Institute of Energy Economics
at the University of Cologne

EWI report

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Hydrogen storage in Germany and Europe: Model-based analysis up to 2050

Pre-publication of selected results

Report on behalf of RWE Gas Storage West GmbH

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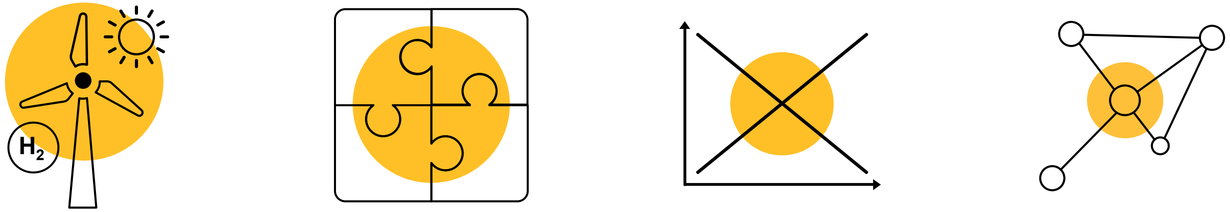


Future H_2 storage demand is uncertain and existing studies show a wide range

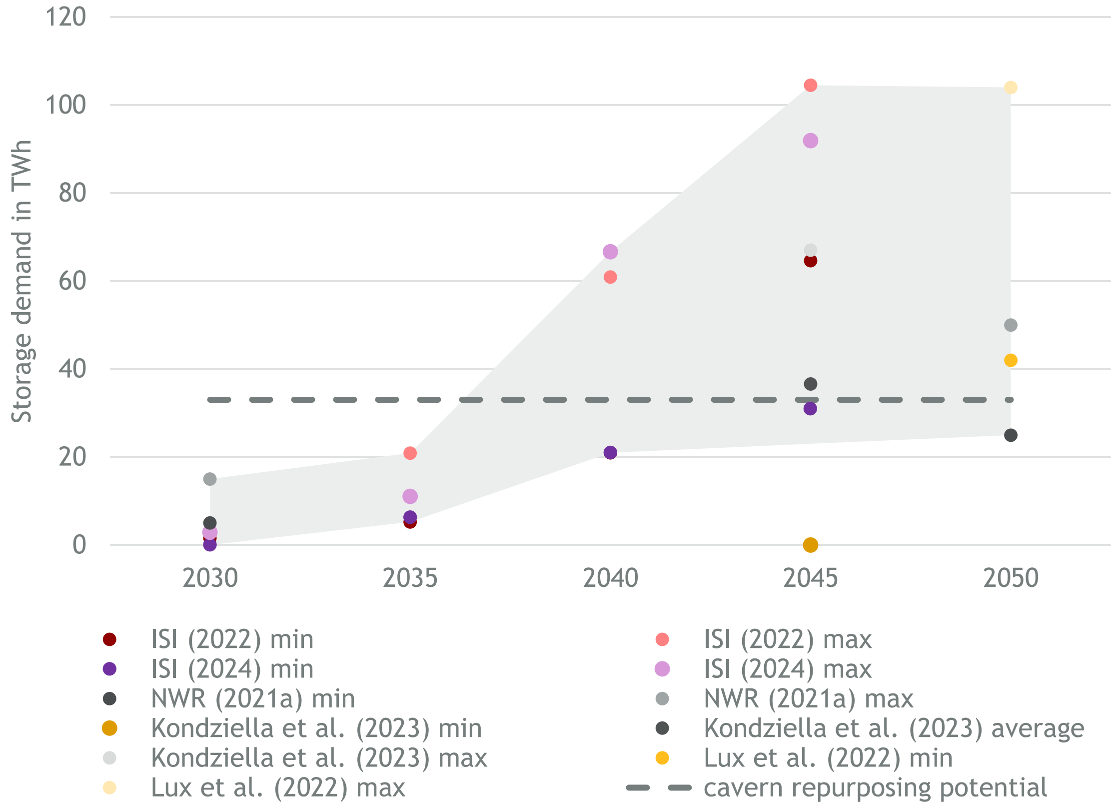
Motivation of this report

- In current energy system studies for Germany and Europe, hydrogen is an important energy commodity of the future. The extent to which infrastructure such as electrolysis, storage or transport capacities will be required depends on a large number of technical and economic influencing factors for which various assumptions are made in these studies.
- Existing studies indicate a difference of around 80 TWh between the minimum and maximum storage demands in Germany for the target year 2050. This is significantly more than the minimum value of less than 30 TWh and illustrates the uncertainty which companies currently face while making investment decisions in H_2 storage facilities.
- This report complements existing studies by showing how storage demands, based on the TYNDP scenario framework[2], change depending on certain assumptions such as storage or import costs, infrastructure expansion and weather conditions.

Research questions:

1. How high is the future H_2 storage demand? What injection and withdrawal capacities will be required?
2. How high is the required H_2 transport capacity in Germany?

H_2 storage demand in Germany: comparison of studies[1]



1: EWI (2024): The importance of hydrogen storage - An analysis of needs, potentials and costs | 2: Ten-Year- Network Development Plans (TYNDP)

The *start scenario* and the sensitivities investigated span a solution space for possible H_2 storage demands

How high is the future H_2 storage demand?

- In this report, optimal storage volumes as well as injection and withdrawal capacities of the H_2 storage facilities are determined for the years 2030, 2035, 2040, 2045, and 2050 as part of a modelling process.
- In the *start scenario*, the energy system is designed based on an average weather year and using input data (e. g. energy demand) from the TYNDP 2022[2]. It is assumed that sufficient capital can be mobilized to expand generation capacities and the necessary infrastructure and to make further investments as required.
- The modeling results depend on a large number of assumptions. In individual sensitivities, the assumptions are varied with regard to a weather situation with a dunkelflaute[2], reduced or delayed investment activities (H_2 import and transport capacities, electrolysis capacities, storage expansion) and higher costs (import price and storage costs)[3].
- The *start scenario* is regarded as the basis for the modeling and as the starting point for the sensitivity analyses. No predictions are made on the probability of the realization of the *start scenario* and the sensitivities considered. The sensitivities are intended to reflect the possibility of lower investment activity and higher costs than in the *start scenario*.

Selected factors influencing the H_2-storage demand[1]

H_2 import price	H_2 import capacity	H_2 transport capacity
H_2 storage costs	Possibility and pace of storage expansion	Weather
H_2 production capacities	Import options and import countries	H_2 market structure
Net transmission capacities	Power generation capacities	H_2 demand from end sectors
Technology costs	Technological progress	Regulatory assumptions

1: The factors highlighted in yellow are examined in more detail as sensitivities. | 2: Selected assumptions on infrastructure are based on the TYNDP 2024 (as of April 2024) due to data availability. This includes, for example, domestic and non-European H_2 transport capacities. Regarding the energy demand, the differences between the two scenario frameworks are minor. | 3: Period of time in which little or no energy can be generated with wind and solar power

Sensitivities each highlight one varied aspect - the rest of the modeling corresponds to the *start scenario*

	Extreme weather	Electrolysis capacity	H_2 import capacity	Expansion limitation NL	Expansion limitation EU	H_2 transport capacity	H_2 storage costs	H_2 import price
Definition	Historical weather year for dispatch modeling	Electrolysis capacity in Europe	H_2 import capacity from outside the model region	National limitation of the potential of new cavern storage facilities in the Netherlands	European limitation of new cavern storage construction	H_2 transport capacity between countries within the model region	Specific investment costs for H_2 storage	Costs for importing hydrogen from outside the model region
Start scenario	Average weather year: 2005	Electrolysis capacity for 2030 specified exogenously, modeled endogenously for later years	Import capacity from TYNDP 2024, Ship import via LTC[1] from 2035 and spot from 2045	No national limit of the potential of new storage caverns	No limit on the annual volume of new construction	Reference grid and investment candidates from TYNDP 2024	Average H_2 storage costs incl. learning curve	Import costs via pipeline from TYNDP 2024, via ship from EWI Global PtX Cost Tool
Sensitivity	Extreme weather year with a dunkelflaute: 1997	Electrolysis capacity is modeled endogenously for all years	Expansion delayed by 5 years	Gradual ramp-up of potential to a maximum of 10 TWh in 2050	Annual volume of new construction is limited	Reduced grid expansion (-30 percent)	Higher investment costs	Higher import costs for hydrogen

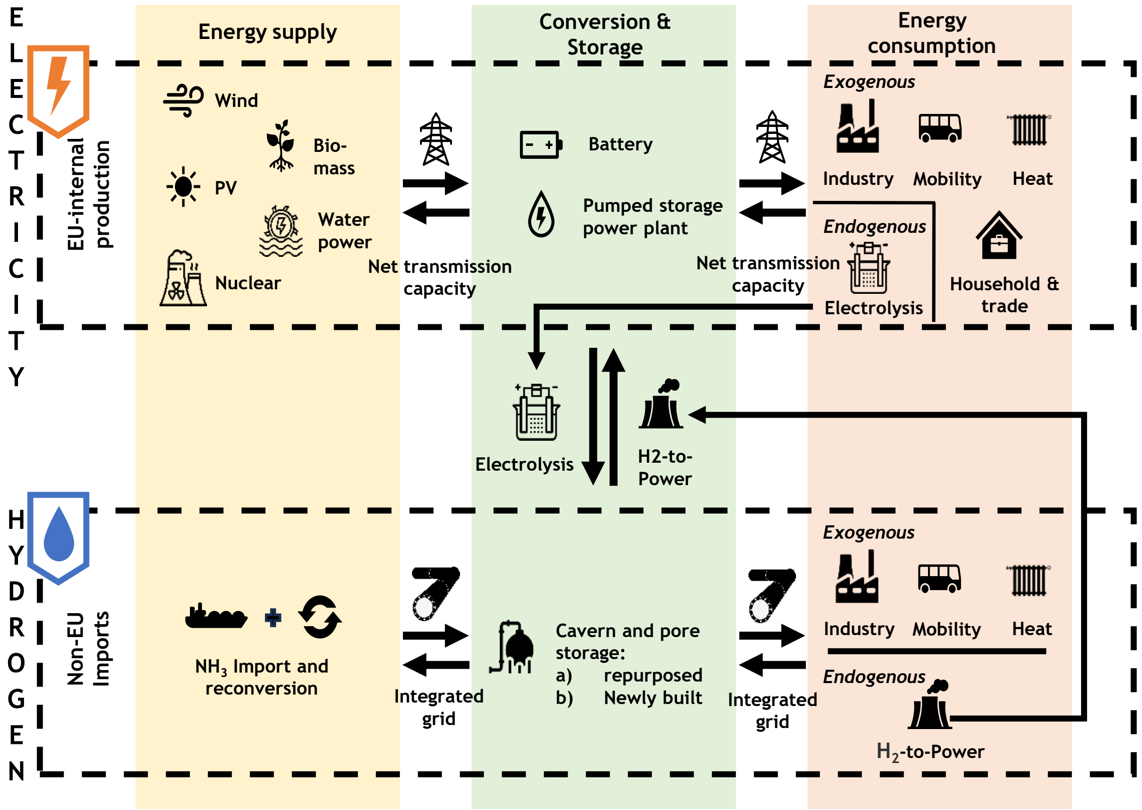
1: LTC: Long-term contract

The H_2 storage demand in Europe is calculated using an EWI energy system model

Model description

- The modeling of the European[2] energy system with a focus on electricity and hydrogen is carried out using the EWI's own HYEBRID model. This is based on the EWI model DIMENSION, extended by a detailed mapping of the H_2-sector.
- The HYEBRID model is a partial equilibrium model of the European electricity and H_2 system. The objective function is to minimize the energy system costs (capacity-related and variable generation costs).
- The energy system model calculates the cost-optimized future development of power plants, renewable energies and flexibility options for the provision of energy.
- By including the European H_2 sector, the H_2 ramp-up in Europe is modeled. The coupling of the electricity and H_2 sectors is optimized endogenously. A distinction is made between investment and dispatch decisions.
- The H_2 sector comprises generation, non-European imports (largely inflexible), intra-European transport via pipelines, underground storage in cavern and pore storage facilities and demand.
- For the first modeled year 2030, the installed capacities (electrolysis, power plants, etc.) are fixed and taken from the TYNDP 2024.

Graphical representation of the HYEBRID energy system model[1]

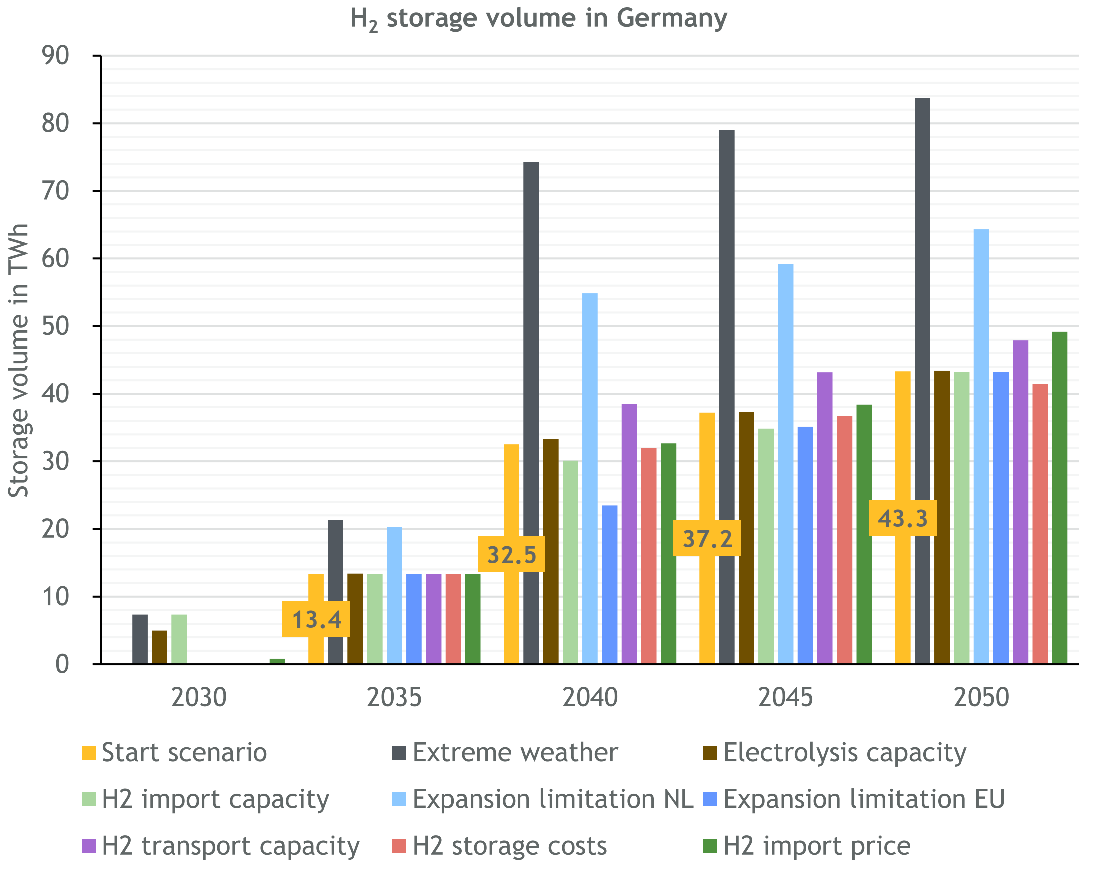


1: Keutz and Kopp (2024) - Assessing the Impact of Take-or-Pay Rates in Long-Term Contracts for Hydrogen Imports on a Decarbonized European Energy System under Weather Variability (under review)
2: Model region: EU without BG, MT and CY, plus GB, NO and CH. In the remainder of the document, the model region is referred to as Europe (abbreviation EU) for easier understanding.

A dunkelflaute and limited expansion in neighboring countries leads to significantly higher storage demands in Germany

All model runs show considerable H_2 storage demand

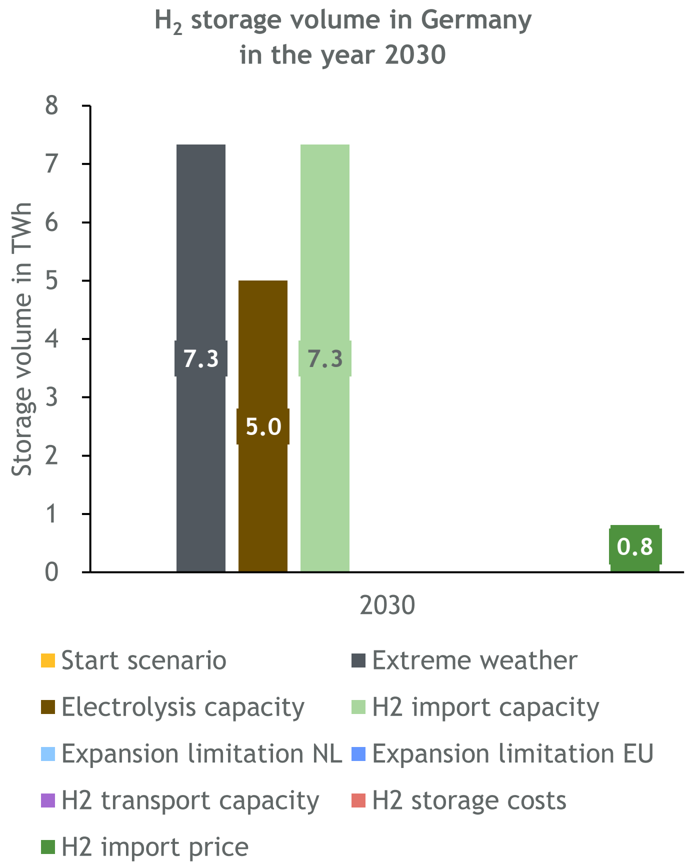
- Already in the first year under consideration, 2030, there is a significant H_2 storage demand in some sensitivities, see details on slide 7.
- In 2035, the storage demand in all sensitivities except *extreme weather* and *expansion limitation NL* corresponds to the repurposing potential of 13.4 TWh determined for this year. The construction of new caverns is more cost-intensive than repurposing. In most sensitivities, the need to build new caverns only arises from 2040 onwards.
- Across all model runs, Germany will be a net importer of hydrogen from 2035 onwards. A more diverse relation emerges when balancing the electricity flows. In most model configurations and years, DE is a net exporter of electricity. Exceptions are, for example, the *extreme weather* sensitivity starting in 2040 and the sensitivity with reduced *import capacities* in 2050.
- In the target year 2050, all models show a considerable storage demand. The lowest storage demand in Germany is 41.4 TWh and results from increased *storage costs*, while the highest volume of 83.8 TWh is calculated when considering the *extreme weather* sensitivity. While most of the results are similar in terms of the amount of H_2 storage required (41.4 to 49.2 TWh), the sensitivities with a pronounced dunkelflaute and with *expansion limitation NL* (64.3 TWh) show the highest differences.



Some sensitivities show a storage demand for the year 2030 - the reasons for this are complex

Exogenous assumptions limit storage demand in 2030

- In 2030, there could be a demand for H_2 storage that covers the entire repurposing potential[1] available in Germany in that year.
- In the *start scenario,* there is no storage demand in 2030, as it is assumed that sufficiently high and relatively inexpensive imports and the exogenous electrolysis capacity can always meet the H_2 demand.
- In the *extreme weather* sensitivity, the considerable storage demand is due to the fact that the H_2 peak load driven by reconversion is significantly higher.
- In the *electrolysis capacity* sensitivity, an optimization between domestic generation capacity (specified exogenously in the 2030 *start scenario*), imports and storage expansion is conducted already in 2030. This results in a significant H_2 storage demand and decreased installed electrolysis capacity in Germany and Europe.
- The *import capacity* sensitivity assumes a 5-year delay in the expansion of import capacities from countries outside the model region. This means that in 2030, the entire H_2 demand must be covered within the model region, resulting in a need for H_2 storage.
- In the *expansion limitation NL* and *expansion limitation EU* sensitivities, the changes in assumptions compared to the *start scenario* do not affect the year 2030, and no storage demand is determined in the model region in this year either. In the *transport capacity* sensitivity with a more restrictive intra-European transport grid, the grid does not reach its limits in 2030, so that the storage demand does not change compared to the *start scenario*.
- Higher H_2 *import prices* lead to higher utilization of local (volatile) electrolysis, which in turn creates a minor local H_2 storage demand.



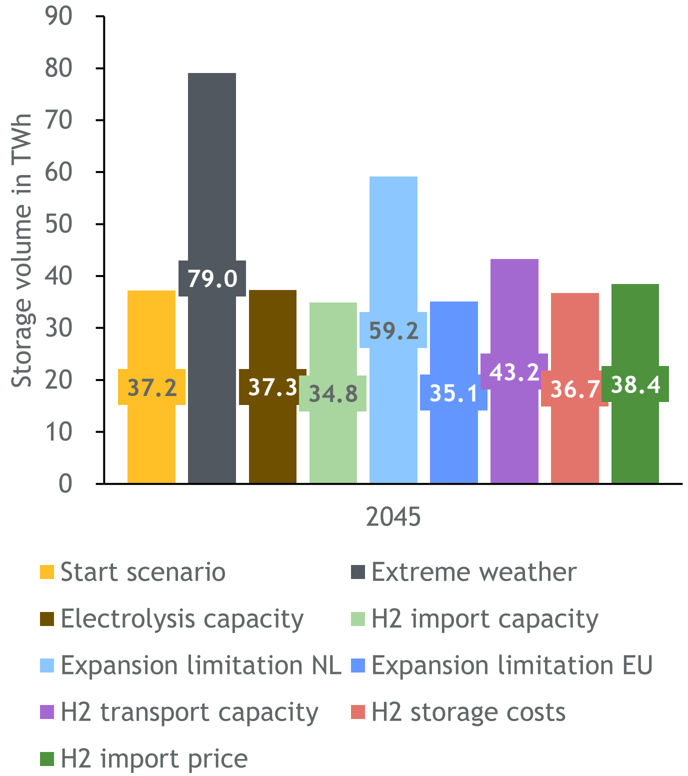
1: The repurposing potential is determined via parallel natural gas operation of existing cavern storage facilities and decreasing natural gas demand per year.

In all model runs, there is a storage demand in 2045 - the highest storage volume is determined in the *extreme weather* sensitivity

The dunkelflaute and expansion limitations in the NL increase storage demands in DE

- The modeling results for the year 2045 are comparatively robust. Almost all model runs show required storage volumes between 34 TWh and 44 TWh. However, the *extreme weather* and *expansion limitation NL* sensitivities show significantly higher storage demands for Germany with 79.0 TWh and 59.2 TWh respectively.
- The model results with similar storage demands can be attributed to two aspects in particular. On the one hand, the hydrogen demand of the end sectors is unchanged in the model runs and the demand for reconversion to electricity is mainly driven by the weather. On the other hand, the import options and local generation capacities differ only little, so that the demand for H_2 storage changes only slightly.
- A higher storage demand in Germany in the case of the *expansion limitation NL* is due to the fact that H_2 storage in DE compensates for the decreased potential of H_2 storage in NL. In relation to the entire model region, the storage demand changes only slightly. Only a geographical shift in the storage volume can be witnessed.
- The highest storage volume is modelled for the *extreme weather* sensitivity in 2045. As mentioned, this is due to the high H_2 peak load in particular, which is influenced by the reconversion. As this is a dunkelflaute affecting large parts of Europe, the aggregated H_2 storage volume increases not only for Germany but for the entire model region (in contrast to the *expansion limitation NL* sensitivity).

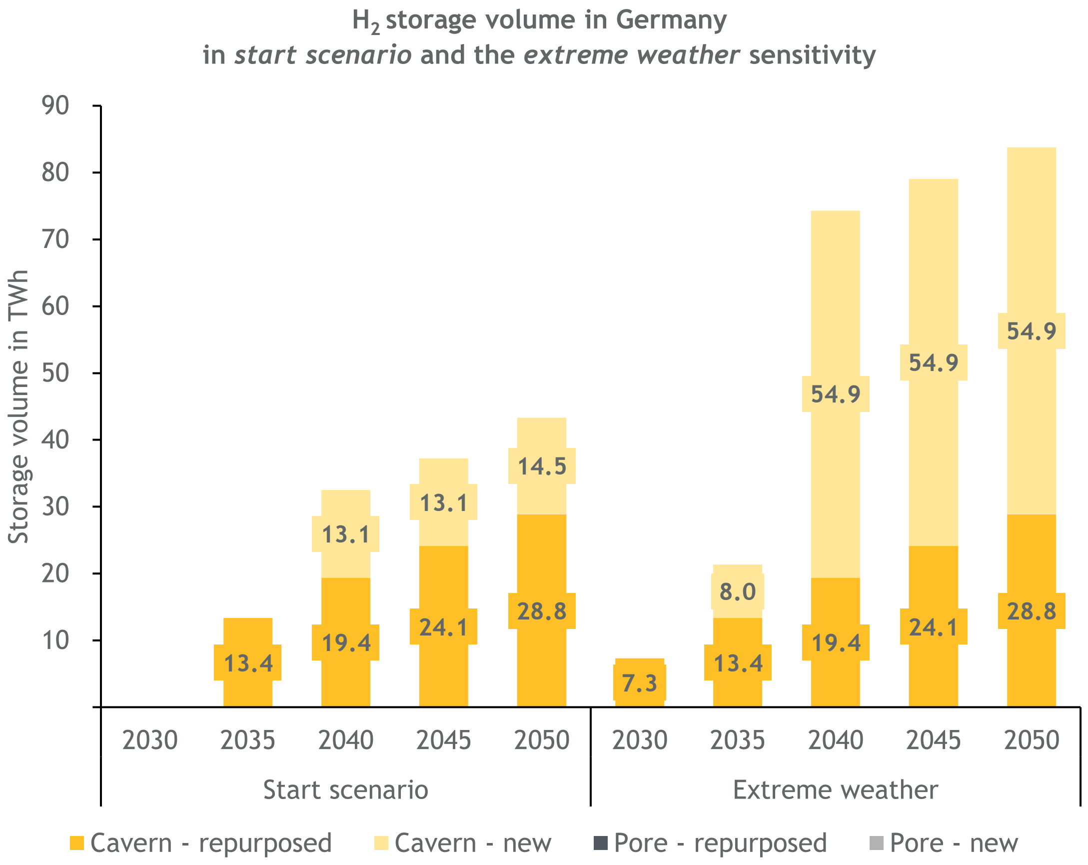
H_2 storage volume in Germany in the year 2045



In the *extreme weather* sensitivity, Germany has a H_2 storage demand of around 84 TWh in 2050

In Germany, caverns are preferred to pore storage

- The *extreme weather* sensitivity is based on a rare, historical weather year with a Europe-wide dunkelflaute (period of time with little to no wind and solar power) lasting several days in January. Ensuring security of supply during an inter-regional dunkelflaute is a key driver of storage demands and withdrawal capacity.
- Compared to the *start scenario*, the *extreme weather* sensitivity already results in an H_2 storage demand in 2030, which is covered by repurposing natural gas cavern storage facilities. Taking the extreme weather situations into account, Germany has approximately twice as much H_2 storage demand in all years compared to the *start scenario*.
- The predetermined repurposing potential for existing natural gas cavern storage facilities is exhausted in the *start scenario* from 2035 onwards and in the *extreme weather* sensitivity in all years. In addition, new cavern storage facilities are built.
- A significant increase in storage demand by 2040 is due to the exogenous shutdown of all fossil electricity generation in Germany.
- Pore storage facilities are neither repurposed nor newly built in Germany due to expected higher hydrogen losses and sufficient availability of caverns. None of the modeled sensitivities show the deployment of pore storage facilities in Germany.

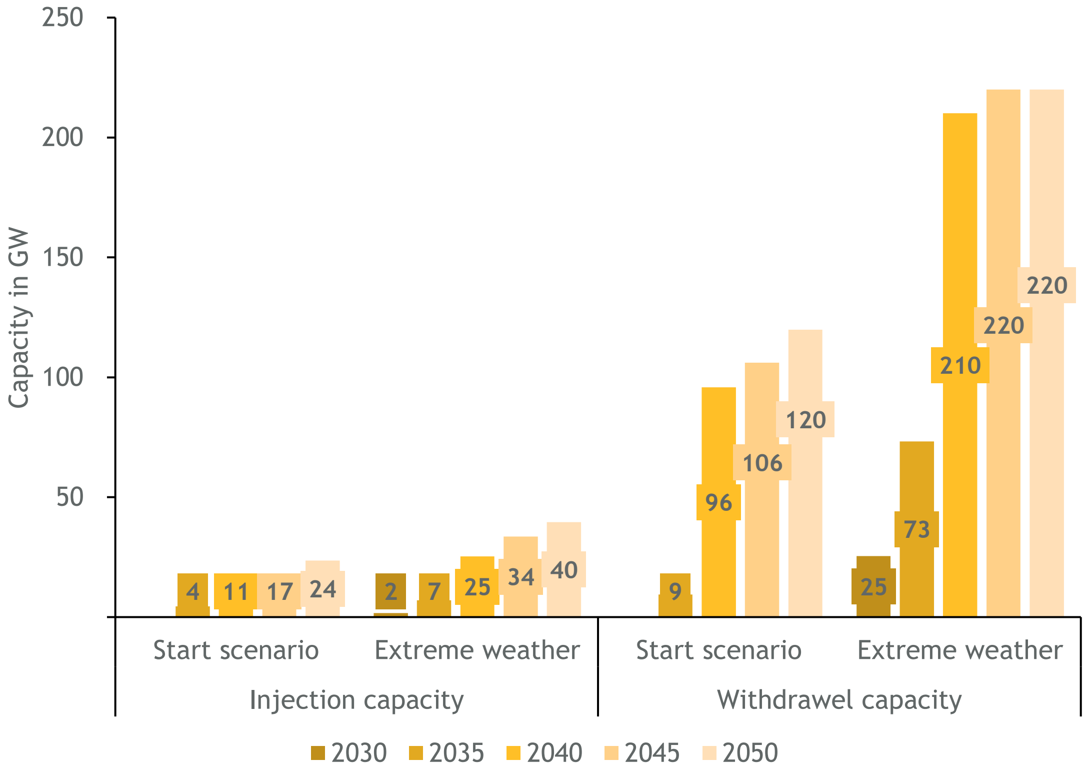


The withdrawal capacity is designed corresponding to the H_2 peak load - injection is more continuous

Higher withdrawal capacity than injection capacity required

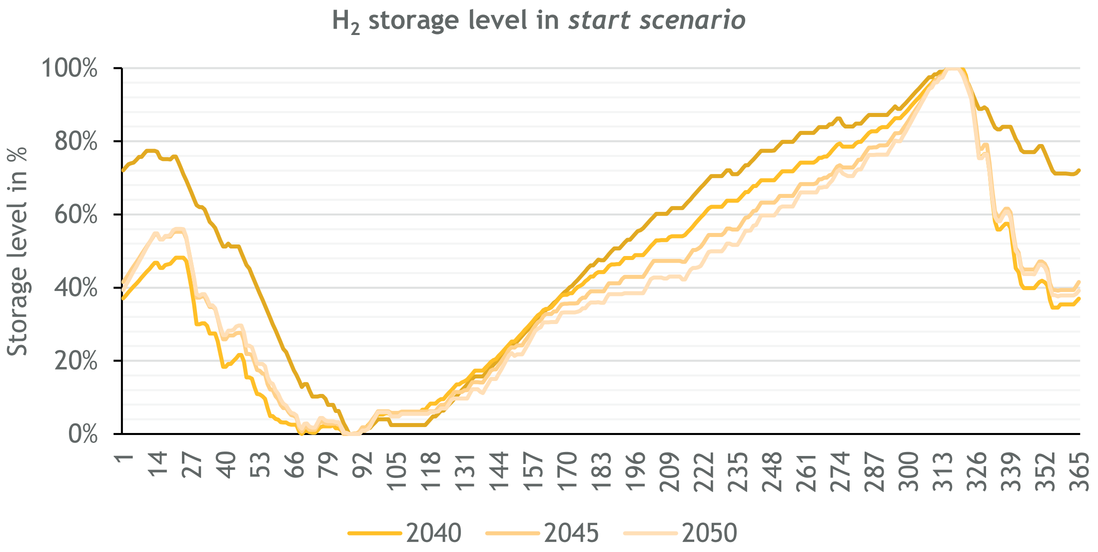
- The injection and withdrawal capacity determines the amount of hydrogen that can be injected or withdrawn in a given time. In the model, these variables are optimized independently of each other and of the storage volume.
- From 2040 onwards, the withdrawal capacity is significantly higher than the injection capacity.
  - High withdrawal capacity is needed to cover H_2 peak load, which are driven mainly by reconversion. Annual withdrawal durations[1] are between 235 h and 405 h in the model starting in 2040.
  - Injection takes place almost continuously from February/March until the beginning of winter. No major power peaks occur here - annual injection durations[2] are between 1,820 h and 3,170 h for 2040 and beyond.
- In all sensitivities, both the storage volumes and the withdrawal capacity increase significantly by 2040. This is due to the fade-out of fossil power generation capacities in this year.
- In all sensitivities considered and across all years, the injection capacity in Germany is sightly lower than the electrolysis capacity, while the withdrawal capacity is sightly higher than the H_2 power plant capacity.

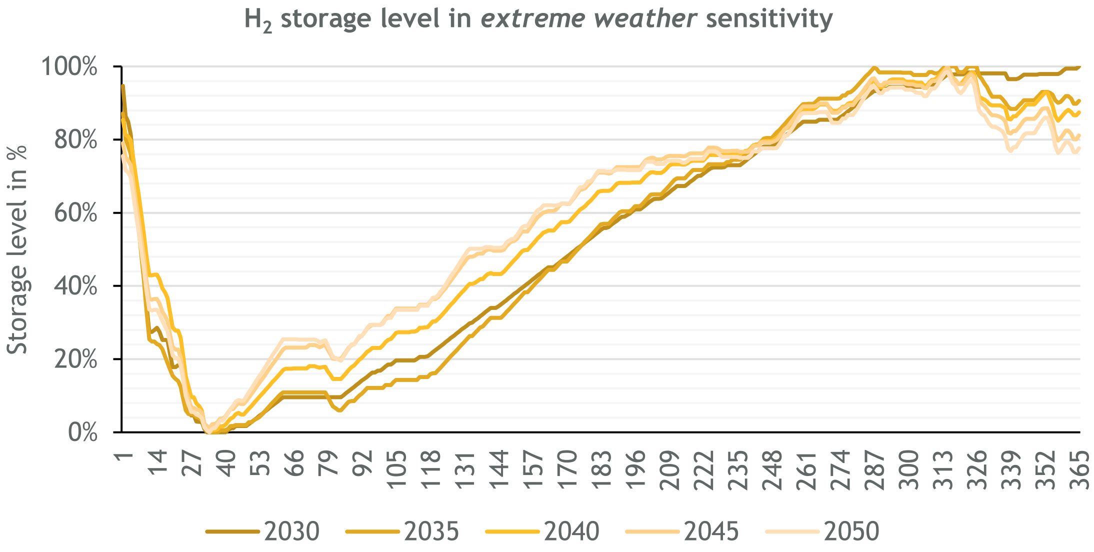
Injection and withdrawal capacity
in *start scenario* and in *extreme weather* sensitivity



1: Full load assumption: Withdrawal duration = storage volume / withdrawal capacity | 2: Full load assumption: Injection duration = storage volume / injection capacity

H_2 storage is used for seasonal balancing - in the event of a dunkelflaute, there is a significant energy shortage in winter





- The H_2 storage level in Germany shows a similar pattern across all years in the *start scenario*. The H_2 storage facilities are filled between March and November and completely emptied in the winter months.
- The H_2 storages are used as seasonal compensation, particularly due to the higher PV supply in summer and the higher H_2 demand in winter.
- The share of stored hydrogen in total demand per year is around 8 percent in 2035 and around 12 percent from 2040 onwards.
- In the *extreme weather* sensitivity, the dunkelflaute in January leads to a short withdrawal period at the beginning of the year. From February onwards, the H_2 storage facilities are filled almost continuously until the beginning of winter.
- The share of stored hydrogen in annual consumption increases compared to the *start scenario*. In 2030 and 2035, the share is around 8 and 12 percent respectively, and between 21 and 25 percent from 2040 onwards.
- The course of the storage level is highly dependent on the assumed weather year. The H_2 storage volumes and injection and withdrawal capacity demands may also be higher if further technical restrictions are taken into account.

In the *start scenario*, the necessary investments in Germany over all years account for around EUR 32.5 billion

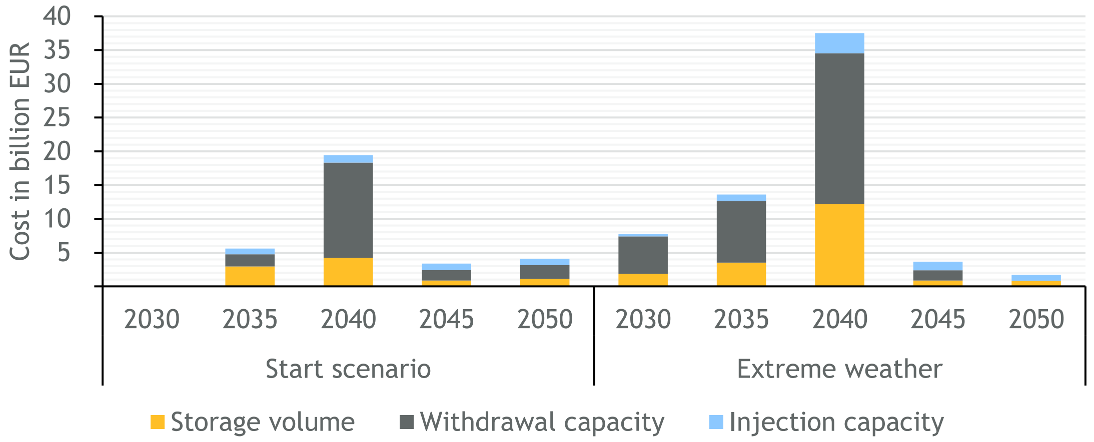
The withdrawal capacity dominates the investment costs

- The costs assumed in the model[3] are based on a cavern field with 8 caverns of 500,000 m³ each. This corresponds to a working gas volume (WGV) of 360 million m³ or 1.08 TWh. The same WGV is assumed for pore storage facilities.
- In addition, cost effects in the form of a learning rate are assumed. In relation to the reference costs of 2040, this results in a cost difference of +33 percent in 2030 and -10 percent in 2050. For cavern storage facilities, losses of 2 percent of the withdrawn amount of hydrogen are assumed. These are significantly higher for pore storage facilities at approx. 24 percent.[4]
- In the *start scenario*, the withdrawal capacity accounts for the largest share of costs at EUR 19.5 billion, followed by EUR 9.1 billion for the storage volume and EUR 3.8 billion for the injection capacity.
- Withdrawal capacity accounts for the largest share of costs in the *extreme weather* sensitivity, and at EUR 38.5 billion it almost doubles compared to the *start scenario*. Costs are calculated at EUR 19.2 billion for the storage volume and EUR 6.5 billion for the injection capacity.
- In both scenarios, the largest share of investments will be due by 2040 because of the increased expansion of H_2 power plants.
- The investment costs were calculated without interest or annuities and are based on real costs for the year 2024.

Specific investment costs for H_2 storage in 2040[1,2]

	Cavern storage		Pore storage	
	repurposing	newly built	repurposing	newly built
Storage volume [EUR/MWh]	190.1	234.6	205.9	244.8
Injection capacity [EUR/kW]	163.3	163.3	227.8	227.8
Withdrawal capacity [EUR/kW]	163.3	163.3	182.2	182.2

Investment cost for H_2 storage in Germany
in *start scenario* and in *extreme weather* sensitivity



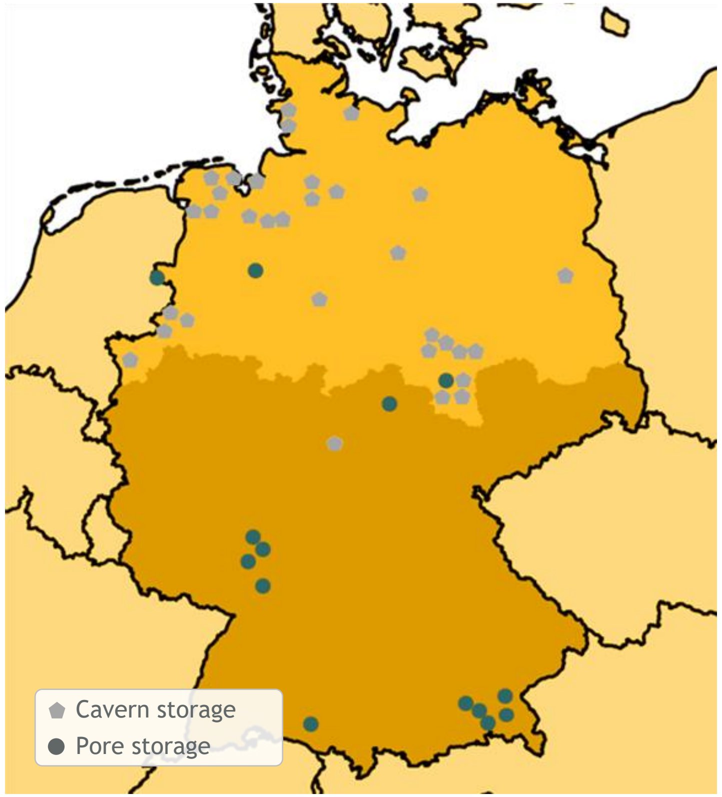
1: FOM and operating costs are also taken into account in the model. | 2: Assuming a constant ratio of volume to injection and withdrawal capacity, this corresponds to total investment costs of EUR 0.51/kWh to EUR 0.55/kWh, depending on the storage type. | 3: Deviation only in the *storage costs* sensitivity | 4: Both assumptions are currently still subject to uncertainty.

The regional distribution of the H_2 storage facilities and H_2 power plants determines the capacity demand of the H_2 grid

How high is the required H_2 transport capacity in Germany?

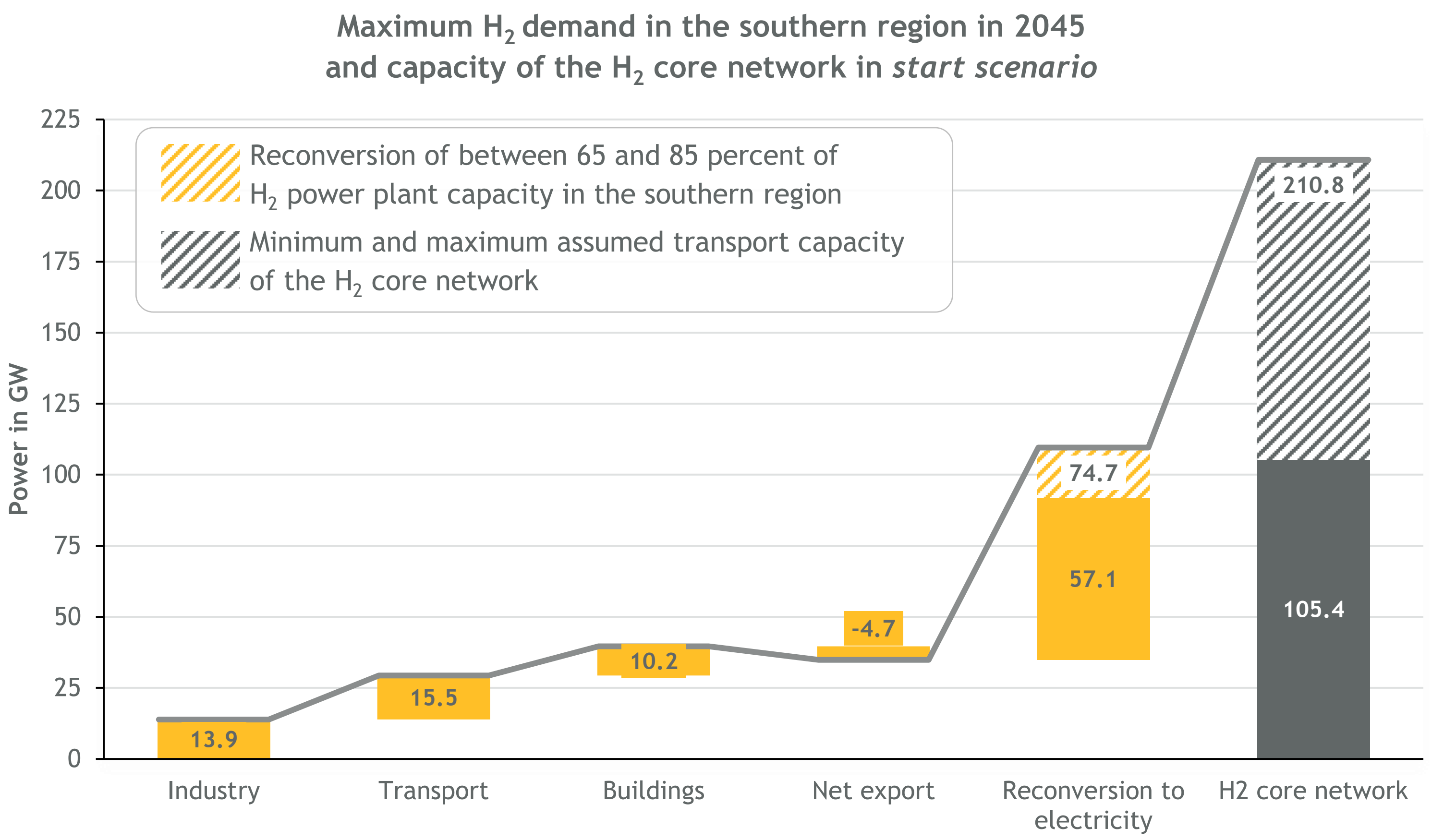
- The results from the previous modeling show that in Germany, only cavern storage facilities are being repurposed or newly built for H_2 storage. These caverns are mainly located in the north of Germany, while H_2 consumers such as industrial clusters and large cities are mainly located in the west and south of Germany. In addition, the regional H_2 demand is strongly influenced by the spatial distribution of future H_2 power plants, which is subject to great uncertainty.
- To analyze the domestic H_2 transport demand in Germany, the inputs (H_2 demand of the end consumer sectors) and the results of the modelling for the *start scenario* and the *extreme weather* sensitivity (H_2 demand of the electricity sector and H_2 imports and exports) are regionalized. For this purpose, Germany is divided into a northern region with a generation surplus and a southern region with increased energy demand[2]. To reflect the uncertainties in the distribution of the H_2 power plants, 75% of the H_2 power plant fleet is assumed to be located in the southern region in accordance with current locations of gas power plants and a deviation of ±10 percent is analyzed.
- The H_2 transport capacity of the cross-regional pipelines of the German H_2 core network is calculated using the ideal gas equation. Pipeline-specific information from the H_2 core network draft of 15.11.2023[3] is used, and a flow velocity of between 15 and 30 m/s is assumed. In the full expansion stage, a transport capacity of 105 GW to 211 GW is calculated depending on the flow velocity.
- The H_2 residual load of the regions is compared with the planned inner-German transport capacity of the H_2 core network from the north to the south. The year 2045 (targeted climate neutrality in Germany) is considered.

Regions and storage locations in Germany[1]



1: Pore storage facilities are shown here, although they are not repurposed to H_2 in the model results. This is intended to show the geographical shift in future storage volumes. | 2: The division is based on the borders of the federal states except for North Rhine-Westphalia, where the division is made on the basis of NUTS3 regions to locate cavern storage facilities in the north and larger demand centers in the south. This is no indication towards an optimal power plant distribution or future pricing. | 3: FNB Gas (2023a), FNB Gas (2023b)

In the *start scenario*, the transport capacity of the H_2 core network is likely to be sufficient to cover H_2 demand in the south

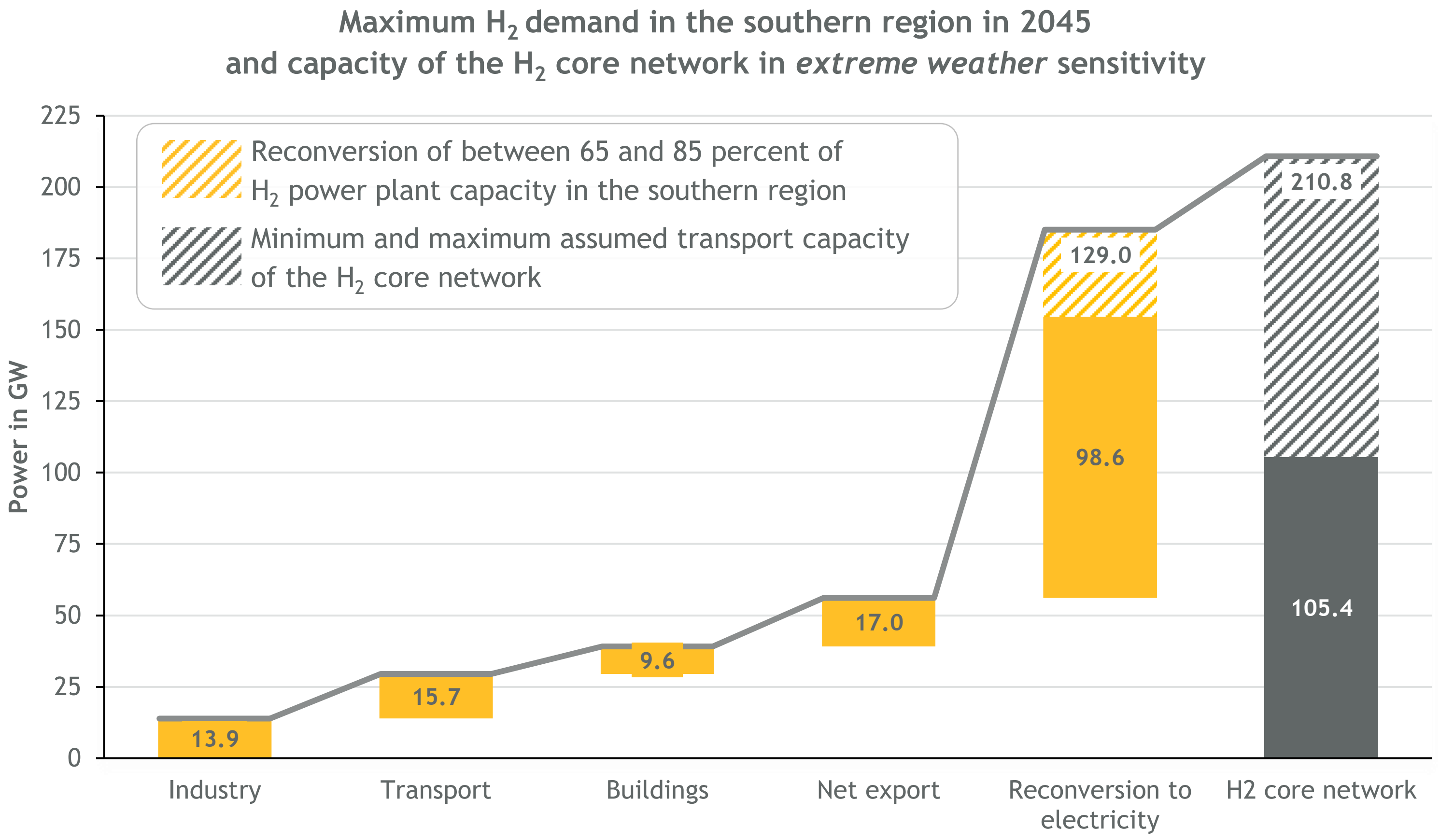


Comments

- In the hour of the highest H_2 demand in the south in 2045 in the *start scenario*, 57 GW to 75 GW of hydrogen will be used for electricity generation, depending on the southern region's share of the H_2 power plant fleet[1].
- In addition, around 40 GW of hydrogen will be demanded by the end consumer sectors at this time. A net of almost 5 GW will also be imported from neighboring countries.
- The future transport capacity of the H_2 core network may not be sufficient in 2045 if up to 85 percent of the H_2 power plants are located in the southern area and the core network only allows a low flow rate.
- This calculation assumes that all cross-area lines are available to supply the entire southern area. A corresponding withdrawal capacity is also required. The current planning status of the H_2 core network includes a H_2 withdrawal capacity of around 56 GW in the southern region[2]. Additional expansion would be required in this scenario.

1: The *start scenario* results in an electrical H_2 power plant capacity of 41.8 GW in 2045.
2: This is based on additional calculations with information of the H_2 core network draft of July 22, 2024.

Higher reconversion demand in the *extreme weather* sensitivity could lead to transport bottlenecks in the H_2 core network



Comments

- In the *extreme weather* sensitivity, the capacity of the H_2 power plant fleet in Germany in 2045 is around 72 GW[1], of which 65 to 85 percent are assumed to be in the south in this analysis.
- This leads to an H_2 demand for electricity generation of 99 GW to 129 GW in the hour of the highest H_2 residual load in the south.
- In addition, the H_2 demand of the end consumer sectors changes slightly compared to the *start scenario* to a total of 39 GW. At the same time, a net of 17 GW of hydrogen will be exported from the southern region to other European countries[2].
- The maximum H_2 residual load of the southern area is therefore 155 GW to 185 GW. Under the assumptions made here, the core network can only provide this amount at a high flow rate. A corresponding withdrawal capacity is also necessary.

1: This is a model result of the extreme weather sensitivity, which is necessary for security of supply with electricity at all times under the assumptions made.
2: This sensitivity results in H2 exports from Germany in the hour under consideration, as Germany contributes to H2 security of supply in neighboring countries due to its high storage capacity.

This report confirms a need for H_2 storage in Germany from 2030 onwards

Significant H_2 storage demands expected in Germany

- The H_2 storage demand in Germany in the year 2050 is between 41.4 and 49.2 TWh in most model runs, whereby the results with a pronounced dunkelflaute and with a restriction on storage expansion in the Netherlands show significantly higher values of 83.8 and 64.3 TWh respectively. H_2 storage demands of up to 7.3 TWh can already be seen for 2030.
- High withdrawal capacities are used to cover the peak load in the H_2 sector, which is primarily defined by reconversion. H_2 injection takes place more steadily and with lower capacity. Here, the results show a large jump in the year 2040 when fossil electricity generation is faded out in Germany.
- In general, cavern storage facilities are initially repurposed and, as soon as this potential is exhausted, new ones are built. Pore storage facilities only play a subordinate role due to higher investment and operating costs (expansion mainly in scarcely connected countries without cavern potential).
- Storages are used as a seasonal balance, particularly due to the higher PV supply in summer and the higher H_2 demand in winter.
- From 2035, Germany will be a net importer of hydrogen in all model sensitivities considered and will play a central role in H_2 storage in Europe alongside the Netherlands, the UK and Poland.

Insufficient supply for H_2 residual load in the south possible

- Due to the regional distribution of the cavern storage potentials, the H_2 power plants in the south of Germany would have to be supplied from the cavern storage facilities in the north. This may not be sufficient to fully cover demand in every possible scenario, particularly at times of high H_2 residual loads in the south.
- The transport capacity of the German H_2 core network is presumably sufficient under average weather conditions (*start scenario*).
- In the *extreme weather* sensitivity, the maximum H_2 residual load during the dunkelflaute is higher due to the significantly higher H_2 power plant capacity. In this case, the transport capacity of the core network may not be sufficient in 2045.
- If the transport capacity within Germany is not sufficient for a H_2 supply to the south from the storage facilities in the north, investments in pore storage facilities in the south of Germany and the use of demand flexibility could be an option to increase supply security. An increase in the transport capacity of the H_2 core network is also plausible. The limitation of transport capacity was not taken into account in the optimization of storage requirements.

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