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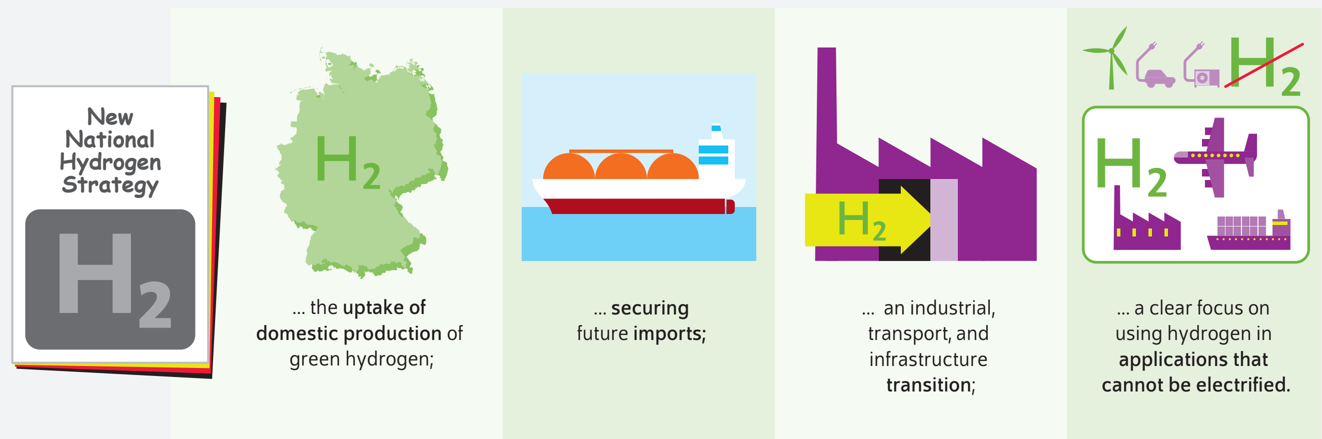
AT A GLANCE

# National Hydrogen Strategy: Clear focus and consistent implementation necessary

By Martin Kittel, Dana Kirchem, Wolf-Peter Schill, and Claudia Kemfert

- Report analyzes Germany's revised National Hydrogen Strategy and compares it to the first strategy from 2020
- Overview of production processes and possible applications for hydrogen and its derivatives
- Analysis of planned hydrogen quantities for 2030 under different scenarios varying in hydrogen demand and import
- Hydrogen quantities planned for 2030 pose a substantial challenge and are associated with major uncertainty
- Acceleration of the uptake of domestic production and imports with a focus on certain applications

**Conditions for a successful National Hydrogen Strategy are...**




Source: Authors' depiction.



FROM THE AUTHORS

*"The Federal Government's new National Hydrogen Strategy specifies future applications while suffering from substantial uncertainty regarding the planned hydrogen quantities. Currently, the import targets for 2030 seem hard to achieve."*

— *Wolf-Peter Schill* —

MEDIA

**Audio Interview** with Martin Kittel (in German)
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# National Hydrogen Strategy: Clear focus and consistent implementation necessary

By Martin Kittel, Dana Kirchem, Wolf-Peter Schill, and Claudia Kemfert

**ABSTRACT**

Replacing fossil fuels with renewable energy sources is one cornerstone of the energy transition. In certain sectors, green hydrogen will play an important role in the future, as is envisioned in the revised National Hydrogen Strategy recently presented by the German Federal Government. This Weekly Report discusses important changes in this strategy compared to the first National Hydrogen Strategy from 2020. It focuses on the analysis of the hydrogen quantities planned for 2030, which can likely only be realized with significant effort. In addition, it is uncertain how large the remaining share of non-green hydrogen would be. Green hydrogen imports are of particular significance and must be secured early on. It is now important to implement the strategy in a timely and consistent fashion. In this context, focus should remain on the areas of application that are required from an energy system perspective and for which direct electrification, which is more energy efficient, is not possible, especially in industry as well as aviation and shipping.

Germany aims to be carbon neutral by 2045 according to the Federal Government's targets, with an at least 65 percent reduction in carbon emissions by 2030 compared to 1990. To achieve these targets, renewable energy sources should be expanded, energy efficiency increased, and sector coupling advanced. Sector coupling refers to using electricity from renewable energy sources directly or indirectly for previously non-electric applications in industry, heating, and transport. Hydrogen produced from renewable energy sources is expected to play an important role for certain applications in the future. It could be used where renewable electricity cannot be used directly, for example in parts of industry or the transport sector.

To spur on the market uptake of hydrogen in Germany and abroad, the previous Federal Government under Angela Merkel presented a National Hydrogen Strategy for the first time in 2020.[1] In summer 2023, the strategy was revised.[2]

This Weekly Report discusses important elements of the new National Hydrogen Strategy and analyzes the amounts planned for 2030 regarding domestic production, imports, and potential shortfalls. For more context, various production methods (colors) and forms (derivatives) of hydrogen are explained and an overview of plausible areas of application is given. Finally, an overview of potential options for importing hydrogen is provided.

## Colors, derivatives, and transport options

### Hydrogen: colorless but colorful

Hydrogen is a colorless gas. Despite that, when discussing hydrogen, it is referred to by different "colors" to differentiate between different production methods (Figure 1).[3]

**1** Bundesregierung, *Die Nationale Wasserstoffstrategie* (2020) (in German; available online. Accessed on September 23, 2023. This applies to all other online sources in this report unless stated otherwise).

**2** Bundesregierung, *Fortschreibung der Nationalen Wasserstoffstrategie* (2023) (in German; available online).

**3** Cf. Nationaler Wasserstoffrat, *Einordnung verschiedener Pfade der Herstellung von Wasserstoff („Farbenlehre")* (2022) (in German; available online).


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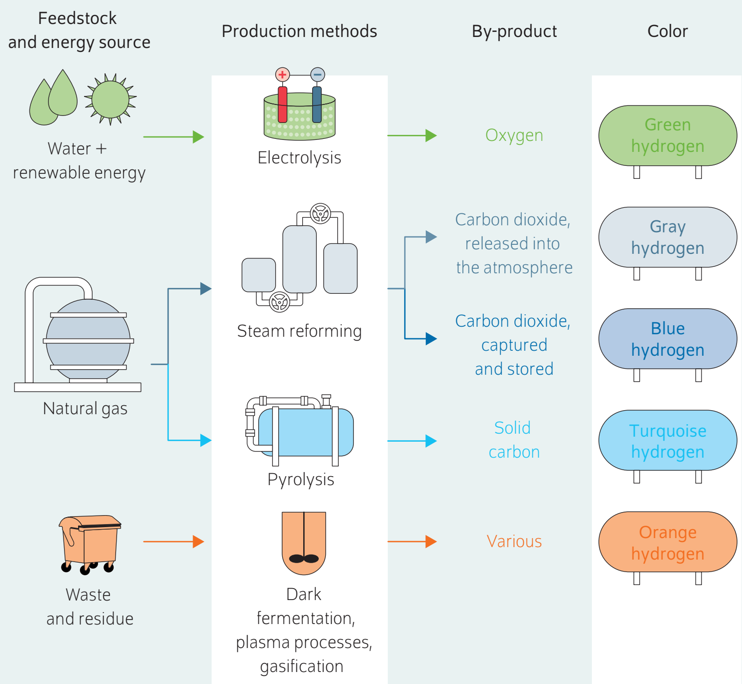
Figure 1

**Hydrogen production processes and assigned colors**




Source: Authors' depiction based on the German Advisory Council on the Environment (Sachverständigenrat für Umweltfragen, SRU).



Green hydrogen, which is produced from water electrolysis and renewable energy, is the only hydrogen type guaranteed to be climate neutral.

Previously, "gray" hydrogen was overwhelmingly used. Gray hydrogen is produced from natural gas using steam methane reformation, a process in which steam is used to split the gas into hydrogen and carbon dioxide ($CO_2$), a greenhouse gas, at high temperatures. The $CO_2$ is then released into the atmosphere.

In the discussion on the energy transition, the primary focus is on three other production processes.[4] Of particular significance is "green" hydrogen, which is produced by water electrolysis, a process in which water is broken down into its components, hydrogen and oxygen, using electricity from renewable energy sources. As the production of green hydrogen does not create greenhouse gas emissions, it is considered climate neutral.

Blue and turquoise hydrogen are two further types that are produced using fossil fuels. As of yet, they have not been tested on a large scale and have limited technological maturity.[5] Blue hydrogen, like gray hydrogen, is produced via steam reformation of natural gas. However, the carbon dioxide emissions released are captured to a great extent,[6] transported away, and stored, for example underground. Alternatively, the $CO_2$ could be used as a raw material, although it must be ensured that the carbon does not enter the atmosphere later. Turquoise hydrogen is produced from natural gas via a pyrolysis process, wherein it is split into solid carbon and hydrogen under high temperatures. Carbon is not released into the atmosphere but can instead be stored or used as a raw material. However, it should not be burned so as to avoid producing $CO_2$ again.

In the case of blue or turquoise hydrogen, further greenhouse gas emissions can occur in upstream process chains during the extraction and transport of natural gas, and in the case of blue hydrogen, additionally in downstream process chains during the transport and storage of carbon. Overall, blue and turquoise hydrogen are considered less emissions intensive than gray hydrogen, but not completely emissions free, making them incompatible with completely climate neutral scenarios.[7]

In addition, there are a variety of other processes for producing hydrogen, including orange hydrogen from primarily biogenic waste and residual materials.[8] In some chemical processes, hydrogen is also produced as a by-product. Only green hydrogen from electrolysis using renewable energy is potentially well scalable and guaranteed to be climate neutral.

## Important hydrogen derivatives

In addition to pure hydrogen, hydrogen-based derivatives are likely to be of significance for some applications, especially in the chemical industry and the transport sector.[9] This includes hydrogenous compounds such as ammonia, methanol, or methane. Ammonia is produced from hydrogen and nitrogen. In Power-to-X (PtX) processes, green hydrogen and a carbon source can be used to produce synthetic liquid (Power-to-Liquid, PtL, also known as e-fuels) or gaseous (Power-to-Gas, PtG) hydrocarbons.[10] However, production is associated with high conversion losses and, accordingly, requires a lot of additional electricity from renewable

**4** Cf. Sachverständigenrat für Umweltfragen, *Wasserstoff im Klimaschutz: Klasse statt Masse. Stellungnahme* (2021) (in German; available online). There are other "colors" in the discussion that play no role in the National Hydrogen Stategy. One such color is "yellow" hydrogen, which is also produced via water electrolysis, but uses the network electricity mix instead of 100 percent renewable energy.

**5** Cf. Matia Riemer and Vicki Duscha, "Carbon capture in blue hydrogen production is not where it is supposed to be – Evaluating the gap between practical experience and literature estimates," *Applied Energy* 349 (2023): 121622.

**6** It is uncertain how many residual emissions would result along the value chain for blue hydrogen, cf. for example Robert W. Howarth and Mark Z. Jacobson, "How green is blue hydrogen?" *Energy Science & Engineering* 9, vol. 10 (2021): 1676-1687; as well as Matteo C. Romano et al., "Comment on 'How green is blue hydrogen?'" *Energy Science & Engineering* 10, vol. 7 (2022): 1944-1954.

**7** Sachverständigenrat für Umweltfragen, *Wasserstoff im Klimaschutz*.

**8** Wissenschaftliche Dienste Deutscher Bundestag, *Oranger Wasserstoff: Herstellung von Wasserstoff aus Abfall* (Berlin: 2021) (in German, available online).

**9** Sachverständigenrat für Umweltfragen, *Wasserstoff im Klimaschutz*; Falko Ueckerdt et al., *Dossier: Cornerstones of an Adaptable Hydrogen Strategy — Summary* (2021) (available online).

**10** Cf. Florian Ausfelder and Dinh Du Tran, *Optionen für ein nachhaltiges Energiesystem mit Power-to-X-Technologien. 4. Roadmap des Kopernikus-Projektes P2X, Phase II* (2022) (in German; available online).

energy sources.[11] This is offset by the potential advantages of hydrogen derivatives, for example, in the transport sector.

## The challenge of transporting hydrogen

Compared to other energy carriers, hydrogen has an extremely low density. This means its transport is particularly challenging.

Pipelines are suitable for transporting large amounts of gaseous hydrogen over great distances and have cost benefits compared to road or rail transport. However, pipelines need special material and the construction of new or the retrofitting of existing gas pipelines requires considerable coordination and effort.[12]

Transporting liquid hydrogen via sea routes would also be an option. However, hydrogen has an extremely low boiling point of –253 degrees Celsius, making liquefaction very energy intensive. In addition, expensive isolation technologies are required for the transport containers for liquid hydrogen. Moreover, pressure build-up and corresponding energy losses can occur during transport due to evaporation.

One approach to solving these transport problems is to convert hydrogen into chemical compounds that are easier to transport, such as the derivatives ammonia or methanol. Then existing transport and storage infrastructure could be used to some extent. However, there are additional energy losses during conversion, especially if pure hydrogen is to be produced again from ammonia after transport, for example.[13] However, these losses would not be significant if the corresponding derivative is needed in the respective form anyway (for example, ammonia for fertilizer production).

## Green hydrogen supply likely to remain scarce for the foreseeable future

Generally, green hydrogen and its derivatives can be used for applications in almost all sectors and replace fossil fuels. However, due to energy losses during production, transport, and even somewhat by the end use, the energy efficiency of hydrogen and its derivatives is significantly lower than that of direct electric alternatives. At the same time, the expansion of wind power and solar energy as well as production and transport infrastructure for hydrogen is practically limited until 2045—both domestically and internationally.[14] In addition, there is a considerable need for coordination in the uptake of international hydrogen value chains. Thus, green hydrogen is likely to remain scarce for the foreseeable future as well as comparatively expensive.[15] In addition, Germany will be competing for a globally limited hydrogen supply along with many other countries.

## Focused use in specific applications

Due to scarce production capacities and direct electric alternatives with higher energy efficiency, the use of green hydrogen seems to be possible and reasonable only in specific applications until 2045. Many studies from the field of energy system analysis conclude that green hydrogen and its derivatives should be used preferentially in sectors in which direct electrification would be disadvantageous or impossible.[16]

Such sectors include primarily subsectors in energy-intensive industry. In some processes, hydrogen and its derivatives can be used both as energy sources and as a raw material. This applies to the extraction of iron from iron ore using direct reduction when producing neutral steel as well as the provision of basic materials to the chemical industry.

In the transport sector, the use of hydrogen and its derivatives is primarily relevant for aviation and shipping. For road traffic, in contrast, the use of hydrogen for passenger vehicles compared to battery-electric vehicles is not competitive. However, it is still unclear which type of powertrain will be successful in the future for certain areas of application in heavy goods vehicle traffic. In addition to hydrogen fuel cells, there are also the options of pure battery-powered trucks as well as catenary hybrid vehicles.[17]

A further long-term area of application for hydrogen that is becoming increasingly important is long-duration electricity storage. With rising shares of wind and solar power, such storage is increasingly required to reconcile their variable production profiles with electricity demand.[18] Long-duration energy storage can be realized, for example, as a combination of electrolysis, cavern hydrogen storage, and hydrogen gas turbines for reconversion.

Some of the potential areas of application for hydrogen described here are currently considered niche. In the future, however, they are likely to become more significant and could produce energy amounting to several hundred terawatt hours (TWh) in the long term.[19]

**11** For some examples, cf. Sachverständigenrat für Umweltfragen, *Wasserstoff im Klimaschutz;* also see Franziska Holz et al., "Zukunft des europäischen Energiesystems: Die Zeichen stehen auf Strom," *DIW Wochenbericht* no. 6 (2022): 75-82 (in German; available online).

**12** Frithjof Staiß et al., *Optionen für den Import grünen Wasserstoffs nach Deutschland bis zum Jahr 2030. Transportwege – Länderbewertungen – Realisierungserfordernisse. Analyse des Akademienprojekts „Energiesysteme der Zukunft"* (2022) (in German; available online).

**13** The German Environment Agency puts the energy losses for ammonia cracking alone at 13 to 34 percent, depending on the process and hydrogen grade: Umweltbundesamt (2022): *Kurzeinschätzung von Ammoniak als Energieträger und Transportmedium für Wasserstoff* (in German; available online).

**14** Cf. Felix C. Matthes et al., *Die Wasserstoffstrategie 2.0 für Deutschland. Untersuchung für die Stiftung Klimaneutralität* (Berlin: 2022) (in German; available online).

**15** Cf. Ueckerdt et al., *Dossier: Cornerstones of an Adaptable Hydrogen Strategy — Summary.*

**16** In the Kopernikus project Ariadne, these areas of application are defined as "no regret" options, cf. Ueckerdt et al., *Dossier: Cornerstones of an Adaptable Hydrogen Strategy — Summary.* This means that there is a very low risk that funding the use of hydrogen in these areas will be regretted at a later point in time.

**17** Cf. Julius Jöhrens et al., *Vergleichende Analyse der Potentiale von Antriebstechnologien für Lkw im Zeithorizont 2030* (2022) (in German; available online).

**18** Wolf-Peter Schill, "Electricity Storage and the Renewable Energy Transition," *Joule* 4, vol. 10 (2020): 2059-2064.

**19** Cf. Ariadne, Vergleich der „Big 5" Klimaneutralitätsszenarien (2022) (in German; available online); as well as Staiß et al., *Optionen für den Import grünen Wasserstoffs nach Deutschland bis zum Jahr 2030.*

## Revised National Hydrogen Strategy specifies planned market uptake

The German Federal Government presented its revised National Hydrogen Strategy in summer 2023, an updated and expanded version of the first National Hydrogen Strategy from 2020. The strategy defines targets for 2030 as well as short-term, medium-term, and long-term measures,[20] which are divided into four fields of action: securing enough hydrogen, developing a hydrogen infrastructure, establishing applications for hydrogen, and creating an appropriate regulatory framework.[21]

Compared to the 2020 version, the new strategy focuses more on the role of hydrogen in achieving the long-term goal of climate neutrality. At the same time, a bit less focus is on possible export opportunities for German hydrogen technology.[22]

### Availability of hydrogen: electrolysis and imports

Currently, around 55 TWh of primarily gray hydrogen are produced and consumed in Germany each year.[23] Green hydrogen, in contrast, has only been produced in small amounts so far. According to the new strategy, domestic electrolysis capacity of ten gigawatts (GW) is to be installed by 2030. The previous strategy planned for an electrolysis capacity of five GW by 2030; ten GW should be aimed for by 2035 “if possible” and achieved by 2040 at the latest. This target has thus been pushed ahead by up to ten years.

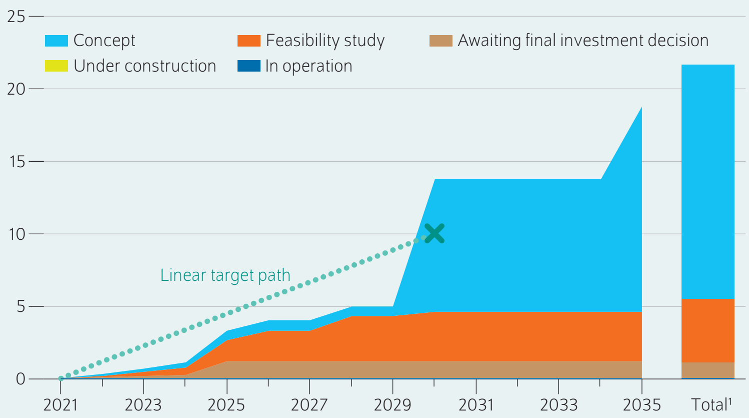
Assuming an electrolysis capacity of 4,000 full load hours per year and around 70 percent electrolysis efficiency, domestic production would amount to 28 TWh of green hydrogen in 2030. This requires an additional 40 TWh of electricity from renewable sources, which is around seven percent of total German gross electricity consumption in 2022. The expansion target of ten GW of electrolysis capacity should be achieved with a mix of instruments, including tenders for system-friendly electrolyzers and European projects as a part of the Important Projects of Common European Interest (IPCEI).[24]

Currently, only around 0.1 GW of electrolysis capacity is installed in Germany, which is one percent of the 2030 target. The capacity currently under construction is also very low (Figure 2). However, there are many large projects with a total capacity of over 20 GW in various stages of planning.[25] To achieve the 2030 target, a large share of these projects must be realized, including those that are currently still in vague, conceptual stages.

Figure 2

**Installed capacity of electrolysis projects in Germany**

In Gigawatts (electric)




1 Total including undated projects.

Note: The linear target path is illustrative only. While the Federal Government set the target for 2030, it did not specify an expansion path until then. Data as of October 10, 2022. An updated figure can be found in the Ampel-Monitor Energiewende (available online).

Source: IEA, IEA Hydrogen Projects Database.



To reach the 2030 target, most of the projects that are still in the early conception phase must also be realized.

In the new strategy, system-friendly electrolysis is explicitly named as a target for the first time.[26] This refers to both the timing of the electrolyzers’ deployment, which is to be primarily during periods of high renewable energy supply, and their locations. Priority should be given to sites that are close to renewable energy power plants and thus place less of a burden on the power grid than sites closer to future centers of hydrogen demand. In practice, this is likely to lead to electrolyzer sites in northern Germany with high wind power output, whereas demand centers are likely to be located primarily in western, central, and southern Germany.[27] Thus, hydrogen, not the renewable electricity required to produce it, should be transported in the future. Electrolysis sites near demand centers are only planned for demonstration and pilot projects to stimulate the market uptake initially.

**20** Since 2020, there has also been a hydrogen strategy at a European level as well as diverse hydrogen measures, for example as a part of the Fit for 55 package as well as of the Important Projects of Common European Interest (IPCEIs) (available online).

**21** In the section on framework conditions, the strategy contains various measures on planning and approval procedures, sustainability standards and certification, and research and skilled labor. This Weekly Report does not go into more detail on this section.

**22** The new strategy contains 18 variations on the term carbon neutral, while the old strategy only had six. Variations on the term opportunity appeared 27 times in the old strategy, while only three times in the new one.

**23** A small share of current hydrogen consumption is produced in chlor-alkali electrolysis, and hydrogen is also produced as a by-product in the petrochemical industry.

**24** More information on these projects is available on the website of the European Commission.

**25** IEA Hydrogen Projects Database, last updated on October 10, 2023 (available online). A data update announced for October 5, 2023, was unfortunately postponed and thus could not be considered in this Weekly Report. Information on the status and potential of electrolysis and other Power-to-X processes in Germany is also provided by the Hydrogen Atlas (available online). However, it contains some data gaps and does not paint a significantly different overall picture than the 2022 IEA data. Up-to-date data can be found on the Open Energy Tracker (in German; available online).

**26** Variations of the term "systemdienlich" (system friendly) appear 14 times in the new strategy. It does not appear at all in the old strategy.

**27** For more on the possible spatial distribution of hydrogen consumers, cf. Frederik vom Scheidt et al., "Integrating hydrogen in single-price electricity systems: The effects of spatial economic signals," *Energy Policy* 161 (2022): 112727.

In addition to domestic production of green hydrogen, the Federal Government assumes significant imports in 2030. To this end, an import strategy is to be developed. Furthermore, diverse international hydrogen partnerships have been initiated: The H2Global Foundation will coordinate and secure the uptake of international hydrogen supply and domestic demand.[28] While green hydrogen should be imported preferentially, the Federal Government assumes that "low-carbon" blue, turquoise, and orange hydrogen can be imported and used during a transition period as much as necessary for the market uptake phase. While the use of these types of hydrogen can be funded indirectly, at least on the application side, direct public support of hydrogen production is limited explicitly to green hydrogen.

## Building hydrogen infrastructure: networks and storage

To connect future hydrogen consumers with production and import locations, the new strategy names concrete targets for a private hydrogen network.[29] A 1,800-kilometer national network is planned initially, which should be constructed by 2028 at the latest by retrofitting existing gas transport capacities in addition to new construction. By 2030, it is to be connected to a European hydrogen network (European Hydrogen Backbone), which is also currently in planning, again with funding under the Important Projects of Common European Interest. By 2032, the network should be expanded to include all major demand, production, and import locations in Germany.

In addition, a concept for the construction of larger hydrogen storage devices should be developed. Existing gas storage should be retrofitted and new storage should be built. Hydrogen storage is mentioned prominently in the new strategy in many places, while it only played a subordinate role in the first strategy.

Beyond pipelines, hydrogen and its derivatives can be transported on land via rail[30] or road.[31] However, as quantities and distances increase, pipelines become more economical.[32] For the potential transport of hydrogen derivatives, in particular by sea, the new strategy calls for building upon the import infrastructures for liquefied natural gas (LNG) that are currently under construction. The infrastructure should be "$H_2$ ready" from the beginning and thus be able to be retrofitted for landing hydrogen derivatives with relatively little effort. This is likely in reference to the three fixed LNG terminals currently under construction rather than the floating storage and regasifcation units.[33] To what extent this is practically possible and economically reasonable, however, is unclear.[34]

## Clear focus of hydrogen applications in new strategy

The new strategy aims to establish the use of hydrogen in various sectors. Until 2030, the focus will be on industrial consumers. The strategy describes the replacement of natural gas, crude oil, and coal in material and partly also energetic industrial use, especially in the high-temperature range. Steel production is prominently mentioned, where direct reduction of steel is planned, as well as the chemical industry.

In the transport sector, the use of hydrogen and hydrogen-based e-fuels in aviation and shipping as well as for some special applications is deemed to be "required," such as with heavy commercial vehicles. Possible applications in passenger vehicles, in contrast, are not mentioned even once, unlike in the 2020 strategy.[35]

In the electricity sector, the focus of the new strategy is initially on the flexible operation of system-friendly electrolyzers. In the long term, the (re-)conversion of hydrogen and its derivatives is mentioned as an important application for times in which little wind and solar energy is available. New gas-fired power stations and cogeneration plants should be constructed to be $H_2$ ready, meaning they can be retrofitted for the use of hydrogen or its derivatives as fuel.[36] By 2026, 4.4 GW of hydrogen or ammonia-based "sprinter" power plants will be put out to tender as a specific measure. This involves plants that can be installed in a timely fashion and are able to be integrated into initial hydrogen infrastructure, such as hydrogen demand centers or hydrogen storage. In addition, a further 4.4 GW of hydrogen hybrid power plants will be put out to tender by 2028, i.e., reconversion units of hydrogen-based electricity storage facilities in which hydrogen production and storage take place on site.

In the heating sector, no "broad application" is planned until at least 2030 due to the foreseeable hydrogen shortage. In the long term, applications in the heating sector, primarily in relation to heating networks and cogeneration, are not excluded, however. They can also be tested ahead of 2030.

**28** A federally subsidized double auction is used for this purpose, with long-term offtake agreements for foreign hydrogen producers and shorter-term supply contracts for domestic hydrogen customers. Cf. H2Global Stiftung (available online).

**29** No concrete information on this was included in the 2020 version. The term hydrogen network only appeared twice in the old version; in the new version, it appears 19 times.

**30** There are concrete activities in this regard at DB Cargo, for example (in German, available online).

**31** For more on various options for road delivery to potential hydrogen refueling stations, cf. Fabian Stöckl, Wolf-Peter Schill and Alexander Zerrahn, "Optimal supply chains and power sector benefits of green hydrogen," *Scientific Reports* 11 (2021): 14191.

**32** Cf. M. Reuß et al., "Seasonal storage and alternative carriers: A flexible hydrogen supply chain model," *Applied Energy* 200 (2017): 290-302.

**33** Cf. Franziska Holz et al., "LNG Import Capacity Expansion in Germany – Short-term Relief Likely to Turn into Medium-term Stranded Assets," *IAEE Energy Forum* (2023): 13-18.

**34** Cf. Matia Riemer, Florian Schreiner, and Jakob Wachsmuth, *Conversion of LNG Terminals for Liquid Hydrogen or Ammonia. Analysis of Technical Feasibility und Economic Considerations*, (Karlsruhe: Fraunhofer Institute for Systems and Innovation Research ISI, 2022) (available online).

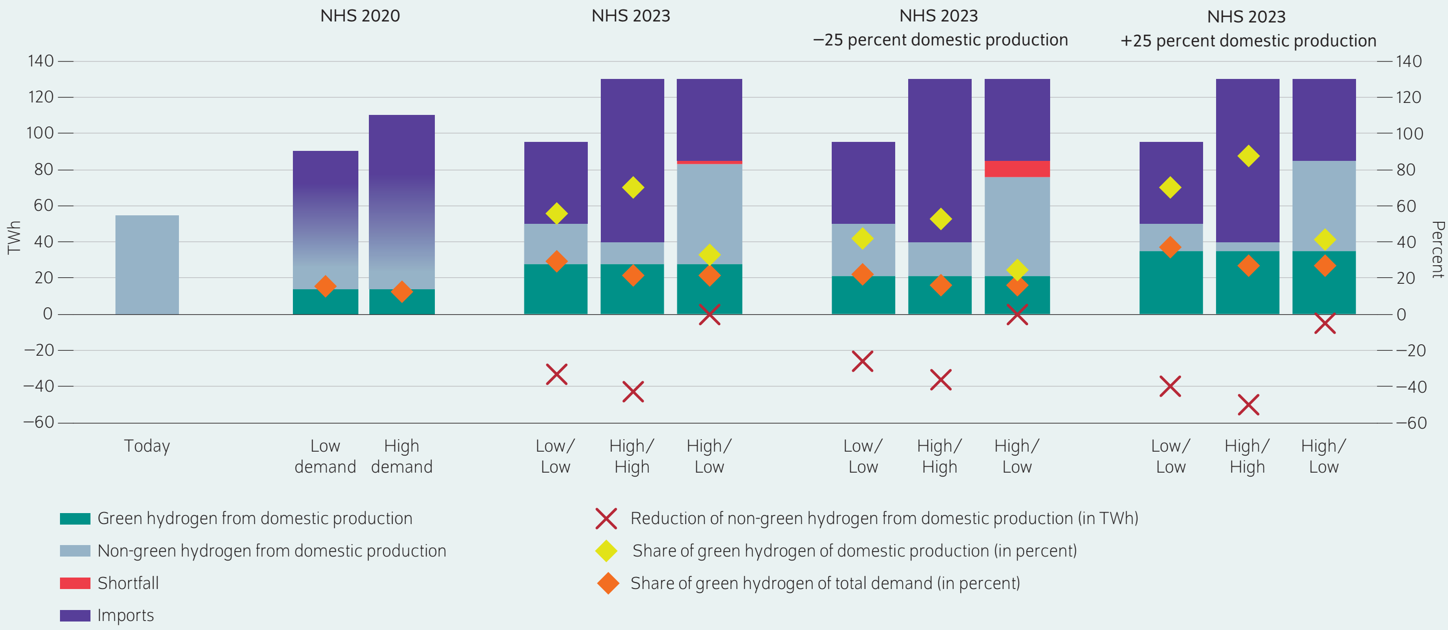
**35** Nevertheless, in his statement at the presentation of the revised National Hydrogen Strategy on July 26, 2023, Federal Minister of Transport Volker Wissing said that hydrogen is also needed in private transport, although this is not mentioned once in the new strategy (in German; available online). On July 26, 2023, Wissing tweeted, "The #hydrogenstrategy will contribute enormously to meeeting the needs in freight and private transport" (in German; available online).

**36** There is, however, no generally accepted definition of what $H_2$ ready means for power plants.

Figure 3

**Hydrogen quantities and colors from imports and domestic production in different scenarios for 2030**

In terawatt hours




Note: NHS = National Hydrogen Strategy. The 2023 NHS varies in terms of assumed total demand and imports. For example, High/Low indicates a scenario with high demand and low imports.

Source: Federal Government, Die nationale Wasserstoffstrategie.



Planned quantities for 2030 are uncertain, especially regarding the remaining share of non-green hydrogen.

## Considerable uncertainty around hydrogen quantities planned for 2030

In its new strategy, the Federal Government assumes 95 to 130 TWh of hydrogen and its derivatives are required, although this amount is not divided into pure hydrogen and its various derivatives. According to Federal Government estimates, "around 50 to 70 percent (45 to 90 TWh)" should be imported.[37] After 2030, the share of imports should continue to increase. In the old strategy, the range of total demand, 90 to 110 TWh, was significantly lower. Additionally, the targeted amounts to be imported were not specified at all.

## Key data provided in the strategy enables different scenarios

The new strategy does not directly indicate the planned level of domestic production of green and other types of hydrogen in 2030; a corresponding visualization is also missing. Therefore, various scenarios that could result from the above-mentioned key data are presented below (Figure 3).

These include a scenario with a low total demand of 95 TWh together with a low import potential of 45 TWh ("Low/Low") and a scenario with a high demand of 130 TWh together with a high import potential of 90 TWh ("High/High"). In addition, a pessimistic scenario regarding the share of imports, with a high demand of 130 TWh and a low import potential of 45 TWh, is presented ("High/Low"). All three[38] scenarios contain a domestic production volume of 28 TWh of green hydrogen. This figure results from the assumption of 4,000 electrolysis full load hours per year and electrolysis efficiency of 70 percent as well as the ten GW of electrolysis capacity as planned by the Federal Government.

## Quantity of non-renewable hydrogen varying starkly

In the "Low/Low" scenario, 22 TWh of domestically produced gray or other non-green hydrogen is still needed in 2030. In the "High/High" scenario, the amount still required decreases to only 12 TWh. This means that the Federal Government implicitly assumes that a scenario with higher hydrogen demand is associated with disproportionately high hydrogen imports. One possible explanation for this could be that higher imports decrease the price and thus increase

**37** The lower value of 50 percent fits the two lower specifications for demand and imports (45/95 = 47 percent) and the upper value of 70 percent fits the two upper specifications (90/130 = 69 percent).

**38** The combination of low demand with high imports ("Low/High") seems implausible and is thus not presented here.

domestic demand. In contrast to the first two cases, the use of non-green hydrogen remains at the current level of 55 TWh in the "High/Low" scenario. Assuming that production of gray hydrogen will not be expanded further, there would still be a shortfall of two TWh.

Thus, depending on the characteristics of total demand and import potential, the demand of non-renewable hydrogen decreases by up to 43 TWh or even increases by two TWh. It should be considered that currently, a share of this non-green hydrogen is a by-product of the petrochemical industry. To what extent it can be replaced by 2030, however, is unclear. This also depends on the general development and decarbonization of the petrochemical industry in Germany.

The share of domestically produced green hydrogen of total hydrogen production in Germany varies between 33 and 70 percent by scenario and would thus only be partially climate neutral. In addition, the share of domestically produced green hydrogen of total hydrogen demand in Germany is only 22 to 29 percent. This would result in Germany being heavily dependent on hydrogen imports.

### Sensitivity: more or less domestic production of green hydrogen

An increase or decrease in domestic production of green hydrogen of 25 percent in 2030 is presented as a sensitivity. This variation depicts both possible deviations from the targeted expansion of electrolysis capacity or its capacity utilization (i.e., full load hours per year), for example due to better or worse weather years.

With a 25-percent decrease in domestic production, only 21 TWh of green hydrogen would be produced. Accordingly, the amount of non-green hydrogen needed increases by seven TWh. In the "High/Low" scenario, the shortfall increases to nine TWh. In constrast, with a 25-percent increase in domestic production, 35 TWh of green hydrogen would be produced, seven TWh more, thus closing the shortfall. In the "High/High" scenario, the required quantity of non-green hydrogen can be reduced to just five TWh.

Expanding domestic electrolysis beyond these sensitivities would make further reductions in the consumption of both non-green and imported hydrogen possible.[39] However, such an expansion of production by 2030 is unlikely to be feasible given the additional expansion of both the electrolysis capacity and the additional electricity from renewable sources needed.[40]

### Ambitious new quantities of hydrogen planned are uncertain

In all considered scenarios of the hydrogen quantities planned for 2030, the role of domestic production of green hydrogen remains limited. Thus, the Federal Government assumes that the hydrogen demand will increase more quickly than domestic electrolysis can be expanded. Therefore, hydrogen imports are of great significance.

The Federal Government can only influence the uptake of electrolysis and hydrogen transport capacities in potential hydrogen export countries to a limited extent. In addition, there are only seven years until 2030. Therefore, even the lowest import target of 45 TWh seems extraordinarily ambitious. Uncertainty regarding the feasibility of imports thus seems high and translates directly into uncertainty about the remaining demand for non-green hydrogen. In the case of high demand and low imports, this could even increase compared to 2023. Therefore, establishing concrete partnerships with potential export countries early on is essential for achieving the targets laid out in the new strategy by 2030.

## International partnerships for green hydrogen imports

Cooperation with other EU states, primarily with neighboring countries on the North and Baltic Seas and in Southern Europe, but also with non-EU countries, has been solidified since 2020 in many cases through new energy partnerships with a focus on hydrogen or common declarations of intent. The Federal Government, moreover, has already concluded various hydrogen partnerships with non-European countries (Figure 4). The Federal Ministry for Economic Affairs and Climate Action (*Bundesministerium für Wirtschaft und* Klimaschutz, BMWK) currently lists a total of 21 countries,[41] although some partnerships are less concrete.

Concrete projects are already planned in some countries. Germany has significantly expanded its hydrogen cooperation with Norway, a country that seems particularly relevant in this discussion. The Norwegian energy company Equinor and the German energy company RWE AG are planning the construction of two GW of electrolysis capacity by 2030. A hydrogen pipeline to Norway is also planned.[42]

Pilot plants, each with ten megawatts (MW)[43] and 100 MW,[44] are currently planned in Tunisia and Morocco. Together with Egypt, the BMWK and the Federal Ministry for Economic Cooperation and Development (*Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung*, BMZ)

**39** For more on possible benefits and disadvantages of higher domestic production of green hydrogen, cf. Frank Merten et al., *Bewertung der Vor- und Nachteile von Wasserstoffimporten im Vergleich zur heimischen Erzeugung. Studie für den Landesverband Erneuerbare Energien NRW e. V. (LEE-NRW)* (2020) (in German; available online).

**40** For an analysis of possible electricity sector effects of green hydrogen production in Germany, cf. Dana Kirchem and Wolf-Peter Schill, "Heimische Produktion von grünem Wasserstoff kann mit Kavernenspeicherung günstiger werden," *DIW Wochenbericht*, no. 41 (2023) (in German; available online).

**41** See the website of the BMWK (in German; available online). Other federal ministries, such as the BMZ or the Federal Ministry of Education and Research, are also participating in hydrogen partnerships or international research collaborations.

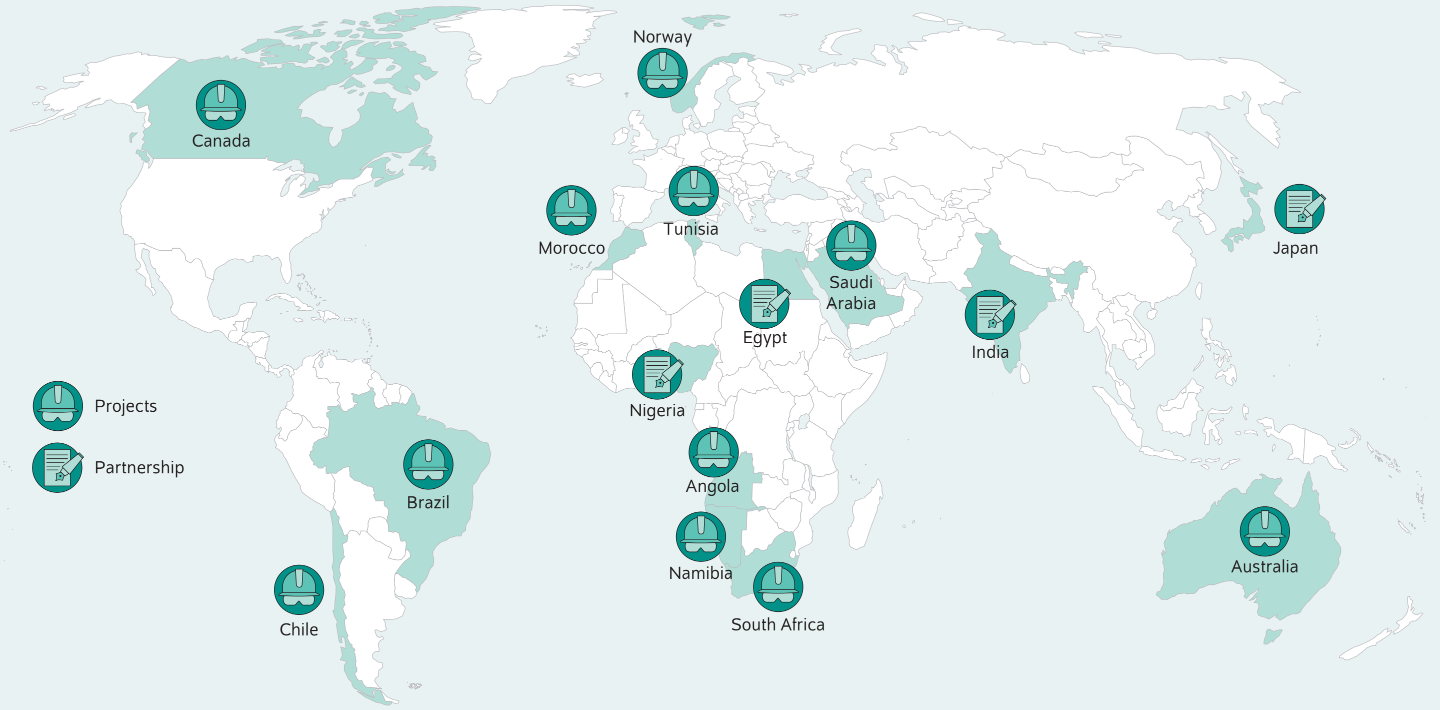
**42** Cf. RWE, "RWE und Equinor vereinbaren strategische Partnerschaft für Versorgungssicherheit und Dekarbonisierung," press release from January 5, 2023 (in German; available online).

**43** BMWK (in German; available online).

**44** BMWK (in German; available online).

Figure 4

**Germany's hydrogen partnerships with non-EU countries**




Note: Illustrated are countries that have already signed a declaration of intent with Germany for hydrogen cooperation or where a concrete hydrogen production project is in the pipeline.

Sources: Federal Ministry for Economic Affairs and Climate Action (Bundesministerium für Wirtschaft und Klimaschutz); Federal Ministry for Economic Cooperation and Development (Bundesministerium für wirtschaftliche Zusammenarbeit und Entwicklung).



Germany has initiated hydrogen partnerships with countries in all regions of the world.

signed a declaration of intent in 2022 with the goal of establishing a green hydrogen sector in Egypt.[45] In 2021 in Angola and Nigeria, the BMZ set up hydrogen diplomacy offices to intensify the cooperation. In addition, German companies in Angola have planned together with Sonagol, the state energy utility, to produce green hydrogen from hydropower beginning in 2025. In Namibia, too, two million tons of ammonia could be produced each year from 2028 with German participation. Of this two million, at least 0.3 million tons are to be exported to Germany, which is around 1.6 TWh.[46] Electrolysis capacity of 200 MW is to be built as a part of the HyShiFT project in South Africa. The BMWK is funding the first project phase, which plans for 40 MW.

As a part of the "Canada-Germany Hydrogen Alliance," Germany and Canada have agreed on initial hydrogen deliveries beginning in 2025. The German-Brazilian technological partnership H2Brasil is currently focusing on funding research, although German and Brazilian companies both agreed to hydrogen production in the Brazilian state of Bahia from 2025. The Haru Oni Project in Chile is receiving much more media coverage, but currently has a very low electrolysis capacity of 1.2 MW.[47] The plant should produce 130,000 liters of synthetic gas and 350 tons of methanol every year, which together totals only 0.003 TWh. By 2030, the electrolysis capacity should be expanded to 25 GW, which would be more than a 20,000-fold increase.

A declaration of intent to cooperate on hydrogen was signed with Saudi Arabia in 2021. In the future, the hydrogen production plant Helios,[48] located in Saudi Arabia, should produce around 1.2 million tons of green ammonia per year for the world market, which is around six TWh per year. Australia is another important hydrogen partner, with which Germany wants to construct a common hydrogen hub as a part of the HyGATE Initiative. Germany also wants to work closely together with India and Japan when it comes to hydrogen in the future, but no common projects have been launched yet.

**45** BMZ (in German; available online).

**46** Cf. RWE, "RWE and Hyphen explore offtake of green ammonia from Namibia," press release from December 2, 2022 (in German; available online).

**47** Website of the Haru Oni Project (available online).

**48** BMWK (in German; available online).

As of 2023, Germany has not agreed upon any concrete or binding import quantities with any partner country. Although the production potential in many partner countries is promising,[49] it is still unclear if the projects can be implemented within the planned time horizon and scope. Concrete, future production quantities are just as unpredictable today as the shares that would actually reach Germany via the world market. Even where concrete project plans exist, the targeted quantities are low compared to the German import targets for 2030. There is also great uncertainty about the import prices that will then result.

## Conclusion: Targeted implementation of the strategy with a focus on applications where direct electrification is impossible is required

In most long-term climate change scenarios, green hydrogen and its derivatives play an important role in applications where direct electrification seems impossible. At the same time, the uptake of domestic production, imports, and the necessary transportation and storage infrastructure take time and must be initiated and implemented early on.

It is in this context in which the Federal Government presented its new National Hydrogen Strategy. To a large extent, the strategy echoes what is now widely acknowledged in the area of energy system analysis: That the use of hydrogen should focus on specific applications due to foreseeable shortages and energy efficiency considerations. According to the strategy, the use of hydrogen in industrial applications as well as in parts of the transport sector will be prioritized initially. However, in communicating the new strategy, this focus was sometimes inadequately expressed. In principle, however, and especially in the longer term, the strategy does not rule out the broader use of hydrogen in a wide range of applications. This seems to be the result of political compromise, which reflects parts of the current government coalition's hopes of greater longer-term hydrogen availability.

Compared to the 2020 version, the new strategy focuses more on the role of hydrogen for achieving climate neutrality by 2045 and less on the export opportunities for German hydrogen technology. Moreover, the new strategy contains many new elements and concrete specifications, for example in the uptake of domestic electrolyzers, transport infrastructure, and hydrogen storage. The quantities planned for 2030 are also better defined. At the same time, the assumed hydrogen demand increases. However, there are significant uncertainties about the remaining amount of gray or non-green hydrogen in 2030. Moreover, it is unclear how the assumed future demand for pure hydrogen and its derivatives will be split and to what extent conversion losses should be accounted for in the figures.

Hydrogen imports will play a major role in the long term, although the import quantities envisaged for 2030 appear extremely ambitious and difficult to achieve from a 2023 perspective. Thus, they must be initiated and secured at an early stage. To this end, many international partnerships have already been started, although concrete projects with quantifiable import quantities barely exist. In these partnerships, green hydrogen should be the focus, as this is the only type guaranteed to be climate neutral.

Now that the new National Hydrogen Strategy has been presented, the implementation phase must be promptly and consistently initiated. This involves the domestic production of green hydrogen; the securing of future possible imports; the demand side, especially in industry; and the expansion of infrastructure. From an energy system perspective and due to a foreseeable shortage in the hydrogen supply, it is important to focus on applications in which direct electrification, which is significantly more energy efficient, is impossible.

**49** Christoph Hank et al., *Site-specific, comparative analysis for suitable Power-to-X pathways and products in developing and emerging countries. A cost analysis study on behalf of H2Global* (Fraunhofer ISE: 2023) (available online).

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