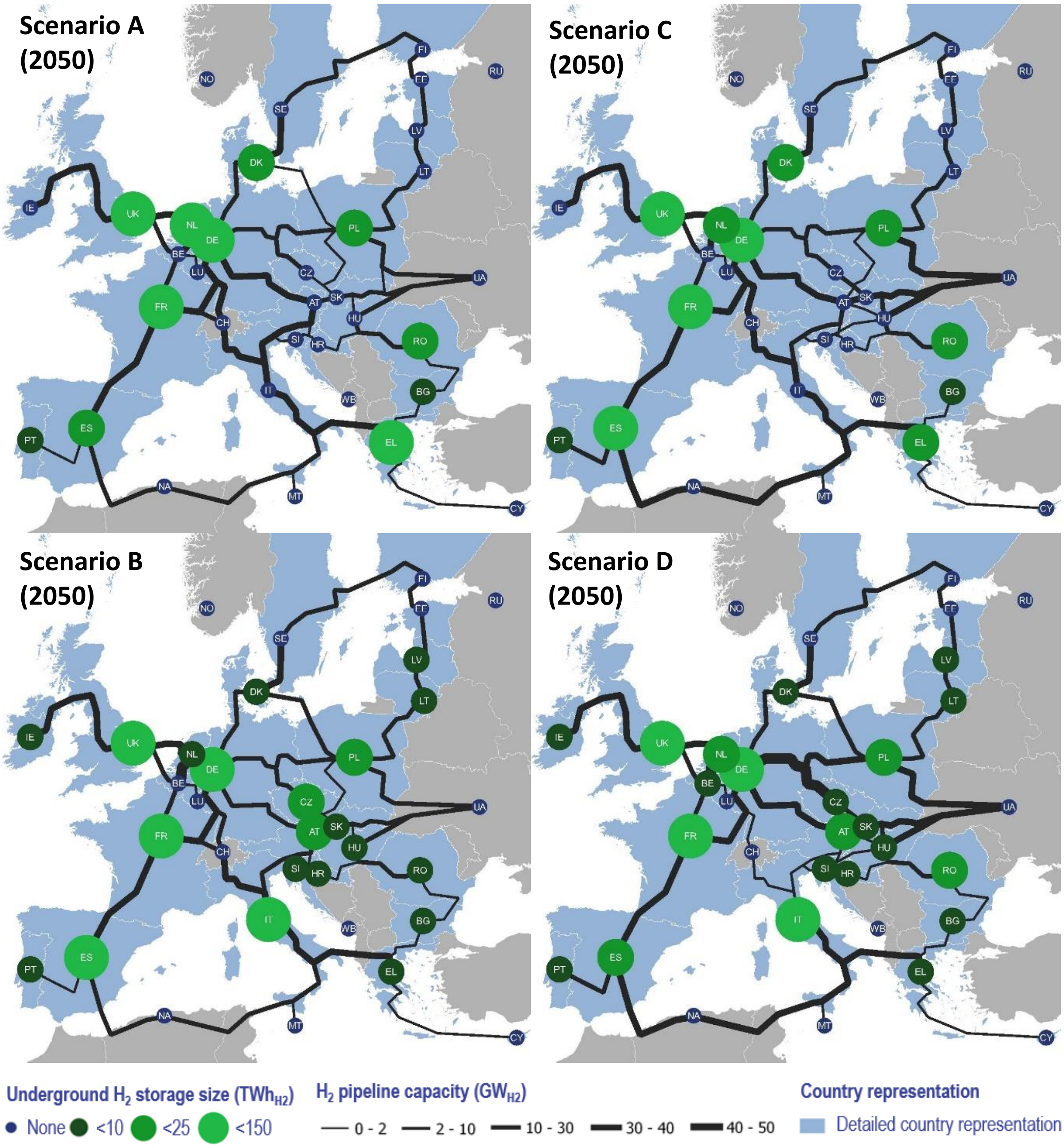


Figure 21: Development of hydrogen transport infrastructure and spatial distribution of underground H_2 storage volume capacity in Europe by 2050

In this context, largest storage capacities occur in countries with both large net hydrogen production and consumptions, i.e. at both large supply (e.g. Spain, France or the UK) and demand centres (e.g. Germany, Italy or Poland), in order to minimize the investments in costly pipeline capacities. The above mentioned countries account for 70% of overall capacities in EU-27&UK. Porous media storage is mainly located in Italy (up to 90 TWh depending on the scenario) followed by France (up to 28 TWh) and Germany (16 TWh). In other Member States underground hydrogen storage is also build, however, to a smaller extent according to country-specific geological conditions and technology availability. Moreover, in scenarios B and D additional capacities, specifically in porous media, occur in Austria (up to 17 TWh) to facilitate hydrogen exchange between the different regions in Europe. At this point it is also important to mention that in scenario B and D, with porous media technology and thus geographically more distributed storage facilities, hydrogen flows are rather unidirectional. In contrast to that, in scenario A and C with centralised H_2 storage in salt caverns H_2 pipelines are mainly bi-directional to allow for the use of limited number of H_2 salt caverns by all countries/nodes within the system. Hydrogen flows and infrastructure capacities within the European gas grid for all scenarios and time horizons are illustrated in Appendix 7.1 and 7.2, respectively.

5. Economic and environmental evaluation

5.1. Energy system cost and value of storage

The cost of the overall energy system, which have been minimized by the model, vary between 200-300 billion EUR/a (Figure 22). The figures include all investment cost calculated as annuity according to technology-specific lifetime fixed costs (typically as a fraction of investment) as well as variable cost such as fuel cost for dispatchable power plants. At this point it important to mention that the system cost increase over time as according to model and scenario definition some energy carriers, in particular fossil fuels such as diesel and gasoline for direct use in mobility sectors, are excluded from the analysis. Hence, in line with growing use of renewable energy and hydrogen substituting fossil fuels the cost of renewable power and hydrogen supply increase.

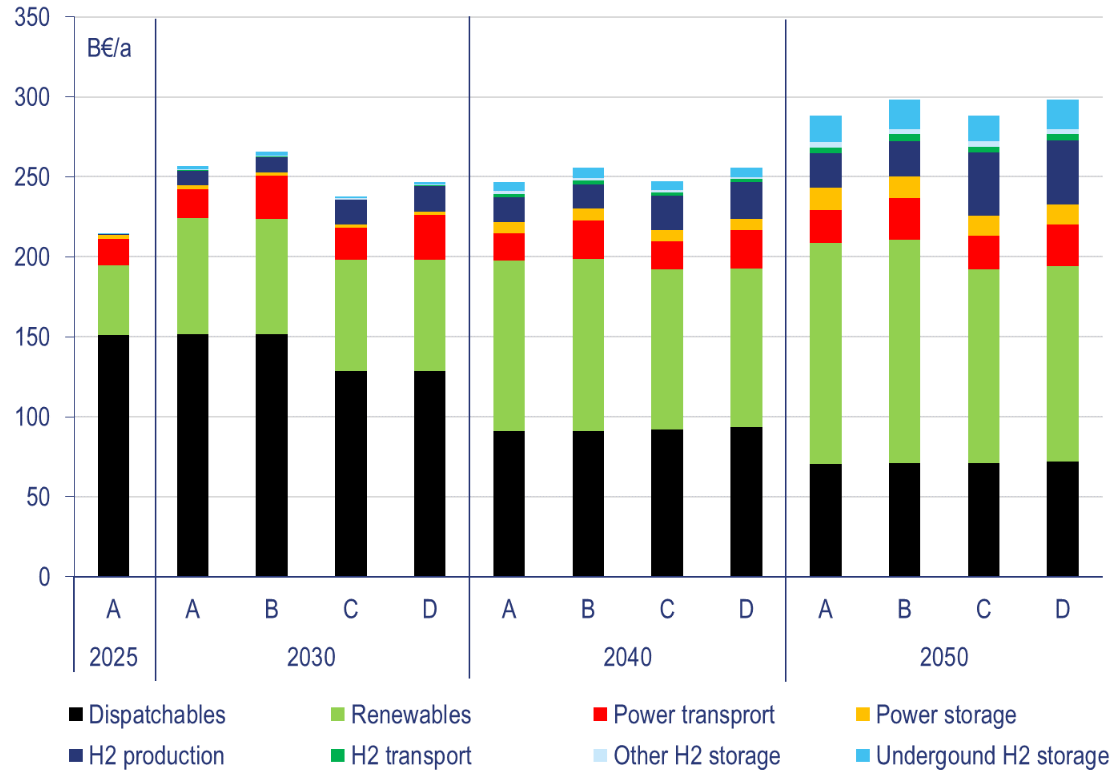


Figure 22: Total energy system cost for EU-27 & UK

As a reference the system cost in scenario A in 2025 amount to ca. 200 billion EUR/a, mainly due to power supply by dispatchable (fossil) power plants responsible for 150 billion EUR/a or more than 70% of total cost. Renewable electricity production and cross-border power transmission account for 40 billion EUR/a or 20% of system cost and 17 billion EUR/a or less than 10%, respectively. Hydrogen supply cost are comparatively very low due to limited demand for hydrogen in this time step. According to CO_2 emission targets the renewable power generation increase substantially up to 120-140 billion EUR/a or 40%-50% of total cost by 2050. Due to the phase out of fossil fuels, the impact of dispatchable power plants decreases to ca. 70 billion EUR/a or ca. 25% of total cost by 2050. Note that in 2050 there is no use of fossil fuels for power generation and all costs are associated to hydrogen and biomass fuelled power plants. Instead, the cost for flexibility measures such as power and hydrogen storage, energy transport and hydrogen supply increase substantially. In this context, hydrogen supply cost reach 20-40 billion EUR/a in 2050. Note that the cost in scenarios A and B account only for domestic electrolysis and corresponding electricity generation is summarized under renewable power supply cost while hydrogen cost in scenarios B and C are calculated based on a pre-defined H_2 import price which intrinsically includes the power cost in H_2 exporting countries. Hence, scenarios A and B are characterised by lower H_2 supply but higher power generation cost in comparison to scenarios C and D. This effect becomes stronger the larger the difference between domestic H_2 production and H_2 imports from outside the EU, i.e., it achieves its maximum in 2050. The cost for cross-border power transmission (20-30 billion EUR/a) are much higher than cost for cross-border hydrogen transport via dedicated pipelines (up to 4 billion EUR/a) whereas short-term power storage cost (up to 15 billion EUR/a) are slightly lower than large-scale seasonal H_2 storage cost (up to 22 billion EUR/a).

Generally, the system cost in scenarios B and D with H_2 storage in porous media are slightly higher by up to 4% or ca. 10 billion EUR/a in comparison to scenarios A and C, respectively, due to higher assumed specific H_2 transport cost and consequently larger use of spatially distributed and more expensive porous media storage technology. However, this effect is rather limited in comparison to other underlaying uncertainties such as unclear future development of prices for other technologies or fuels. In addition, hydrogen imports from outside the EU result in lower system cost only in 2030 (i.e., the cost in scenario C and D are lower than in scenarios A and B, respectively) whereas in 2040 and 2050 there is almost no difference. Hence, in the long-term domestic hydrogen production is cost-competitive with renewable hydrogen imports including corresponding long-distance transport cost. The choice of underground H_2 storage technology is also not crucial from the overall system cost perspective (see differences between scenario A and B as well as C and D, respectively).

The specific hydrogen cost are calculated in a simplified way. First, the average power cost on €/MWh-basis are estimated by dividing all power supply cost (i.e., renewable and dispatchable power production, power transmission and storage) by the overall power consumption including the domestic electrolysis. Then, the absolute H_2-related electricity cost correspond to the average power cost on €/MWh-basis multiplied by power consumption of domestic electrolysis. Finally, specific hydrogen cost on €/kg-basis are calculated by dividing total H_2-related cost (i.e., H_2 production, transport and storage costs as well as H_2-related electricity cost) by the overall hydrogen consumption in EU-27 & UK. As shown in Figure 23**,** the lowest specific H_2 cost of less than 2 €/kg occur in 2025 due to extensive use of grey hydrogen from steam methane reforming based on comparatively cheap natural gas but with corresponding CO_2 emissions. In 2030 ,the average cost for clean hydrogen (i.e. a mix of blue and green hydrogen including imports from outside the EU) are significantly higher (ca. 3.5 €/kg), especially in the case of mainly domestic supply in scenario A and B. In case of more extensive H_2 imports (scenarios C and D), the cost increase can be limited to ca. 2.6 €/kg.

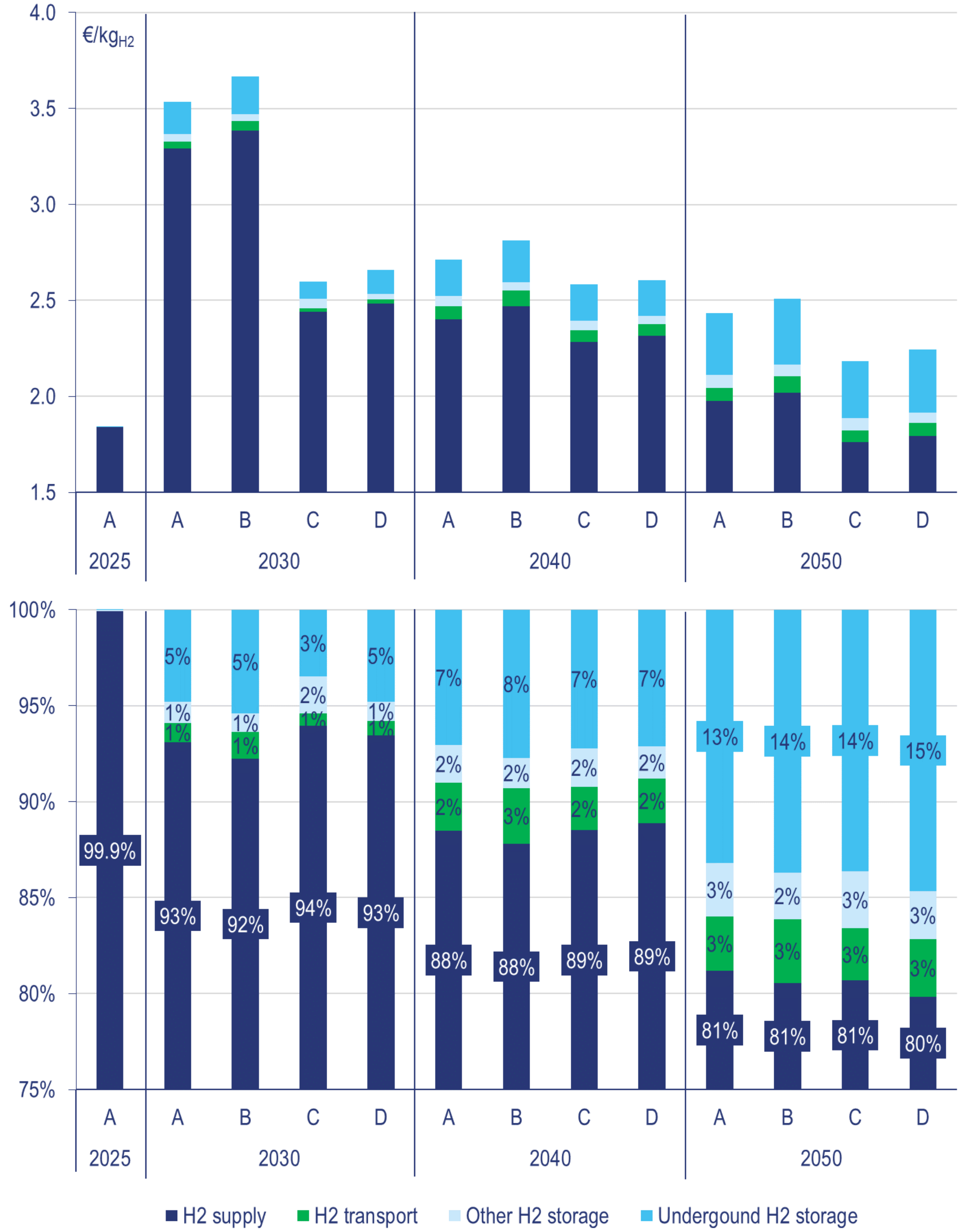


Figure 23: Specific hydrogen cost and value of underground H_2 storage in EU-27 & UK as absolute values in €/kg_{H2} (top) and as share of total H_2 cost in % (bottom)

Thanks to decreasing electrolysis cost and increasing use of cheap renewable electricity, the specific H_2 cost decrease gradually down to 2.0-2.5 €/kg until 2050 with small difference between domestic production and imports from outside the EU. As explained above scenarios A and C have slightly lower H_2 cost than scenarios B and D, respectively, due to assumed lower cost for H_2 transport and the use of cheap salt cavern only. The cost structure is similar over time with major impact of H_2 production and imports accounting for 80%-100% of total specific H_2 cost. However, the increasing share of renewable energy in the system require also more efforts in H_2 transport and storage. Thus, these cost amount to 0.20-0.50 €/kg (or 6-15 €/MWh) being responsible for 7% (in 2030) and up to 21% (in 2050) of total H_2 cost. The value of the underground storage of renewable hydrogen within the entire value chain can be interpreted as the share of storage cost in overall H_2 cost. According to the analysis results it varies between 3%-15% or ca. 0.10-0.35 €/kg (3-11 €/MWh).

5.2. CO_2 emission reduction potential

The expected CO_2 emissions from the power and hydrogen sectors follow the pre-assumed reduction targets (Figure 24). Note that CO_2 emission from the hydrogen sectors account not only for direct emission from grey and blue H_2 production but also for CO_2 intensity of electricity consumed by electrolysis given the corresponding technology mix in the power sector.[7]

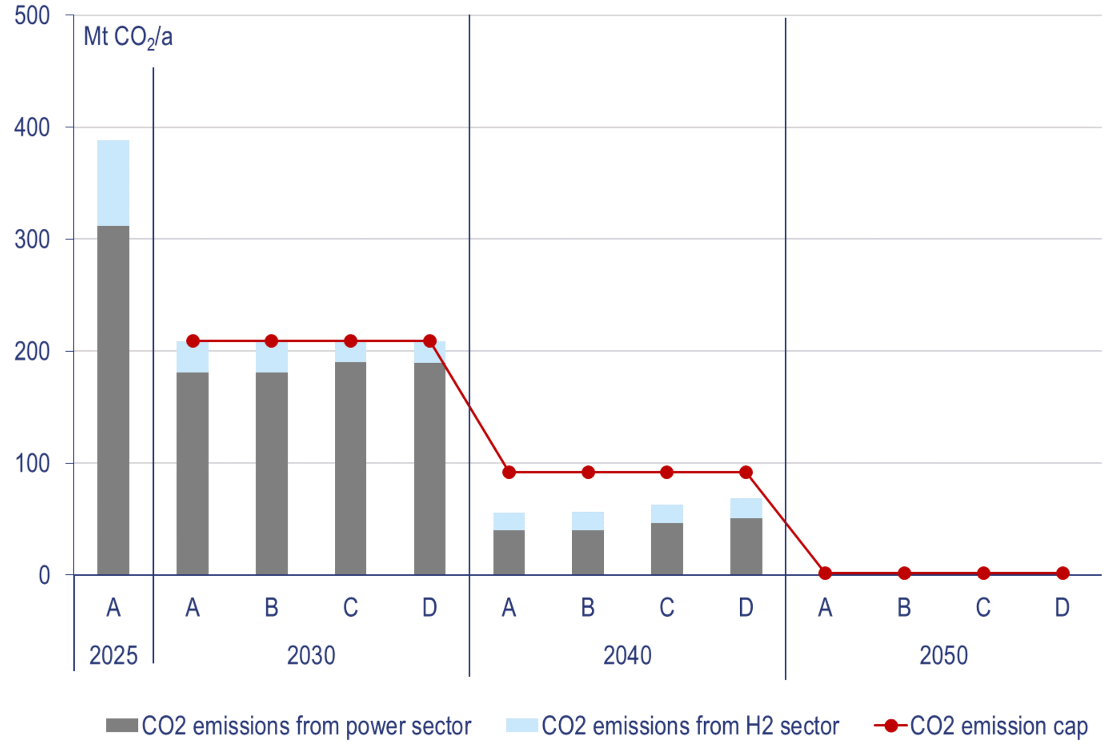


Figure 24: Total CO_2 emissions from power and H_2 sectors in comparison to CO_2 emission caps in EU-27 & UK

[7] For the sake of simplicity, CO_2 emissions for by-product hydrogen are attribute to the industry sector and thus excluded from the underlying analysis.

By 2030 the system reaches the CO_2 cap of ca. 200 Mt CO_2/a due to extensive use of comparatively cheap fossil fuels. Therefore, the overall emission from the hydrogen sector are higher in scenarios A and B with mainly domestic production than in scenarios C and D with clean hydrogen imports, since no emissions from electricity production for electrolysis is taken into account in the latter case. This changes in 2040 when renewable electricity dominates the power sector. In this context, the emissions in scenario A and B are lower than in scenario C and D. This is due to the fact that in scenarios C and D system flexibility in the power sector is mainly provided by larger NG-fuelled gas turbines whereas scenarios A and B take advantage of synergies from comparatively large renewable power supply for both direct electricity use and electrolysis. The additional system flexibility needs in scenarios A and B are provided by large flexible electrolysis capacities, underlying their positive contribution to the energy system. In 2050 there are no CO_2 emissions in line with the target of climate neutrality.

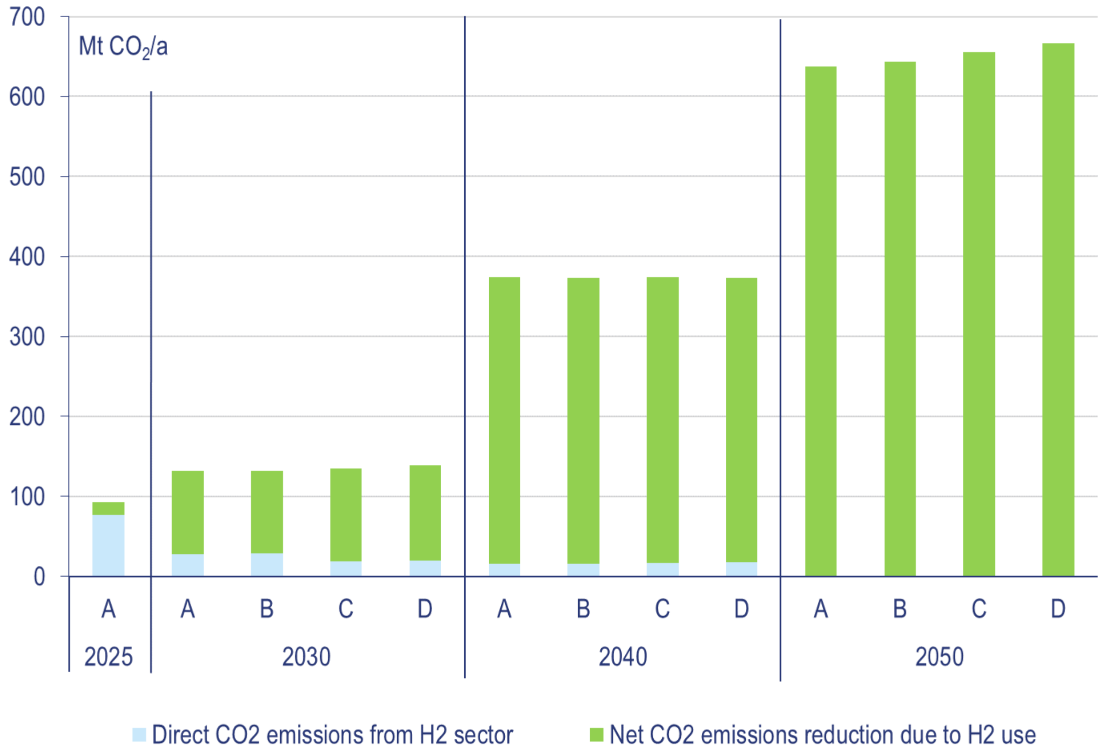


Figure 25: Overall CO_2 emissions from H_2 sector and
net emission reduction potential due to hydrogen use in EU-27 & UK

Figure 25 illustrates direct CO_2 emissions from the hydrogen sector, i.e., due to H_2 supply as explained above, and potential emission reduction due to hydrogen use as net CO_2 savings. The net CO_2 savings are calculated as gross CO_2 savings minus direct CO_2 emissions from the hydrogen sector. The gross CO_2 savings correspond to potential CO_2 emissions from fossil fuels substituted by hydrogen in the mobility, industry, heating and power sectors. Following fossil-based benchmarks are derived:

- in the mobility sector, the savings correspond to diesel and gasoline CO_2 emissions of the same fleet of conventional diesel and gasoline cars as assumed for fuel cell electric vehicles;
- in the industry sector, the savings account for substitution of the same amount of natural gas (e.g. in ammonia and methanol industries) as well as for substitution of coal/coke in steelmaking;
- in the heating sector, the savings account for substitutions of the same amount of natural gas typically used for heat generation;
- in the power sector, the savings take the average CO_2 intensity of power generation from NG-based turbines into account.

In this context, the net savings with 16 Mt CO_2/a are quite limited until 2025. The savings increase to 100-120 Mt CO_2/a by 2030 and achieve up to 640-660 Mt CO_2/a by 2050. Major savings can be realised in the industry and mobility sectors due to the comparatively high specific CO_2 intensity of conventional technologies in these sectors.

6. Discussion and concluding remarks

The analysis results reveal that underground H_2 storage is an important element of the future energy system. With its ability to store large quantities of energy during long time periods at comparatively low cost, it provides crucial flexibility measure to balance out renewable energy on a seasonal basis. In addition, substantial storage sites will be built both at large production and consumption centres, helping to reduce the investments in costly H_2 pipelines between exporting and importing countries.

In fact, underground H_2 storage volume capacities are needed already in the short-term until 2030 with 20 - 40 TWh_{H2} or 7 - 14 billion m³ also including first porous media sites. In the long term after 2030, the required storage volume capacities grow substantially up to more than 300 TWh_{H2} or 100 billion Sm³ in 2050 with an equal split between salt caverns and porous media. The capacities strongly depend on the overall hydrogen demand (1,700-1,900 TWh/a in 2050) both from different end-use sectors (industry, mobility and heating accounting for up to 90% of total demand) and from power sector (corresponding to around one fifth of the expected hydrogen demand in EU-27&UK). Although potential storage capacities for pure hydrogen might be lower on TWh-basis in comparison to today's conventional natural gas (ca. 1,000 TWh_{CH4}), the need for geological reservoirs will be similar due to lower volumetric density of hydrogen. Moreover, both natural gas and hydrogen storage have the same ratio between volume capacity and demand of ca. 20%.

Nevertheless, there are several effects which influence the optimal design and way of storage operation and differentiate it from conventional natural gas storage. Firstly, the hourly supply pattern for hydrogen will become more variable with increasing share of renewable H_2 production from intermittent power. Even in scenarios with substantial H_2 imports from outside the EU at a constant rate, the electrolysis is an important measure for system flexibility (installed capacity of 370-490 GW_{el} and utilisation of more than 3,900 h/a in all scenarios in 2050) with corresponding impact on storage injection needs. Secondly, the hourly gas demand profile will change by taking additional H_2 consumption at refuelling stations in the mobility sector and especially re-electrification in H_2-fueled power plants into account. In 2050 the dedicated H_2 power plants achieve an installed capacity of up to 230 GW and consume 160-300 TWh_{H2}/a to balance out renewable power generation. As a peakload technology with a utilisation rate of less than 1,000 h/a it has a strong direct impact on storage withdrawal behaviour. Thirdly, geographical distribution of H_2 storage facilities will follow large potentially new H_2 consumption hubs and future electrolysis capacities as a cornerstone of the future hydrogen supply in Europe. As the electrolysis will typically be located in proximity to renewable power generation, hydrogen will be transported from peripheries with large renewables potential to central Europe (e.g. Spain or Greece) with large hydrogen consumption (e.g. Germany or the Netherlands).

In the long term, porous media storage and salt caverns will both be operated at a seasonal basis with 1 to 2 full cycle equivalents per year, respectively. Nevertheless, salt caverns are expected to provide some short-term H_2 buffering to a limited extent, as this technology has a better technical capability to provide such services at lower cost in comparison to porous media. The injection flow rate capacity of underground H_2 storage of 180-250 GW (ca. 40%-

60% of installed electrolysis capacities) is lower by a factor of 2 in comparison to withdrawal flow rate capacities of 400-450 GW (ca. double size of installed capacities of H_2-fueled power plants). In this context, salt caverns are responsible for the major share of both input and output flow rate capacities and are, hence, used for hydrogen injection and withdrawal in large quantities at high speeds. These relationships fit well today's average design of underground storage sites for natural gas.

Most underground hydrogen sites are located in "six big" countries either with large H_2 demand or supply, namely in Germany, France, Italy, the UK, Spain and Poland, being responsible for more than 70% of overall capacities in EU-27&UK. The country-specific split between the technologies is based on a cost trade-off between H_2 transport, volume and flow rate capacities and depends on technology availability (i.e., geological potential), the need for quick H_2 injection and withdrawal (the higher the larger salt cavern capacities) as well as requirements for storage volumes (the higher the quantity of stored H_2 at low flow rates the larger the porous media storage) in the given grid node. Further regional resolution has not been taken into account within this study. According to the modelling results porous media storage occurs mainly in Italy (up to 90 TWh depending on the scenario) followed by France (up to 28 TWh), Austria (up to 17 TWh) and Germany (up to 16 TWh).

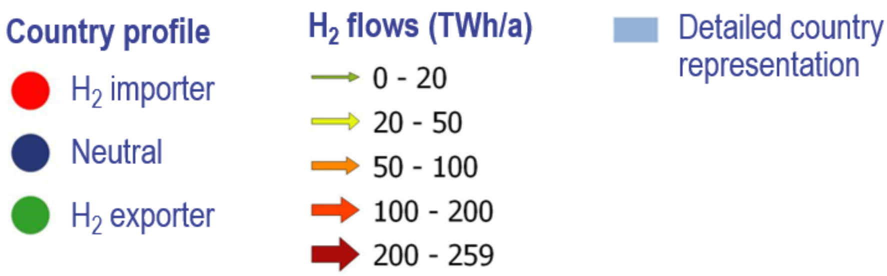
Although underground hydrogen storage is an important pillar for system flexibility and thus security of supply, the overall cost of up to 16-18 billion EUR/a account for only 6% of total system cost. This translates to less than 0.5 €/kg_{H2} (or less than 15 €/MWh_{H2}), being responsible for ca. 15% of the H_2 supply costs of less than 2.5 €/kg in the long-term. This low cost-based value of the underground storage of renewable hydrogen within the entire hydrogen value chain might underestimate the actual benefit of the technology from the macroeconomic perspective, especially when compared to a hypothetical system without H_2 storage. In addition, underground H_2 storage limits the curtailment and allows for a better use of intermittent power. This is due to the proximity of suitable underground storages with existing and future onshore and offshore wind/solar production capacities at Member State level. This is particularly true for porous media storage with a wide potential across many European countries. In this way underground H_2 storage supports achieving the net CO_2 savings from the use of hydrogen in different sectors of up to 660 Mt CO_2/a by 2050.

All in all, the analysis shows the important role of underground hydrogen storage, both in salt caverns and porous media reservoirs, to provide adequate flexibility at low cost in a system with large share of intermittent energy. In fact, the future energy system will require comparable volume capacities (on m^3-basis) as well as injection and withdrawal flow rate capacities as today for natural gas. This underlines that current storage business and industry will be needed in the future at a similar scale. However, the storage location and way of operation (due to changing system requirements) might differ and should be adapted correspondingly. As there is still a number of unanswered technical, economic, environmental and societal questions in respect to H_2 storage in porous media and the build-up of new sites takes reasonable time, the development of the technology and new real-life projects should start as soon as possible. This should be accompanied by adequate measure to ensure favourable boundary conditions in the storage market and thus to open attractive investment opportunities in the new H_2 storage businesses.

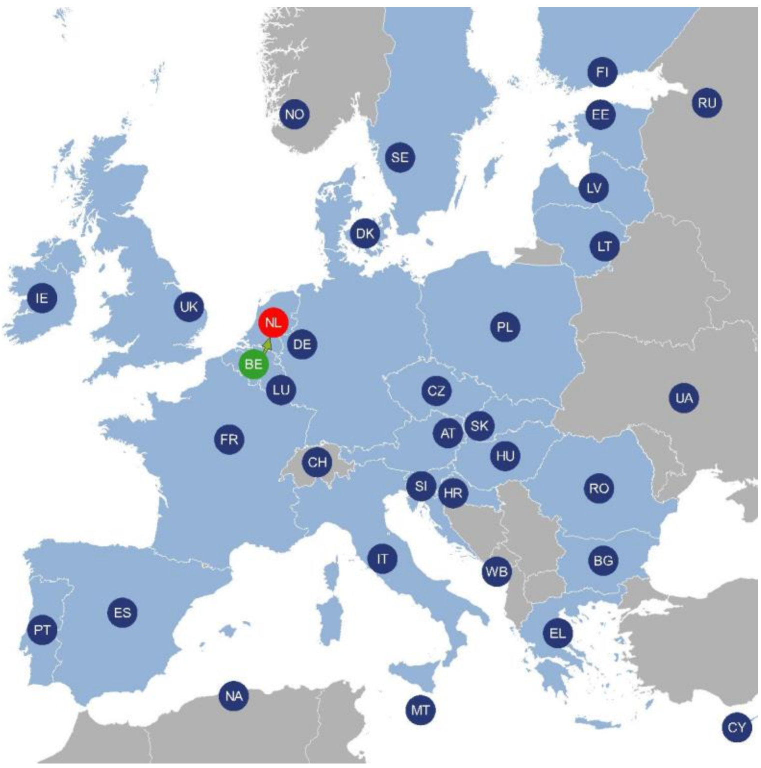
7. Appendix

7.1. Expected hydrogen flows

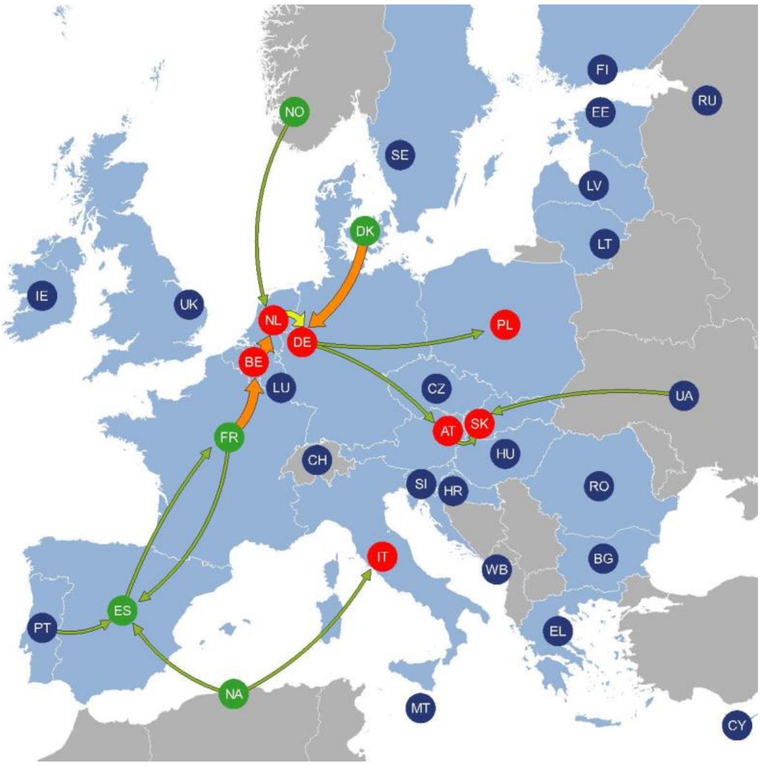
Legend:



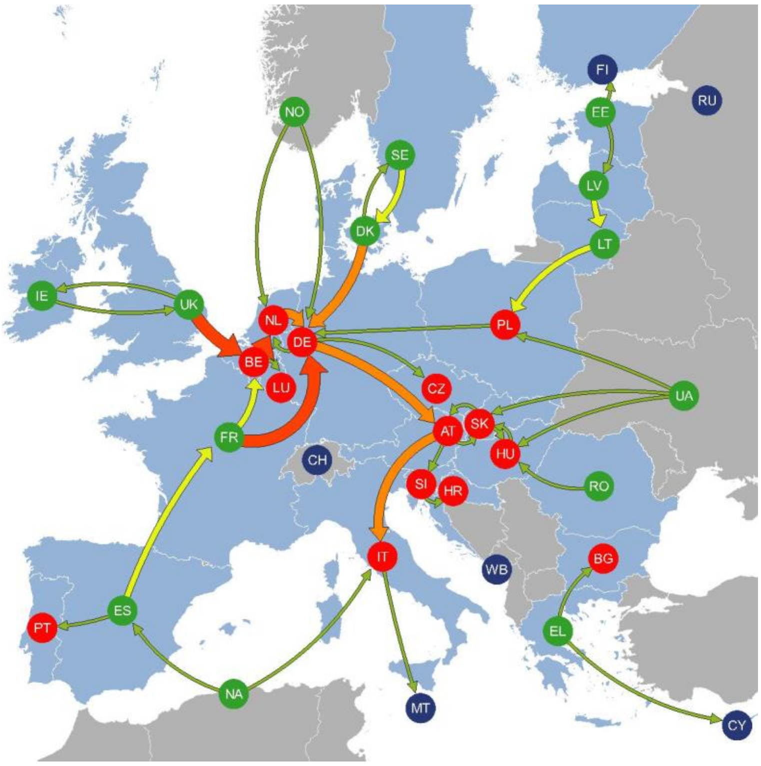
Scenario A (2025)



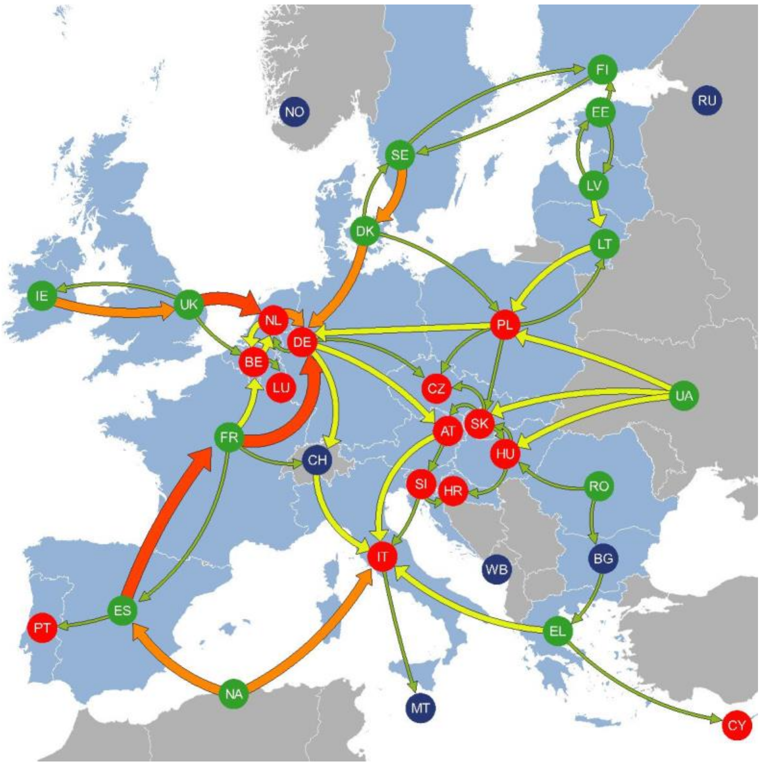
Scenario A (2030)



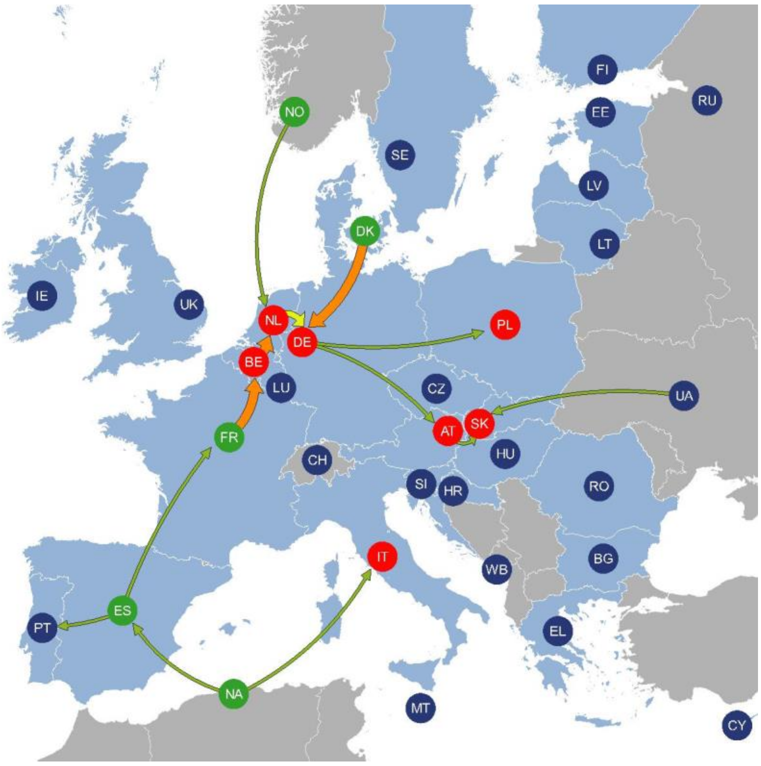
Scenario A (2040)



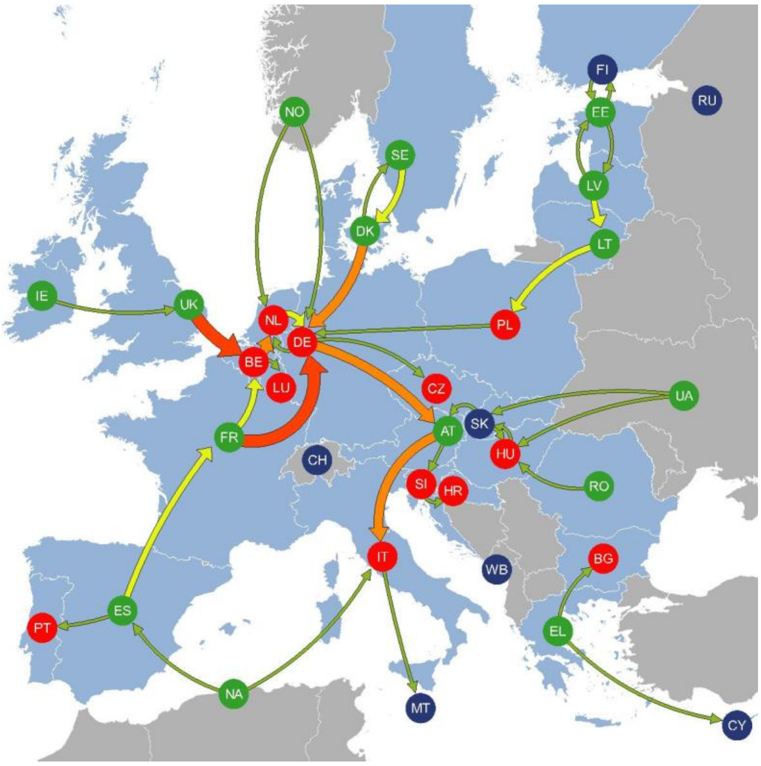
Scenario A (2050)



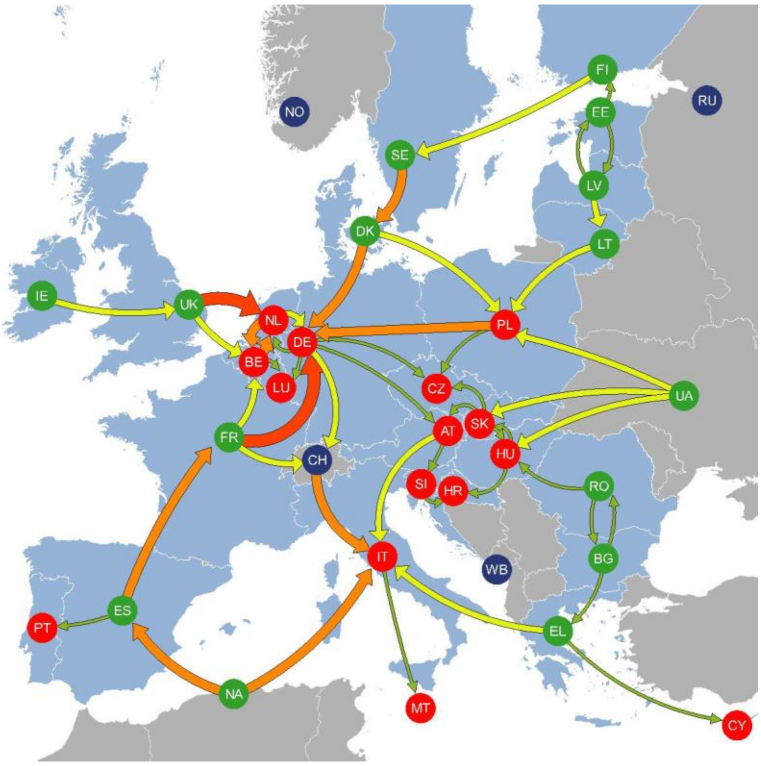
Scenario B (2030)



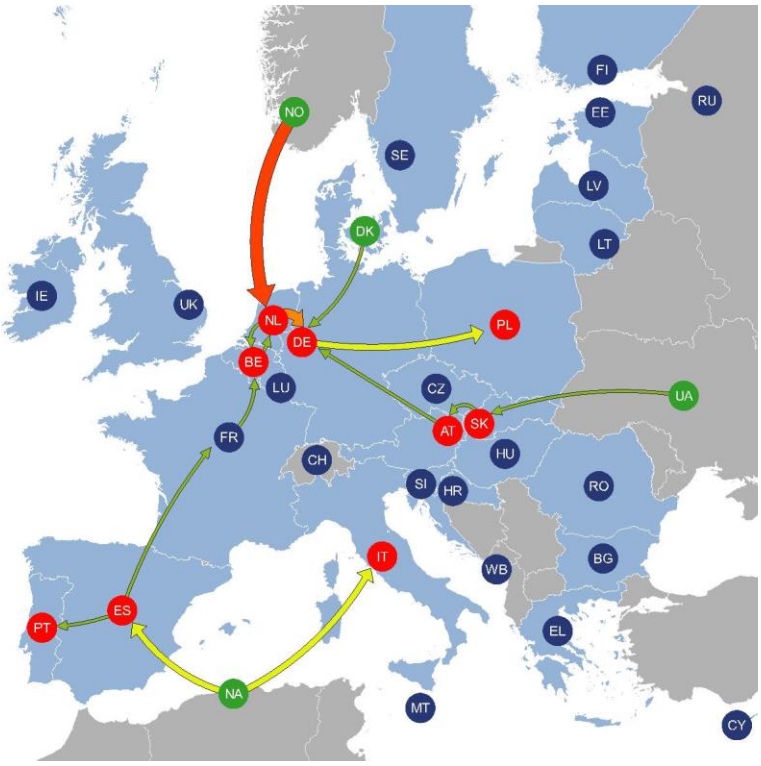
Scenario B (2040)



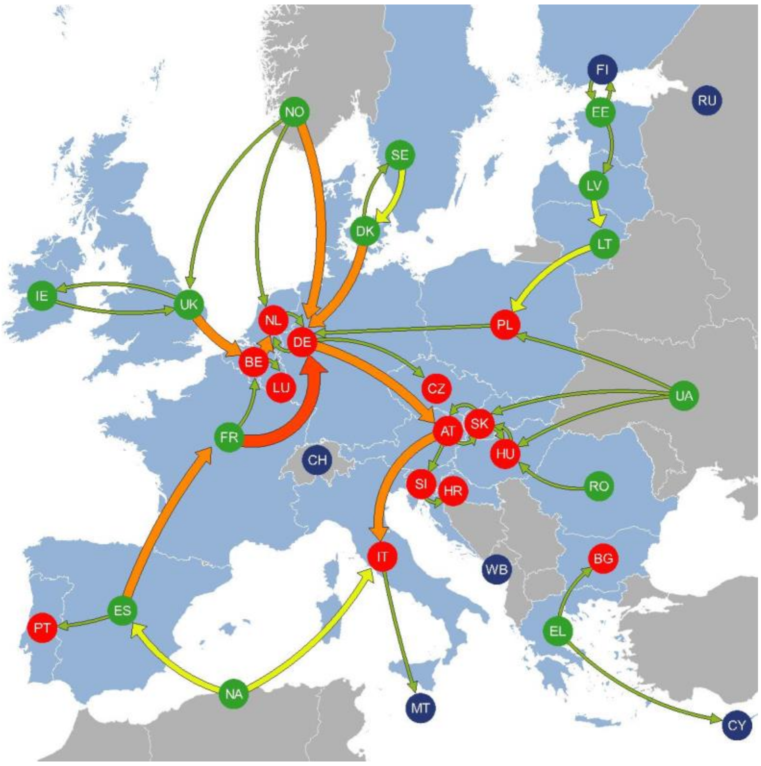
Scenario B (2050)



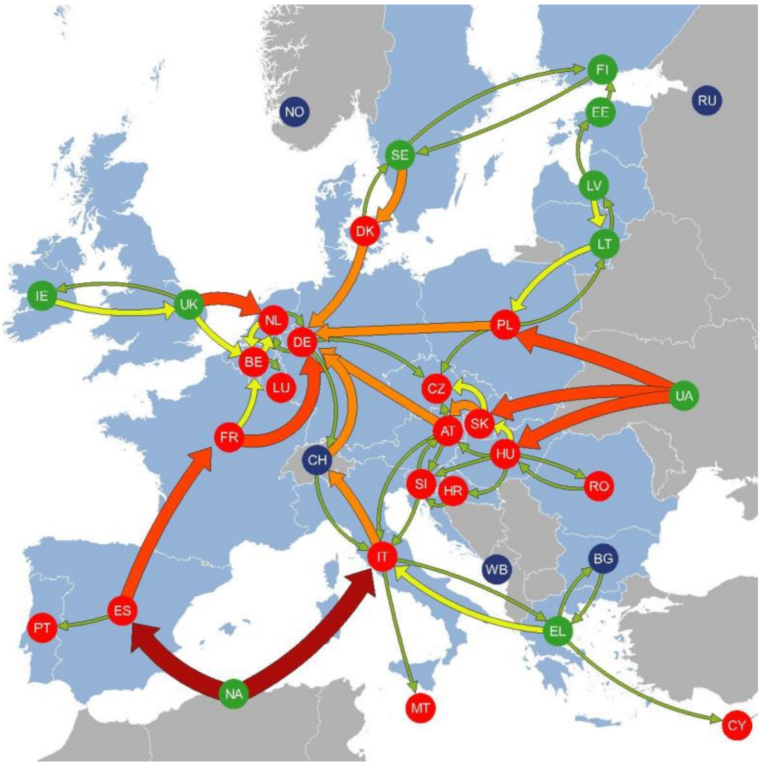
Scenario C (2030)



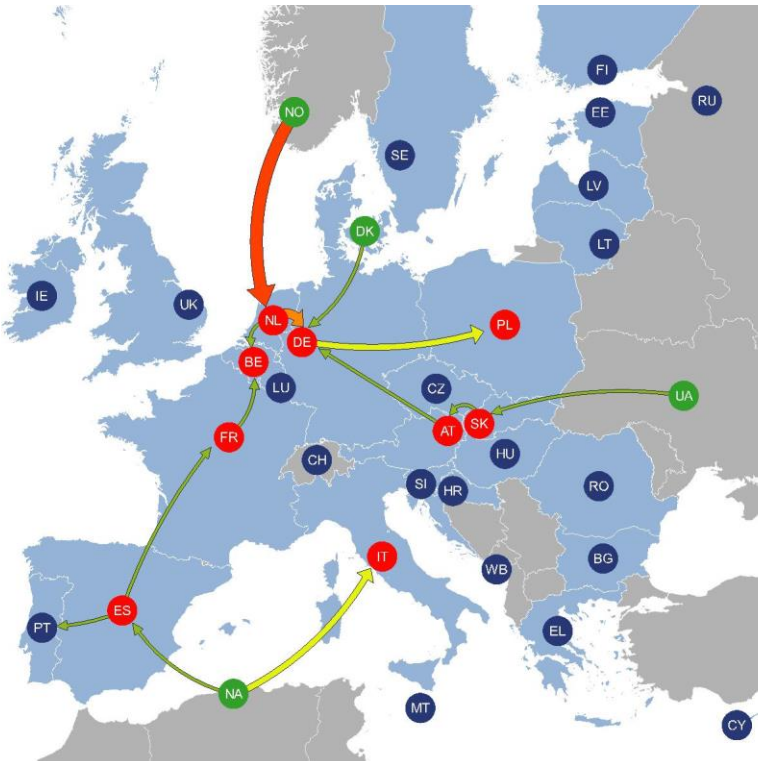
Scenario C (2040)



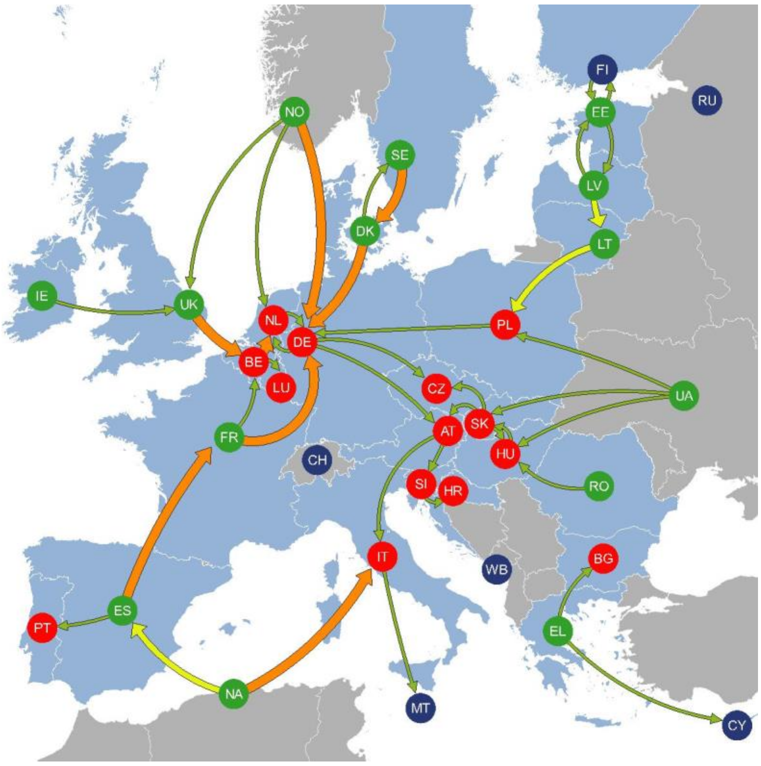
Scenario C (2050)



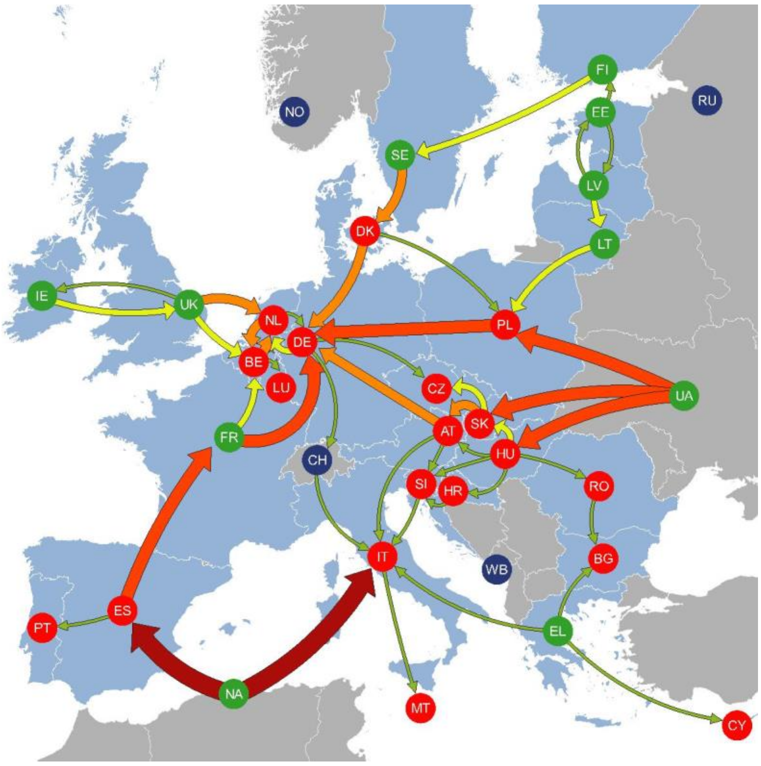
Scenario D (2030)



Scenario D (2040)

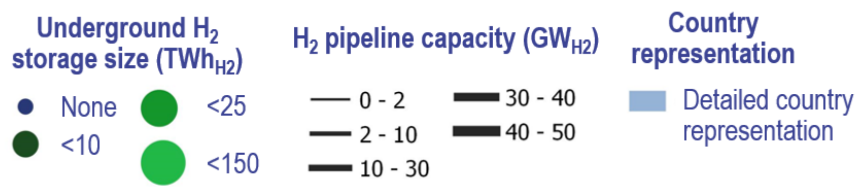


Scenario D (2050)

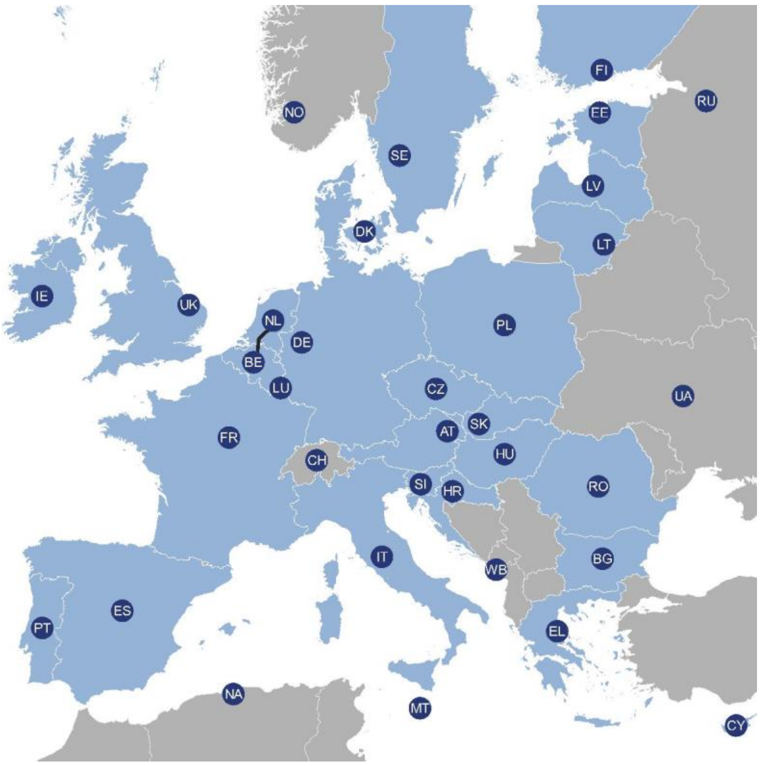


7.2. Expected hydrogen infrastructure capacities

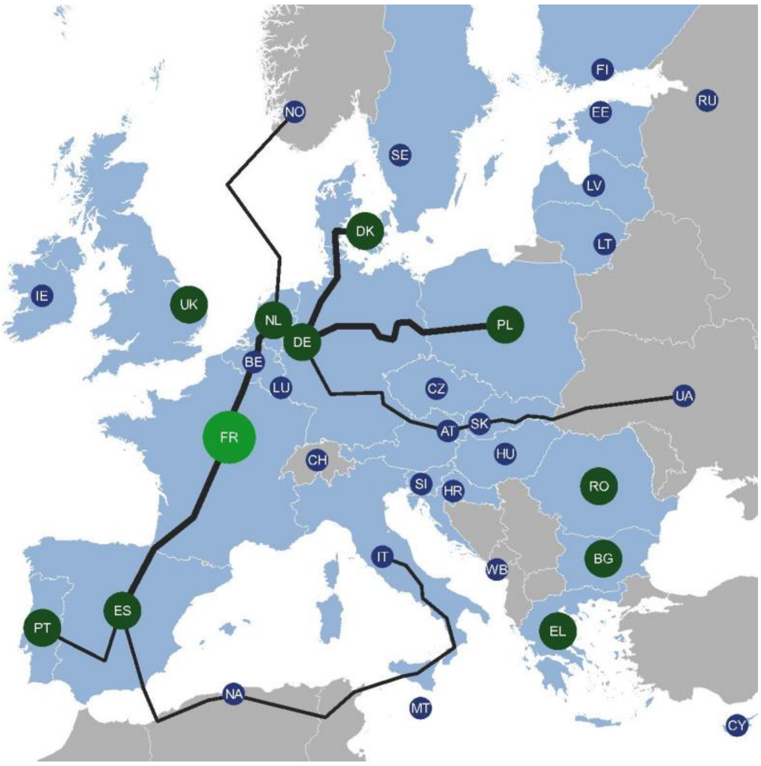
Legend:



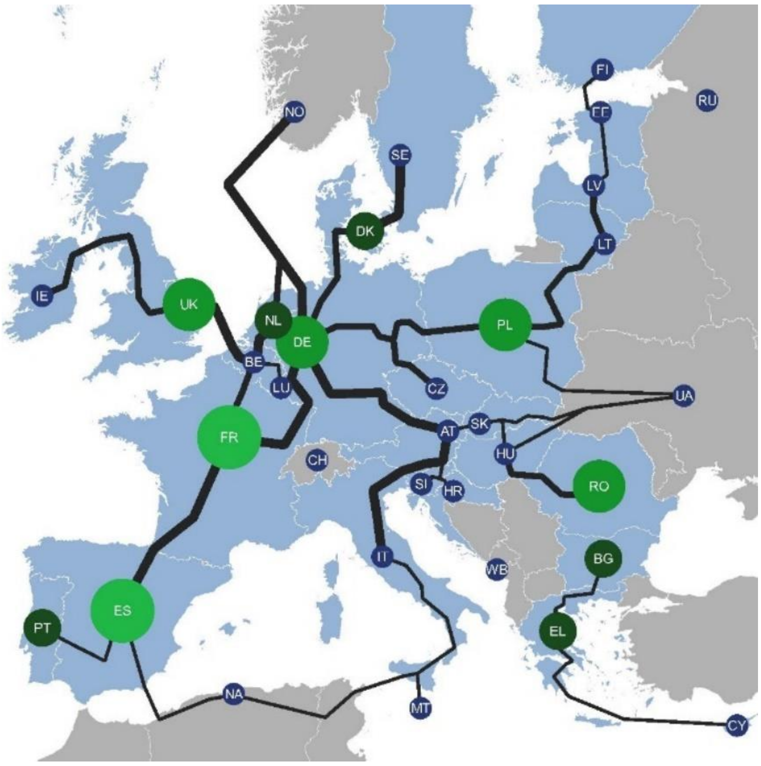
Scenario A (2025)



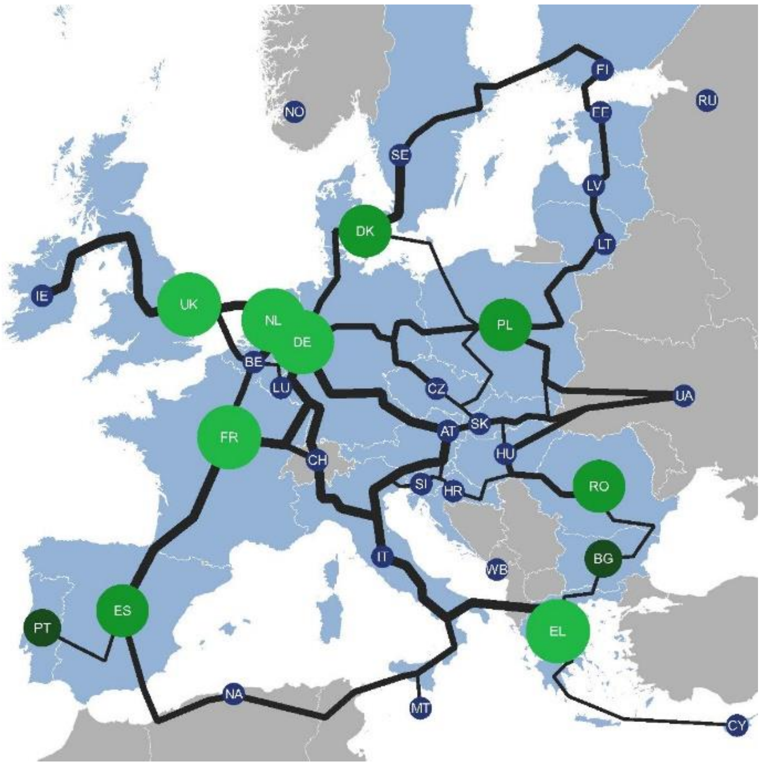
Scenario A (2030)



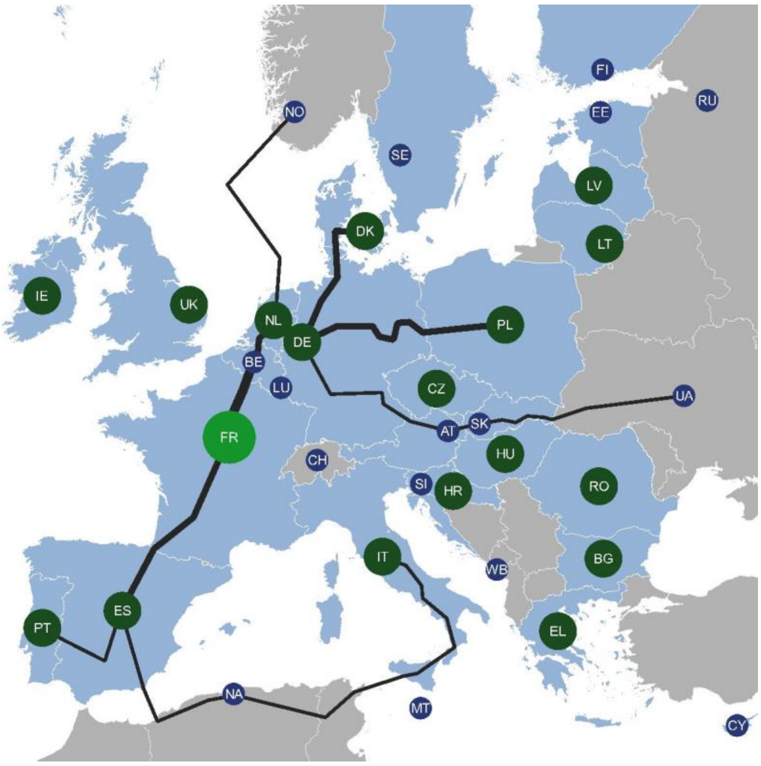
Scenario A (2040)



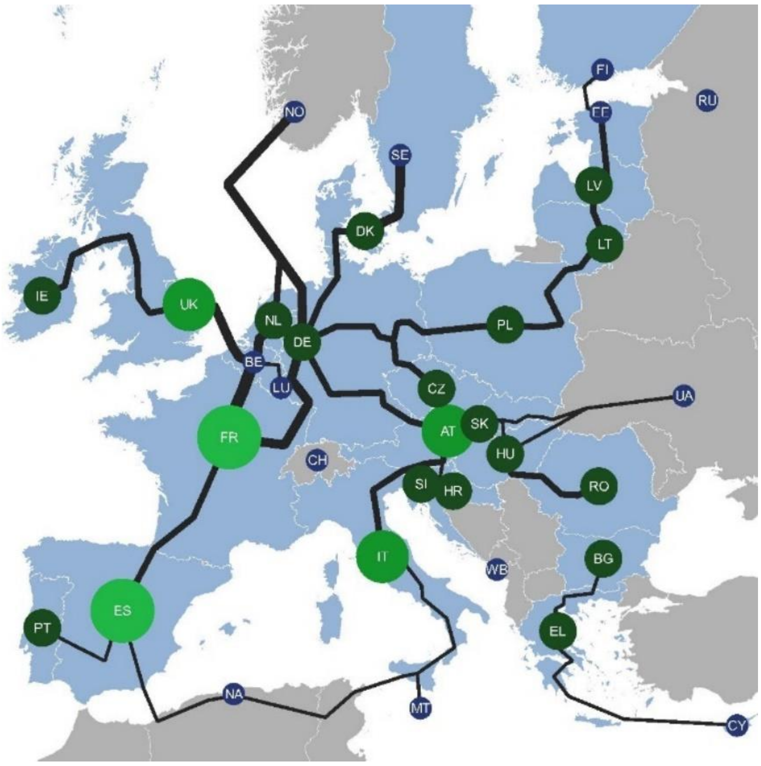
Scenario A (2050)



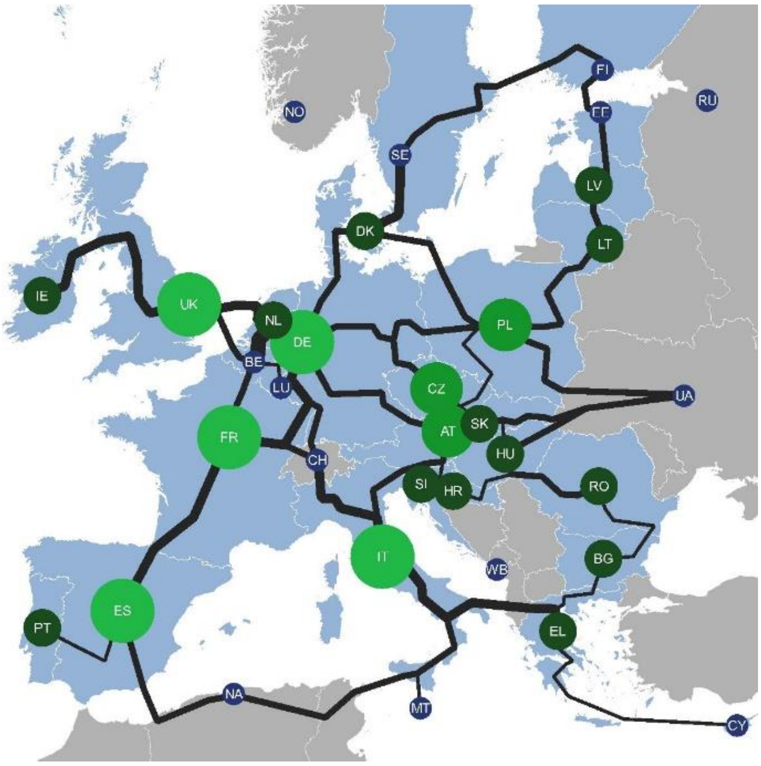
Scenario B (2030)



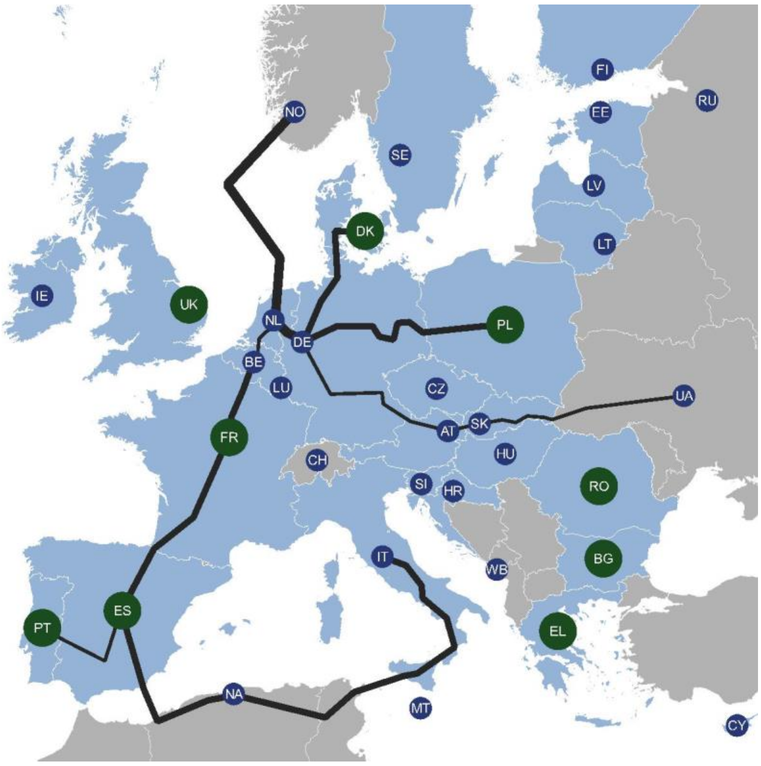
Scenario B (2040)



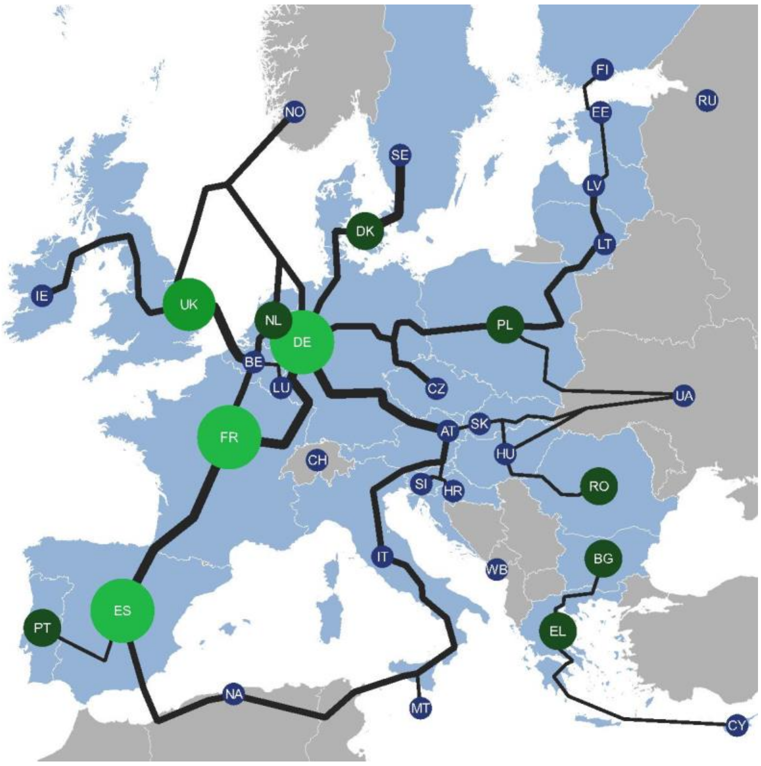
Scenario B (2050)



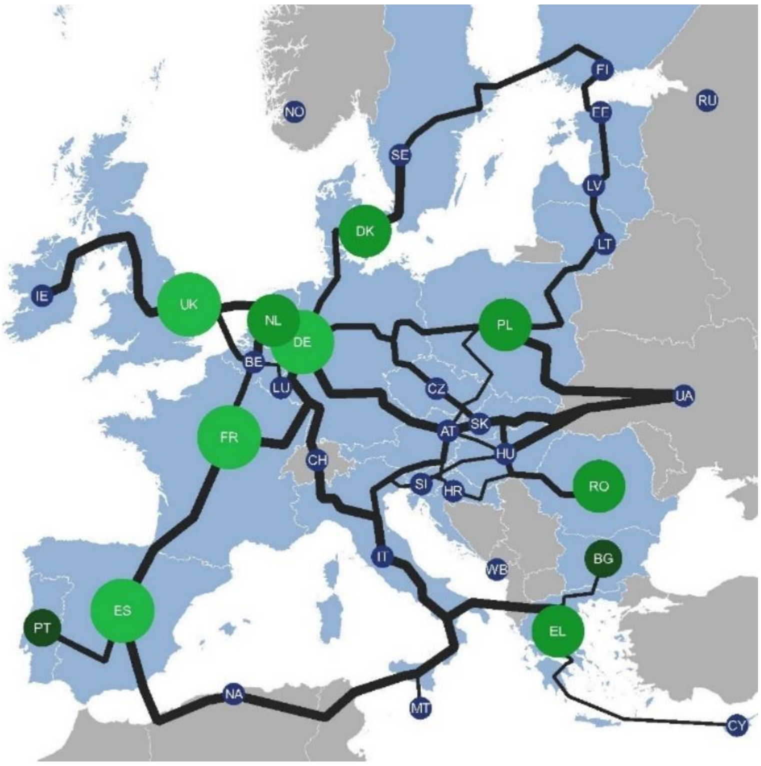
Scenario C (2030)



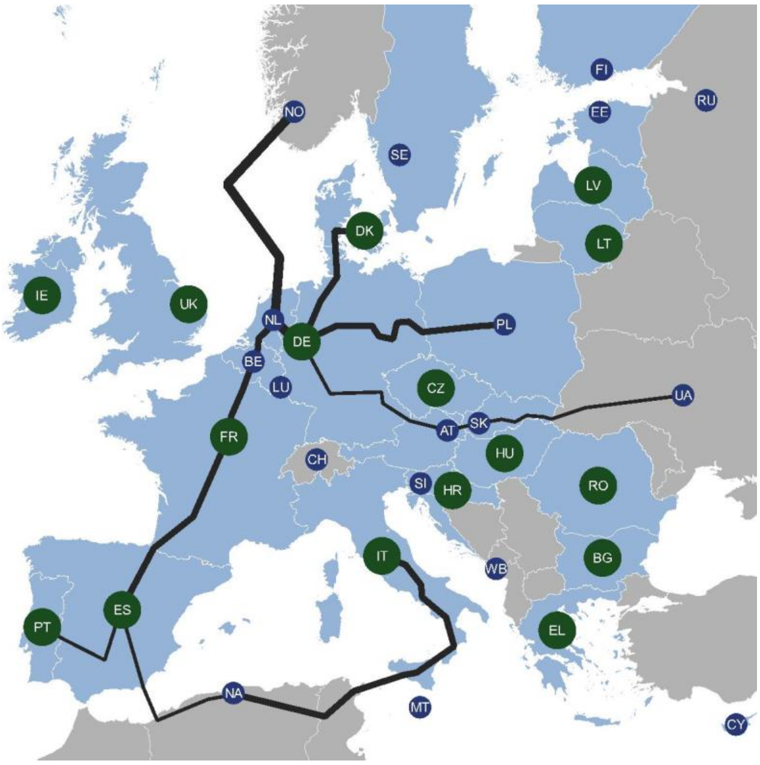
Scenario C (2040)



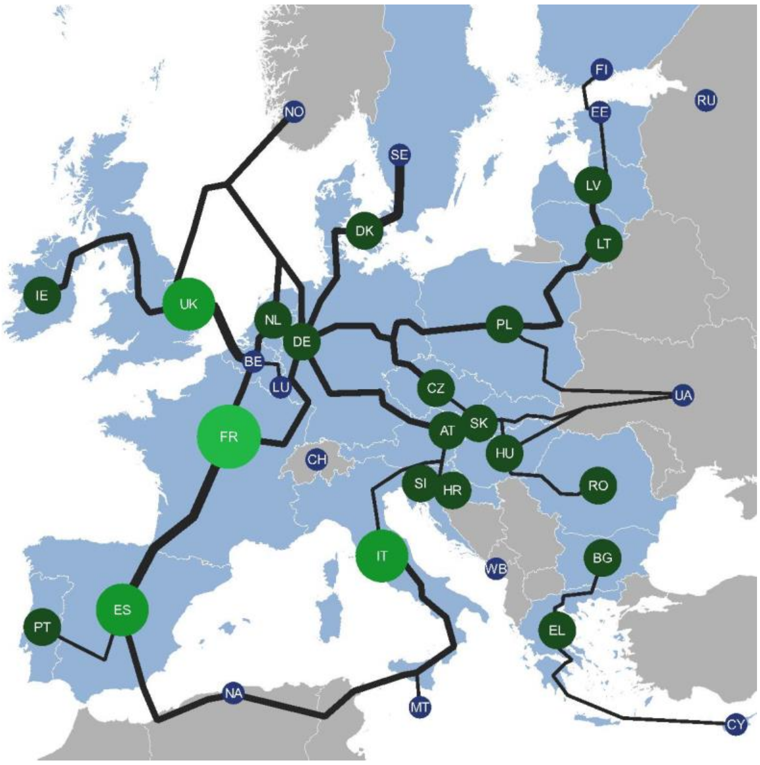
Scenario C (2050)



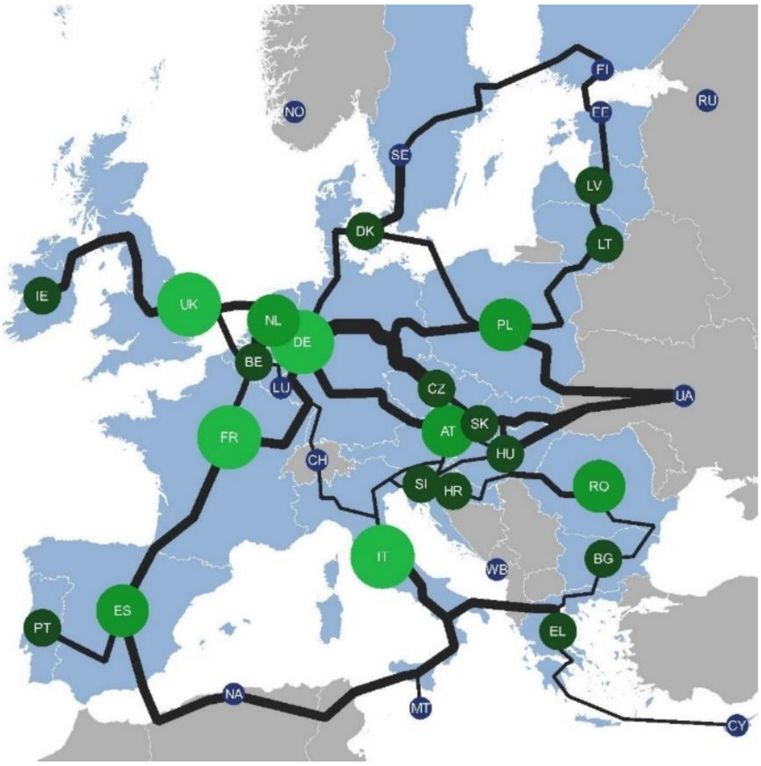
Scenario D (2030)



Scenario D (2040)



Scenario D (2050)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WB
ES
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PT
NA
MT
CY

7.3. Country-specific comparisons for scenario B in 2050

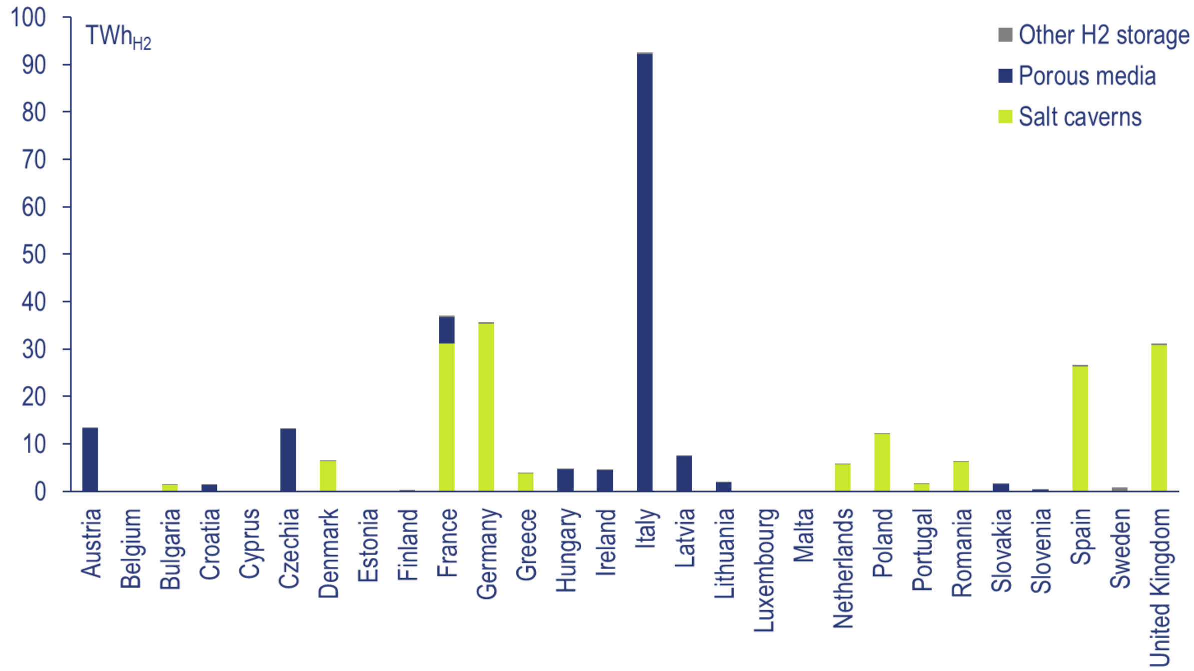

Figure 26: Optimal volume capacity for hydrogen storage (MS level, scenario B in 2050)

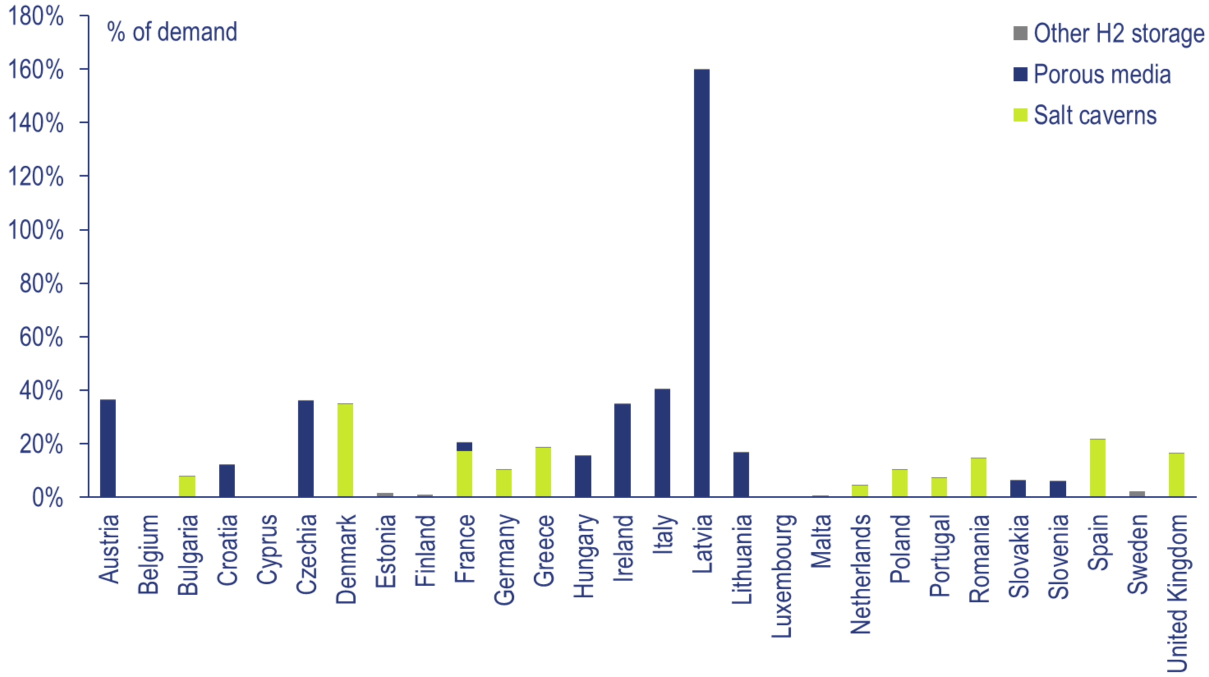

Figure 27: Optimal storage volume capacity as percentage of overall hydrogen demand (MS level, scenario B in 2050)

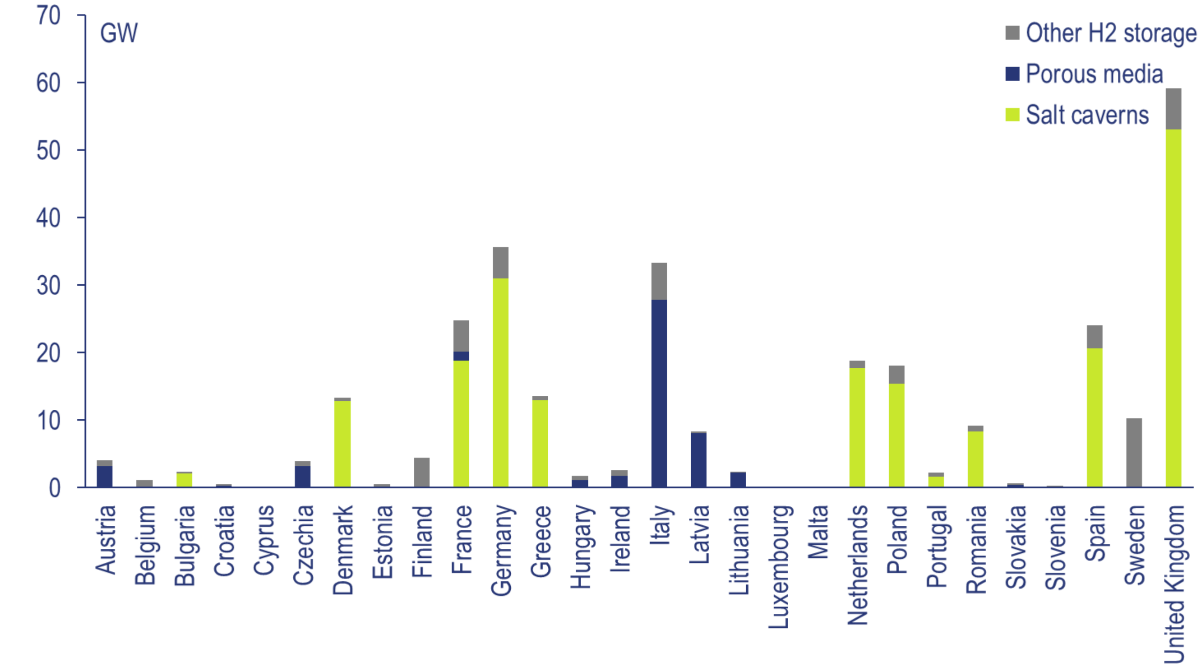

Figure 28: Optimal injection flow rate capacity for hydrogen storage (MS level, scenario B in 2050)

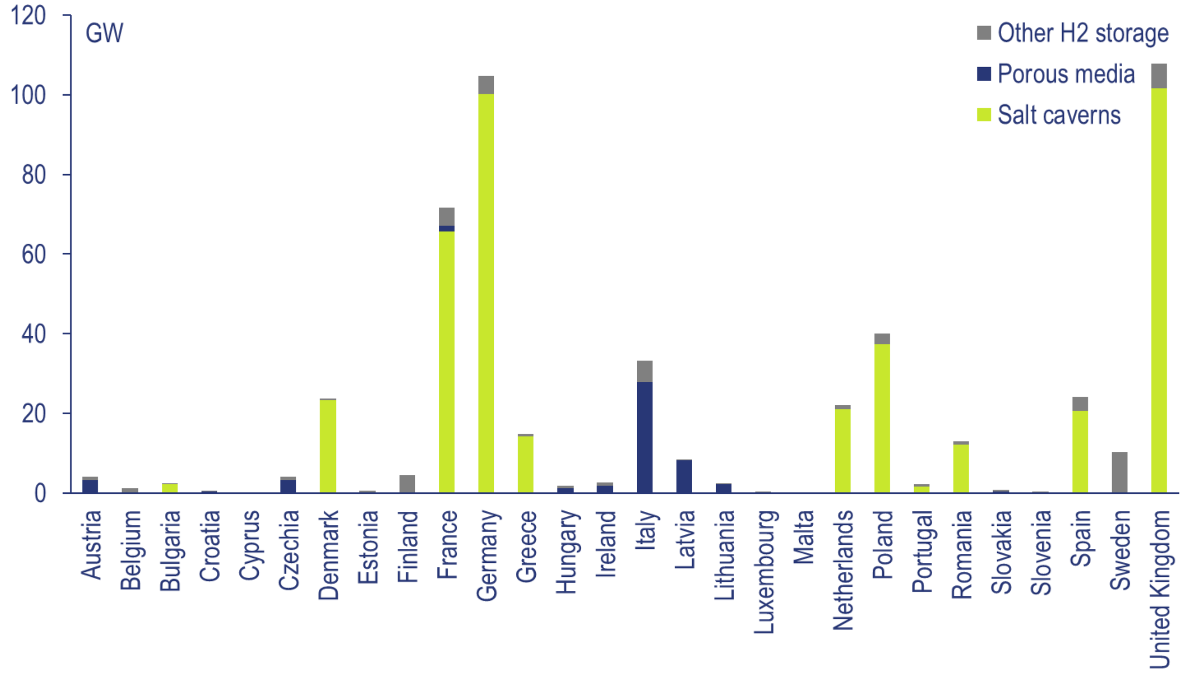

Figure 29: Optimal withdrawal flow rate capacity for hydrogen storage (MS level, scenario B in 2050)

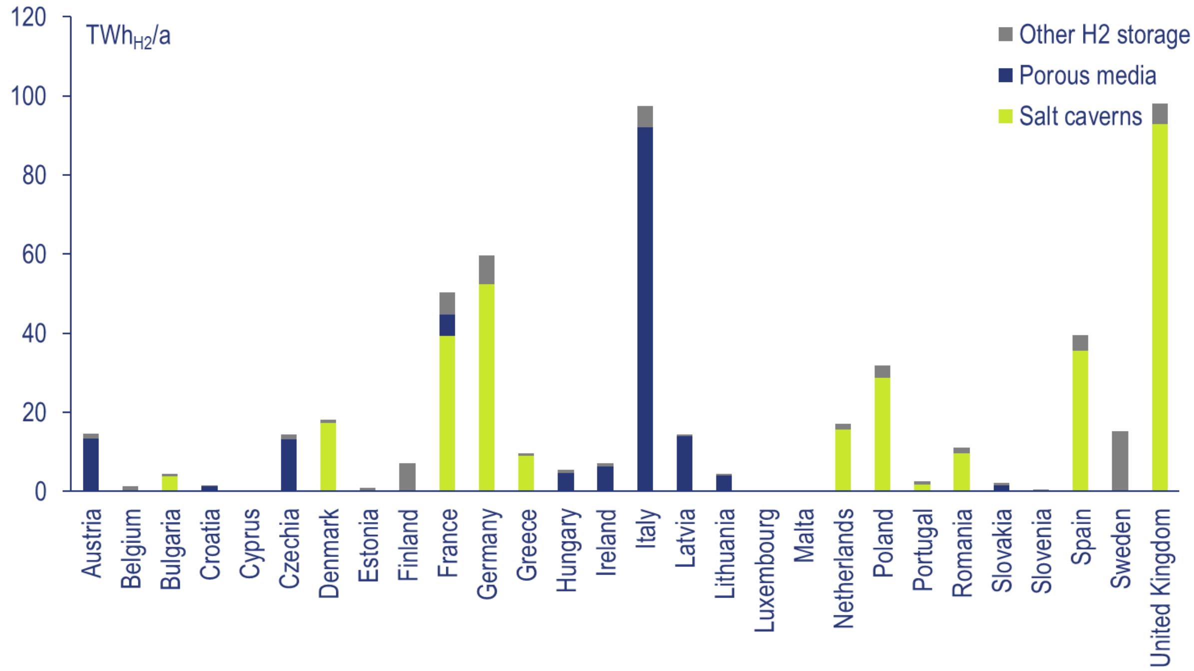

Figure 30: Hydrogen storage throughput (MS level, scenario B in 2050)

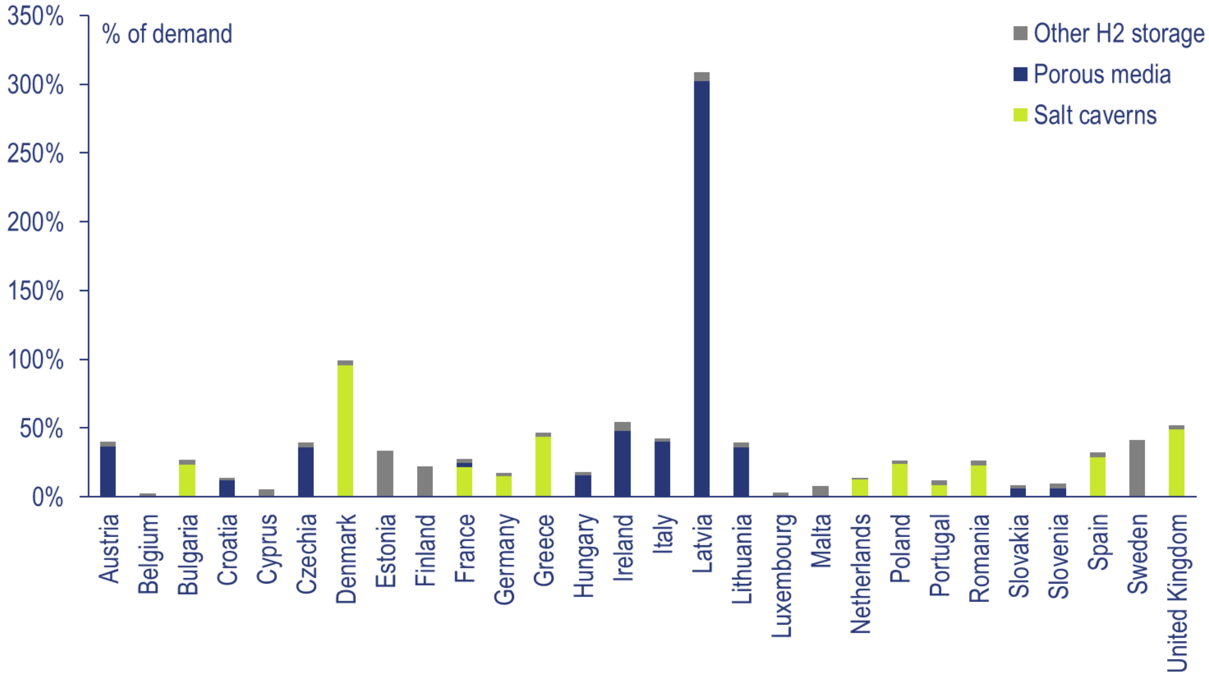

Figure 31: Hydrogen storage throughput as percentage of overall hydrogen demand (MS level, scenario B in 2050)

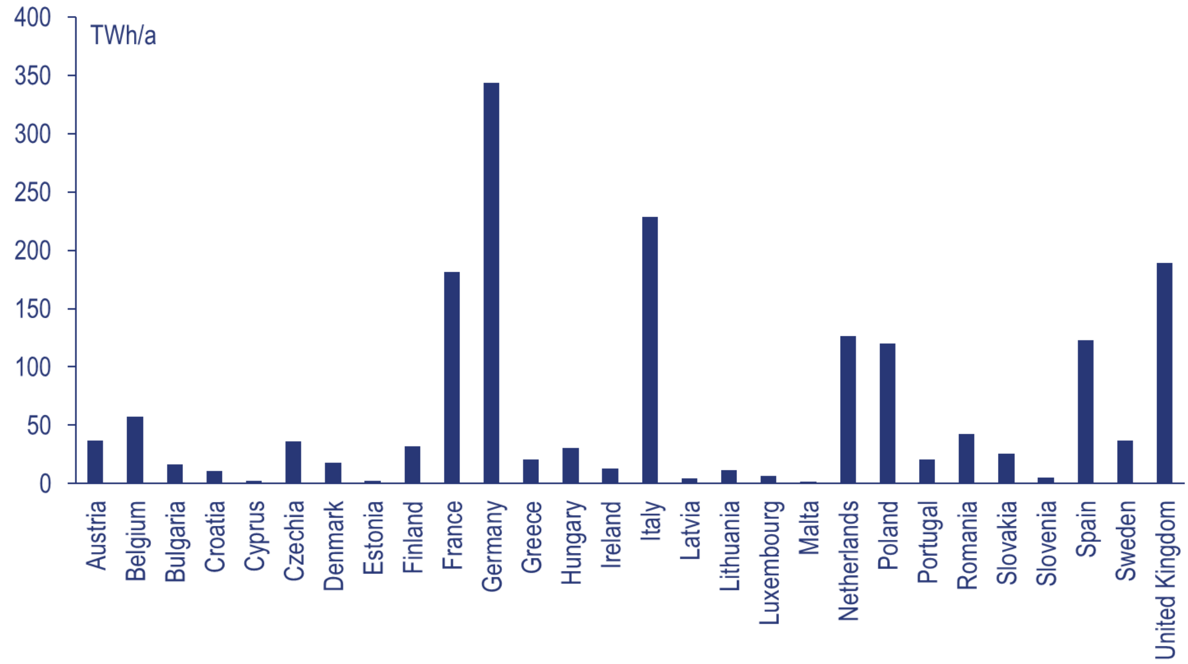

Figure 32: Country-specific hydrogen demand (MS level, scenario B in 2050)

7.4. Country-specific data tables

In the following, country-specific modelling results are provided for all scenarios and time steps.

In total, five parameters are presented:

1. Storage Volume Capacity (TWh_{H2})
2. Storage Throughput (TWh_{H2}/a)
3. Number of Full Cycle Equivalents (= storage volume / storage throughput)
4. Maximum Injection Capacity (GW_{H2})
5. Maximum Withdrawal Capacity (GW_{H2})

For each parameter, data are provided individually for both large-scale hydrogen storage technologies (i.e. salt caverns and porous media). Please note: porous media storages were only considered in scenarios B and D.

1a) Storage Volume Capacity (TWh_{H2}) – Salt Caverns

Scenario	A	A	A	A	B	B	B	C	C	C	D	D	D
Year	2025	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Storage Volume Capacity - Salt Caverns (TWh_H2)													
Austria	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Belgium	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bulgaria	0.0	0.4	0.7	2.4	0.3	0.0	1.2	0.4	0.8	4.2	0.3	0.0	2.0
Croatia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cyprus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Czechia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Denmark	0.0	6.0	7.8	10.7	5.3	5.5	6.3	3.5	7.7	10.4	2.8	5.5	6.7
Estonia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Finland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
France	0.0	12.0	38.2	59.3	11.3	16.4	31.2	4.2	37.9	54.6	3.2	8.2	26.7
Germany	0.0	0.1	16.2	56.0	0.5	4.6	35.3	0.1	25.2	66.0	0.2	4.2	24.0
Greece	0.0	0.2	7.3	25.7	0.2	4.6	3.8	0.3	7.5	24.8	0.2	5.0	8.8
Hungary	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ireland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Italy	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Latvia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lithuania	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Luxembourg	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Malta	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Netherlands	0.0	1.7	0.6	26.0	1.7	0.9	5.7	0.0	1.0	15.7	0.0	2.2	11.0
Poland	0.0	0.7	10.6	19.3	1.1	2.9	12.1	0.1	9.2	23.2	0.0	3.2	14.0
Portugal	0.0	1.1	0.5	2.3	1.7	0.6	1.4	1.2	0.8	0.9	1.5	0.6	2.8
Romania	0.0	0.4	10.7	17.6	0.4	6.1	6.1	0.6	9.0	18.1	0.3	4.4	8.0
Slovakia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Slovenia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Spain	0.0	4.4	26.3	25.0	4.7	21.1	26.4	3.4	25.3	25.2	4.2	17.8	21.0
Sweden	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
United Kingdom	0.0	9.7	22.4	38.7	9.7	17.4	30.8	7.8	19.6	40.7	7.7	15.6	30.6
EU27 + UK	0.1	36.8	141.2	283.1	36.8	80.1	160.2	21.4	143.9	283.9	20.4	66.8	155.6

1b) Storage Volume Capacity (TWh$_{H2}$) – Porous Media

Scenario	A	A	A	A	B	B	B	C	C	C	D	D	D
Year	2025	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Storage Volume Capacity - Porous Media (TWh_H2)													
Austria					0.0	11.8	13.4				0.0	7.2	17.1
Belgium					0.0	0.0	0.0				0.0	0.0	1.4
Bulgaria					0.0	1.0	0.0				0.0	0.5	1.1
Croatia					0.1	0.5	1.3				0.4	0.5	1.0
Cyprus					0.0	0.0	0.0				0.0	0.0	0.0
Czechia					0.3	2.5	13.1				1.3	2.0	3.9
Denmark					0.0	0.0	0.0				0.0	0.0	0.0
Estonia					0.0	0.0	0.0				0.0	0.0	0.0
Finland					0.0	0.0	0.0				0.0	0.0	0.0
France					0.0	19.9	5.5				0.0	25.3	28.0
Germany					0.0	0.0	0.0				0.0	0.0	16.4
Greece					0.0	1.4	0.0				0.0	1.8	0.0
Hungary					0.3	1.7	4.7				0.7	1.9	3.2
Ireland					0.4	1.7	4.5				2.9	1.7	4.2
Italy					1.7	17.7	92.1				0.7	15.3	78.5
Latvia					0.5	5.1	7.4				1.1	4.9	6.6
Lithuania					1.2	2.7	1.9				0.9	3.7	2.2
Luxembourg					0.0	0.0	0.0				0.0	0.0	0.0
Malta					0.0	0.0	0.0				0.0	0.0	0.0
Netherlands					0.0	0.0	0.0				0.0	0.0	0.0
Poland					0.0	0.0	0.0				0.0	0.0	0.0
Portugal					0.0	0.0	0.0				0.0	0.0	0.0
Romania					0.0	3.5	0.0				0.0	3.4	3.0
Slovakia					0.0	4.7	1.5				0.0	2.6	3.1
Slovenia					0.0	0.2	0.3				0.0	0.3	0.1
Spain					0.0	5.5	0.0				0.0	0.1	0.0
Sweden					0.0	0.0	0.0				0.0	0.0	0.0
United Kingdom					0.0	0.0	0.0				0.0	0.0	0.0
EU27 + UK					4.6	79.7	145.7				8.0	71.1	169.6

2a) Storage Throughput (TWh_{H2}/a) – Salt Caverns

Scenario		A	A	A	A	B	B	B	C	C	C	D	D	D
Year		2025	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Storage Throughput - Salt Caverns (TWh_H2/a)														
Austria		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Belgium		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bulgaria		0.0	0.4	0.8	3.2	0.3	0.0	3.8	1.2	0.9	4.4	0.6	0.0	3.0
Croatia		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cyprus		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Czechia		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Denmark		0.0	17.3	18.9	23.0	16.7	20.9	17.4	12.0	17.4	22.9	10.4	19.7	17.2
Estonia		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Finland		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
France		0.0	30.8	43.9	64.5	31.3	23.3	39.2	10.5	39.4	64.6	10.0	13.5	41.0
Germany		0.0	0.8	16.7	60.7	2.8	8.1	52.4	0.3	25.3	66.2	1.0	5.9	39.2
Greece		0.0	0.2	8.2	26.7	0.2	6.9	9.1	0.6	8.5	26.3	0.5	7.3	12.5
Hungary		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ireland		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Italy		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Latvia		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lithuania		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Luxembourg		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Malta		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Netherlands		0.0	6.2	0.6	26.4	6.1	1.6	15.7	0.0	1.0	16.9	0.0	2.9	19.4
Poland		0.0	4.0	13.4	33.4	4.4	9.3	28.6	0.4	13.0	38.1	0.1	9.0	29.9
Portugal		0.0	2.6	0.6	2.5	2.9	0.8	1.7	2.7	0.8	1.8	3.1	0.9	4.3
Romania		0.0	0.4	11.1	18.7	0.5	7.8	9.6	1.9	9.3	18.5	1.0	5.8	9.8
Slovakia		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Slovenia		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Spain		0.0	11.9	28.5	33.2	12.3	26.6	35.5	8.8	26.5	36.2	9.7	22.4	29.9
Sweden		0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
United Kingdom		0.0	16.7	56.7	96.3	16.4	52.3	92.9	24.0	46.5	97.5	24.7	48.6	87.0
EU27 + UK		0.1	91.3	199.2	388.6	94.0	157.3	306.0	62.4	188.7	393.5	61.2	135.9	293.3

2b) Storage Throughput (TWh$_{H2}$/a) – Porous Media

Scenario	A	A	A	A	B	B	B	C	C	C	D	D	D
Year	2025	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Storage Throughput - Porous Media (TWh_H2/a)													
Austria					0.0	11.8	13.4				0.0	7.2	17.1
Belgium					0.0	0.0	0.0				0.0	0.0	1.4
Bulgaria					0.0	1.0	0.0				0.0	0.5	1.1
Croatia					0.1	0.5	1.3				0.9	0.5	1.0
Cyprus					0.0	0.0	0.0				0.0	0.0	0.0
Czechia					1.1	2.5	13.1				2.5	2.0	3.9
Denmark					0.0	0.0	0.0				0.0	0.0	0.0
Estonia					0.0	0.0	0.0				0.0	0.0	0.0
Finland					0.0	0.0	0.0				0.0	0.0	0.0
France					0.0	19.9	5.5				0.0	25.3	28.0
Germany					0.0	0.0	0.0				0.0	0.0	16.4
Greece					0.0	1.4	0.0				0.0	1.8	0.0
Hungary					0.3	1.7	4.7				1.8	1.9	3.2
Ireland					0.3	2.4	6.2				6.4	2.5	6.0
Italy					1.7	17.7	92.1				1.0	15.3	78.5
Latvia					0.6	8.1	14.0				2.7	8.0	12.8
Lithuania					2.5	3.8	4.1				2.8	4.8	4.2
Luxembourg					0.0	0.0	0.0				0.0	0.0	0.0
Malta					0.0	0.0	0.0				0.0	0.0	0.0
Netherlands					0.0	0.0	0.0				0.0	0.0	0.0
Poland					0.0	0.0	0.0				0.0	0.0	0.0
Portugal					0.0	0.0	0.0				0.0	0.0	0.0
Romania					0.0	3.5	0.0				0.0	3.4	3.0
Slovakia					0.0	4.7	1.6				0.0	2.6	3.1
Slovenia					0.0	0.2	0.3				0.0	0.3	0.1
Spain					0.0	5.5	0.0				0.0	0.1	0.0
Sweden					0.0	0.0	0.0				0.0	0.0	0.0
United Kingdom					0.0	0.0	0.0				0.0	0.0	0.0
EU27 + UK					6.5	84.6	156.3				18.2	76.2	179.7

3a) Number of Full Cycle Equivalents – Salt Caverns

Scenario	A	A	A	A	B	B	B	C	C	C	D	D	D
Year	2025	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Number of Full Cycle Equivalents - Salt Caverns													
Austria	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Belgium	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bulgaria	1.0	1.1	1.1	1.3	1.3	0.0	3.1	3.5	1.1	1.1	2.5	0.0	1.5
Croatia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cyprus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Czechia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Denmark	2.1	2.9	2.4	2.1	3.2	3.8	2.8	3.5	2.3	2.2	3.8	3.6	2.6
Estonia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Finland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
France	1.3	2.6	1.2	1.1	2.8	1.4	1.3	2.5	1.0	1.2	3.2	1.6	1.5
Germany	1.2	5.4	1.0	1.1	5.7	1.7	1.5	3.8	1.0	1.0	4.2	1.4	1.6
Greece	1.0	1.1	1.1	1.0	1.2	1.5	2.4	2.2	1.1	1.1	1.9	1.5	1.4
Hungary	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ireland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Italy	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Latvia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lithuania	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Luxembourg	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Malta	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Netherlands	1.0	3.5	1.0	1.0	3.6	1.9	2.8	0.0	1.0	1.1	0.0	1.3	1.8
Poland	1.7	5.6	1.3	1.7	3.8	3.2	2.4	3.4	1.4	1.6	3.8	2.8	2.1
Portugal	1.1	2.3	1.2	1.1	1.7	1.3	1.2	2.4	1.1	2.0	2.1	1.4	1.5
Romania	1.2	1.1	1.0	1.1	1.3	1.3	1.6	3.0	1.0	1.0	3.0	1.3	1.2
Slovakia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Slovenia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Spain	1.4	2.7	1.1	1.3	2.6	1.3	1.3	2.6	1.0	1.4	2.3	1.3	1.4
Sweden	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
United Kingdom	1.5	1.7	2.5	2.5	1.7	3.0	3.0	3.1	2.4	2.4	3.2	3.1	2.8
EU27 + UK	1.2	2.5	1.4	1.4	2.6	2.0	1.9	2.9	1.3	1.4	3.0	2.0	1.9

3b) Number of Full Cycle Equivalents – Porous Media

Scenario		A	A	A	A	B	B	B	C	C	C	D	D	D
Year		2025	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Number of Full Cycle Equivalents - Porous Media														
Austria						0.0	1.0	1.0				0.0	1.0	1.0
Belgium						0.0	0.0	0.0				0.0	0.0	1.0
Bulgaria						0.0	1.0	0.0				0.0	1.0	1.0
Croatia						0.8	1.0	1.0				2.1	1.0	1.0
Cyprus						0.0	0.0	0.0				0.0	0.0	0.0
Czechia						3.2	1.0	1.0				2.0	1.0	1.0
Denmark						0.0	0.0	0.0				0.0	0.0	0.0
Estonia						0.0	0.0	0.0				0.0	0.0	0.0
Finland						0.0	0.0	0.0				0.0	0.0	0.0
France						0.0	1.0	1.0				0.0	1.0	1.0
Germany						0.0	0.0	0.0				0.0	0.0	1.0
Greece						0.0	1.0	0.0				0.0	1.0	0.0
Hungary						0.8	1.0	1.0				2.7	1.0	1.0
Ireland						0.8	1.4	1.4				2.2	1.5	1.4
Italy						1.0	1.0	1.0				1.4	1.0	1.0
Latvia						1.1	1.6	1.9				2.5	1.6	1.9
Lithuania						2.0	1.4	2.2				3.3	1.3	2.0
Luxembourg						0.0	0.0	0.0				0.0	0.0	0.0
Malta						0.0	0.0	0.0				0.0	0.0	0.0
Netherlands						0.0	0.0	0.0				0.0	0.0	0.0
Poland						0.0	0.0	0.0				0.0	0.0	0.0
Portugal						0.0	0.0	0.0				0.0	0.0	0.0
Romania						0.0	1.0	0.0				0.0	1.0	1.0
Slovakia						0.0	1.0	1.0				0.0	1.0	1.0
Slovenia						0.9	1.0	1.0				2.7	1.0	1.0
Spain						0.0	1.0	0.0				0.0	1.0	0.0
Sweden						0.0	0.0	0.0				0.0	0.0	0.0
United Kingdom						0.0	0.0	0.0				0.0	0.0	0.0
EU27 + UK						1.4	1.1	1.1				2.3	1.1	1.1

4a) Maximum Injection Capacity (GW_{H2}) – Salt Caverns

Scenario	A	A	A	A	B	B	B	C	C	C	D	D	D
Year	2025	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Maximum Injection Capacity - Salt Caverns (GW_H2)													
Austria	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Belgium	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bulgaria	0.0	0.1	0.3	1.5	0.0	0.0	2.1	0.6	0.3	1.1	0.2	0.0	1.5
Croatia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cyprus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Czechia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Denmark	0.0	7.7	8.6	10.8	7.2	9.1	12.9	5.0	8.3	9.6	4.4	8.5	9.7
Estonia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Finland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
France	0.0	15.5	18.8	26.6	16.0	12.8	18.8	4.6	15.9	16.6	4.3	6.6	22.9
Germany	0.0	0.5	8.9	35.8	1.8	5.5	31.0	0.2	11.5	30.6	0.6	4.1	22.2
Greece	0.0	0.0	2.6	12.4	0.0	2.6	13.0	0.2	2.6	12.4	0.1	2.3	8.7
Hungary	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ireland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Italy	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Latvia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lithuania	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Luxembourg	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Malta	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Netherlands	0.0	3.4	0.3	20.3	3.2	0.8	17.7	0.0	0.6	10.5	0.0	1.7	14.8
Poland	0.0	2.6	6.9	14.4	2.5	3.8	15.4	0.2	5.6	15.9	0.0	3.8	14.1
Portugal	0.0	1.2	0.2	1.4	1.6	0.3	1.7	1.2	0.2	1.3	1.6	0.3	2.4
Romania	0.0	0.1	4.5	8.3	0.1	3.9	8.4	0.8	2.9	6.1	0.4	2.3	5.2
Slovakia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Slovenia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Spain	0.0	7.0	9.7	17.2	7.1	10.8	20.6	4.9	9.4	17.0	5.2	8.7	15.4
Sweden	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
United Kingdom	0.0	14.3	27.0	52.4	13.4	22.2	53.0	8.8	19.4	57.7	8.8	19.3	50.6
EU27 + UK	0.0	52.3	87.7	201.1	53.1	71.7	194.6	26.5	76.6	178.8	25.7	57.7	167.6

4b) Maximum Injection Capacity (GW_{H2}) – Porous Media

Scenario	A	A	A	A	B	B	B	C	C	C	D	D	D
Year	2025	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Maximum Injection Capacity - Porous Media (GW_H2)													
Austria					0.0	3.1	3.3				0.0	1.9	4.3
Belgium					0.0	0.0	0.0				0.0	0.0	0.3
Bulgaria					0.0	0.2	0.0				0.0	0.1	0.3
Croatia					0.0	0.1	0.3				0.5	0.1	0.3
Cyprus					0.0	0.0	0.0				0.0	0.0	0.0
Czechia					0.4	0.6	3.2				1.1	0.5	1.0
Denmark					0.0	0.0	0.0				0.0	0.0	0.0
Estonia					0.0	0.0	0.0				0.0	0.0	0.0
Finland					0.0	0.0	0.0				0.0	0.0	0.0
France					0.0	4.8	1.3				0.0	6.0	6.8
Germany					0.0	0.0	0.0				0.0	0.0	3.9
Greece					0.0	0.3	0.0				0.0	0.4	0.0
Hungary					0.1	0.4	1.2				0.8	0.5	0.8
Ireland					0.5	0.6	1.8				2.2	0.7	1.8
Italy					0.5	4.8	27.8				0.6	4.2	27.6
Latvia					0.6	4.1	8.1				1.1	3.9	8.0
Lithuania					0.9	1.8	2.2				0.8	2.1	2.6
Luxembourg					0.0	0.0	0.0				0.0	0.0	0.0
Malta					0.0	0.0	0.0				0.0	0.0	0.0
Netherlands					0.0	0.0	0.0				0.0	0.0	0.0
Poland					0.0	0.0	0.0				0.0	0.0	0.0
Portugal					0.0	0.0	0.0				0.0	0.0	0.0
Romania					0.0	0.8	0.0				0.0	0.8	0.8
Slovakia					0.0	1.2	0.4				0.0	0.6	0.8
Slovenia					0.0	0.0	0.1				0.0	0.1	0.0
Spain					0.0	1.3	0.0				0.0	0.0	0.0
Sweden					0.0	0.0	0.0				0.0	0.0	0.0
United Kingdom					0.0	0.0	0.0				0.0	0.0	0.0
EU27 + UK					3.1	24.4	49.7				7.2	21.9	59.4

5a) Maximum Withdrawal Capacity (GW_{H2}) – Salt Caverns

Scenario	A	A	A	A	B	B	B	C	C	C	D	D	D
Year	2025	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Maximum Withdrawal Capacity - Salt Caverns (GW_H2)													
Austria	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Belgium	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Bulgaria	0.0	0.7	0.3	1.5	0.7	0.0	2.1	0.7	0.3	3.3	0.7	0.0	3.2
Croatia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Cyprus	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Czechia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Denmark	0.0	7.6	8.6	29.8	7.0	9.1	23.4	3.7	8.3	30.8	4.0	8.5	24.9
Estonia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Finland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
France	0.0	13.2	18.8	82.8	13.5	12.8	65.7	4.6	15.9	66.2	4.3	6.6	69.7
Germany	0.0	0.5	8.9	101.6	1.8	5.5	100.1	0.2	11.5	88.0	0.6	4.1	70.2
Greece	0.0	0.7	2.6	15.1	0.7	2.6	14.2	0.7	2.6	16.9	0.7	2.3	17.1
Hungary	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Ireland	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Italy	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Latvia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Lithuania	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Luxembourg	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Malta	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Netherlands	0.0	2.5	0.3	34.5	3.2	0.8	21.0	0.0	0.6	23.8	0.0	1.7	29.3
Poland	0.0	2.6	6.9	39.6	2.5	3.8	37.4	0.1	5.6	44.6	0.0	3.8	39.8
Portugal	0.0	0.8	0.2	1.8	0.8	0.3	1.7	0.8	0.2	1.3	0.8	0.3	2.4
Romania	0.0	0.8	4.5	14.4	0.8	3.9	12.2	0.8	3.6	16.8	0.8	2.3	10.4
Slovakia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Slovenia	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Spain	0.0	7.0	9.7	17.2	7.0	10.8	20.6	3.9	9.4	17.0	5.0	8.7	15.4
Sweden	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
United Kingdom	0.0	3.1	27.0	90.8	3.0	22.2	101.6	6.0	19.4	98.0	5.8	19.3	87.1
EU27 + UK	0.0	39.5	87.7	429.1	41.0	71.7	399.9	21.5	77.4	406.5	22.6	57.7	369.6

5b) Maximum Withdrawal Capacity (GW_{H2}) – Porous Media

Scenario	A	A	A	A	B	B	B	C	C	C	D	D	D
Year	2025	2030	2040	2050	2030	2040	2050	2030	2040	2050	2030	2040	2050
Maximum Withdrawal Capacity - Porous Media (GW_H2)													
Austria					0.0	3.1	3.3				0.0	1.9	4.3
Belgium					0.0	0.0	0.0				0.0	0.0	0.3
Bulgaria					0.0	0.2	0.0				0.0	0.1	0.3
Croatia					0.1	0.1	0.3				0.5	0.1	0.3
Cyprus					0.0	0.0	0.0				0.0	0.0	0.0
Czechia					0.4	0.6	3.2				0.5	0.5	1.0
Denmark					0.0	0.0	0.0				0.0	0.0	0.0
Estonia					0.0	0.0	0.0				0.0	0.0	0.0
Finland					0.0	0.0	0.0				0.0	0.0	0.0
France					0.0	4.8	1.3				0.0	6.0	6.8
Germany					0.0	0.0	0.0				0.0	0.0	3.9
Greece					0.0	0.3	0.0				0.0	0.4	0.0
Hungary					0.4	0.4	1.2				0.8	0.5	0.8
Ireland					0.1	0.6	1.8				2.0	0.7	1.8
Italy					1.6	4.8	27.8				0.6	4.2	29.6
Latvia					0.2	4.1	8.1				1.1	3.9	8.0
Lithuania					0.8	1.8	2.2				0.8	2.1	2.6
Luxembourg					0.0	0.0	0.0				0.0	0.0	0.0
Malta					0.0	0.0	0.0				0.0	0.0	0.0
Netherlands					0.0	0.0	0.0				0.0	0.0	0.0
Poland					0.0	0.0	0.0				0.0	0.0	0.0
Portugal					0.0	0.0	0.0				0.0	0.0	0.0
Romania					0.0	0.8	0.0				0.0	0.8	0.8
Slovakia					0.0	1.2	0.4				0.0	0.6	0.8
Slovenia					0.0	0.0	0.1				0.0	0.1	0.0
Spain					0.0	1.3	0.0				0.0	0.0	0.0
Sweden					0.0	0.0	0.0				0.0	0.0	0.0
United Kingdom					0.0	0.0	0.0				0.0	0.0	0.0
EU27 + UK					3.6	24.4	49.7				6.3	21.9	61.3

7.5. Storage filling levels for selected countries

Storage filling level in France in Scenario B & D in 2030 and 2050

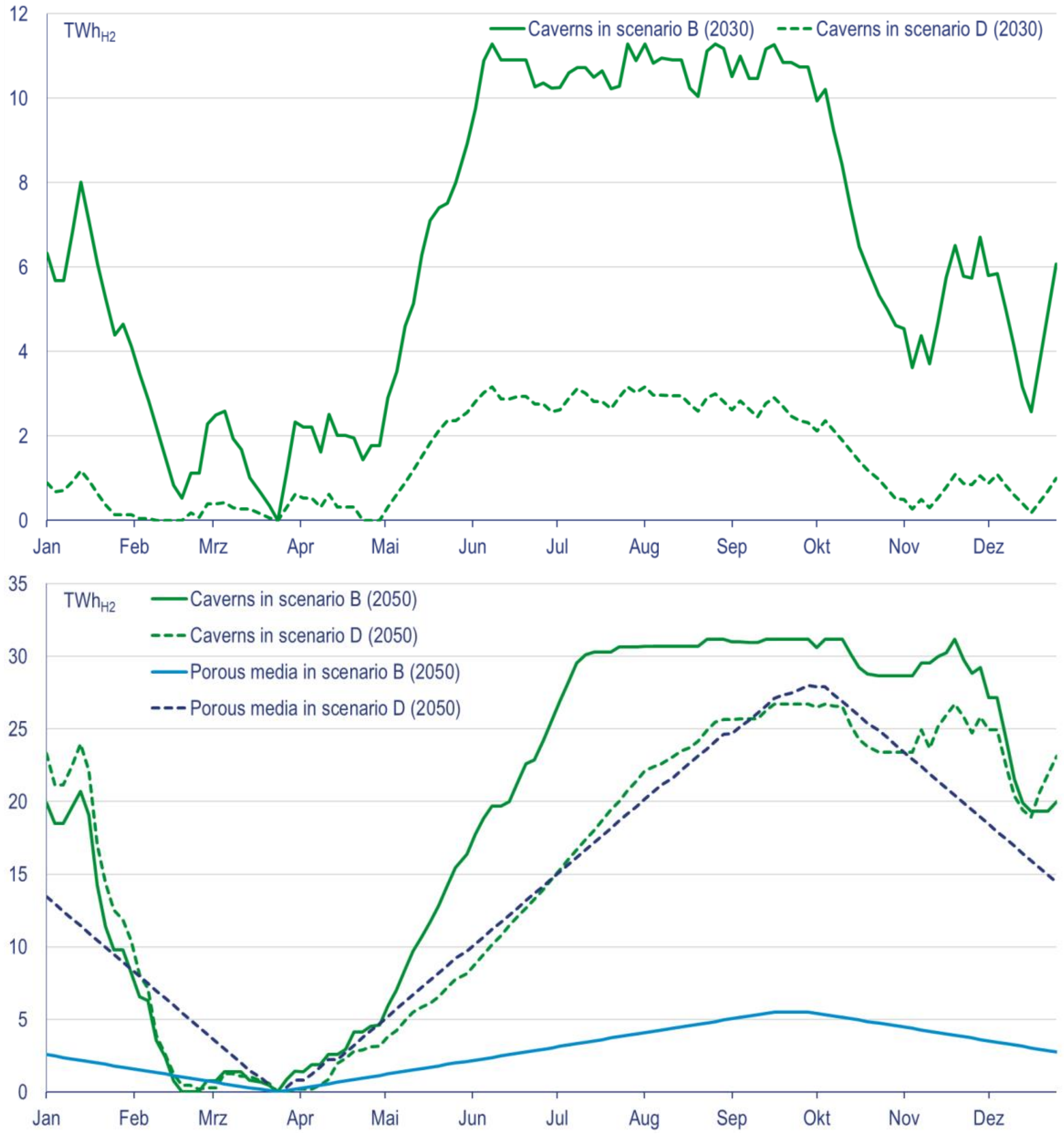

Figure 33:Storage filling level in France in scenarios B & D in 2030 (top) and 2050 (bottom)

Storage filling level in Germany in Scenario B & D in 2030 and 2050

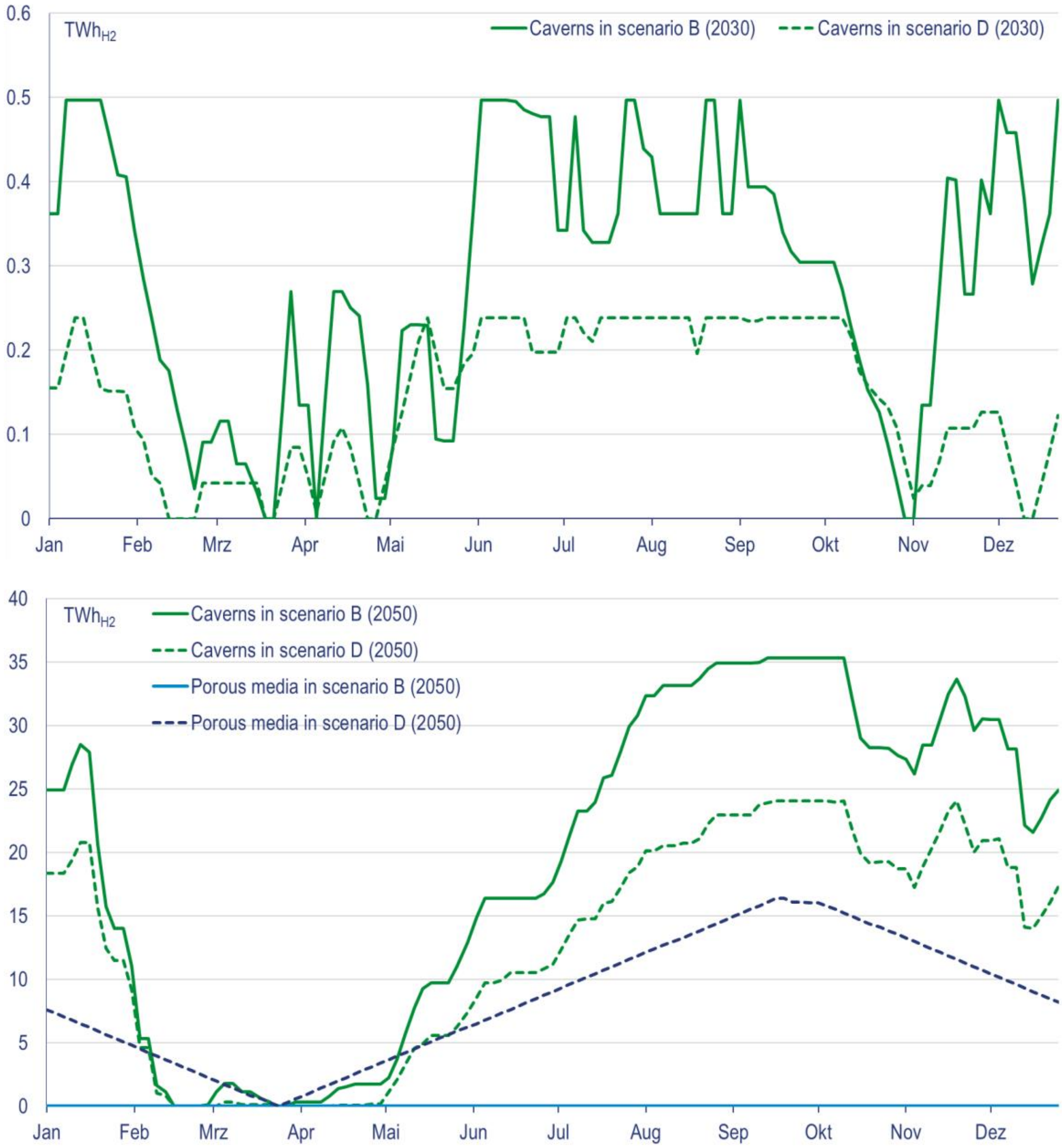

Figure 34:Storage filling level in Germany in scenarios B & D in 2030 (top) and 2050 (bottom)

Storage filling level in Italy in Scenario B & D in 2030 and 2050

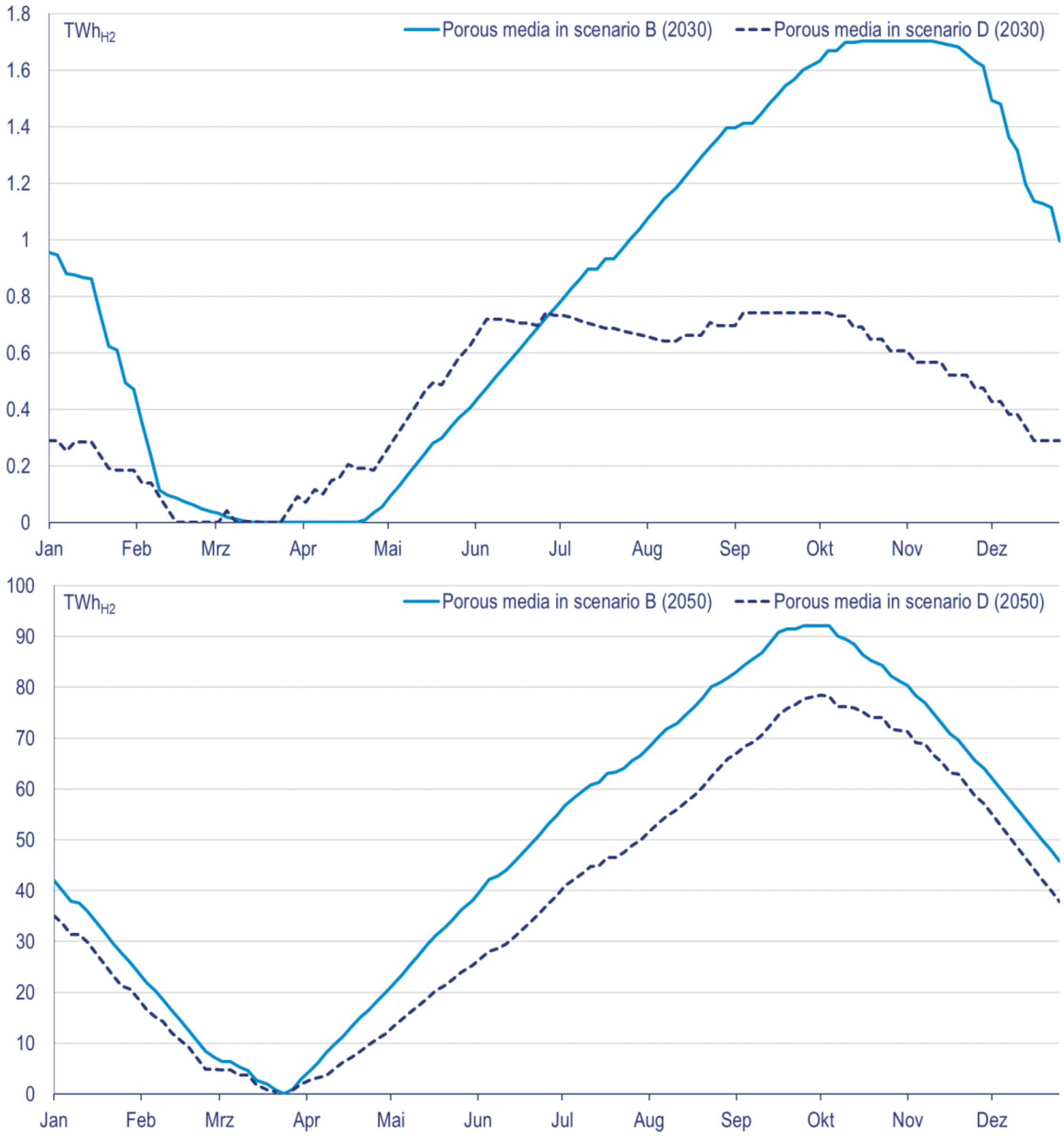

Figure 35:Storage filling level in Italy in scenarios B & D in 2030 (top) and 2050 (bottom)

Storage filling level in Poland in Scenario B & D in 2030 and 2050

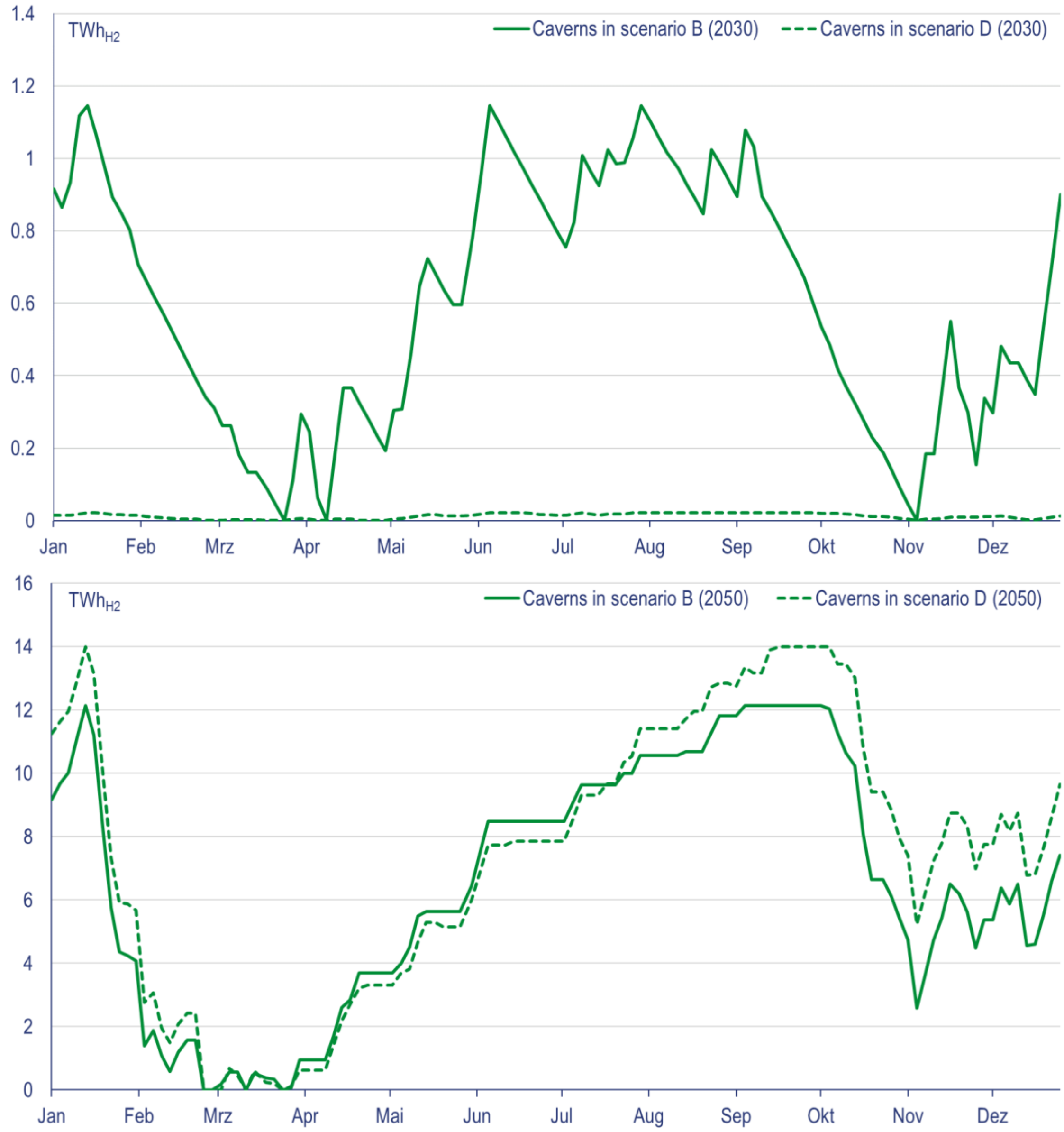

Figure 36: H_2 storage filling level in Poland in scenarios B & D in 2030 (top) and 2050 (bottom)

Storage filling level in Spain in Scenario B & D in 2030 and 2050

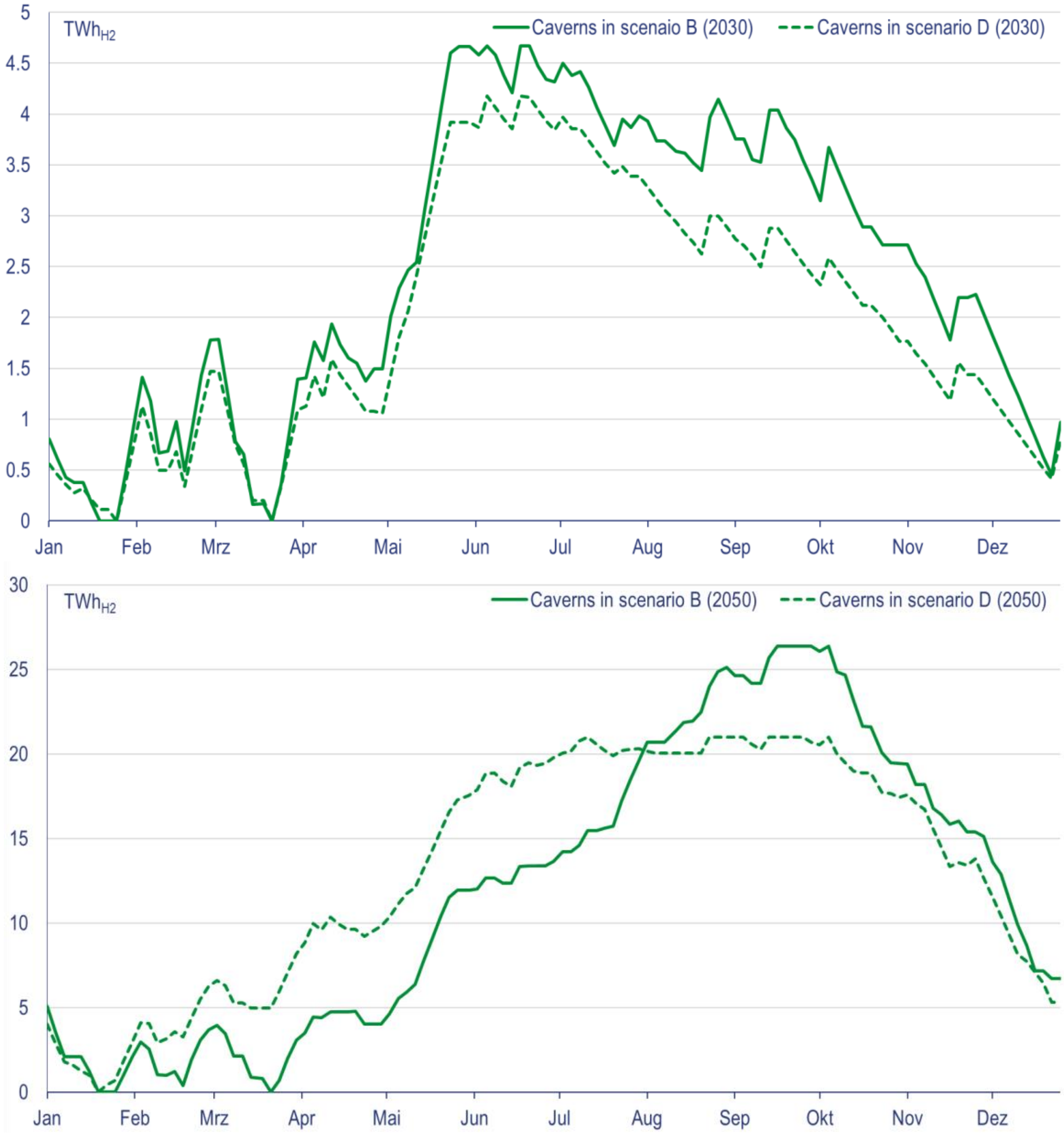

Figure 37:Storage filling level in Spain in scenarios B & D in 2030 (top) and 2050 (bottom)

8. Abbreviation

€	Euro
a	Annum (year)
B	Billion
CCS	Carbon capture and storage
CO_2	Carbon dioxide
EU	European Union
EUR	Euro
H_2	Hydrogen
MS	Member State
NG	Natural gas
PV	Photovoltaics
SMR	Steam methane reforming
WP	Work Package

9. References

EC (2022). *REPowerEU: A plan to rapidly reduce dependence on Russian fossil fuels and fast forward the green transition,* European Commission - Press release, Brussels, 18 May 2022.

Hystories project consortium

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