H2.B HYDROGEN CENTER BAVARIA

Hydrogen Roadmap Bavaria

Perspectives and recommendations towards the ramp-up of the Bavarian hydrogen economy

Initiated by

Bavarian Ministry of Economic Affairs, Regional Development and Energy

May 2022

Preamble

The Hydrogen Roadmap Bavaria, first published by the Hydrogen Center Bavaria (H2.B) in April 2022, was developed in a lengthy consultation and analysis process from the beginning of 2021 to the beginning of 2022 with the involvement of the Hydrogen Alliance Bavaria and other hydrogen stakeholders in Germany.

The assumptions and forecasts made in the roadmap, as well as recommended actions and milestones derived from them, are based on the framework conditions in the energy industry and economic policy as well as the prevailing state of opinion and data at the end of 2021.

The Russian war of aggression on Ukraine has an immediate and significant impact on EU energy policy. The European industrial nations are questioning the status quo of their primary energy supply, some have already begun to restructure their energy supply.

However, at present it is not possible to make precise and fully comprehensive statements about the consequences of the war in Ukraine on energy and economic policy. Nevertheless, the following consequences can be deduced that will also affect the field of hydrogen:

- The ramp-up of the hydrogen economy needs to be accelerated to diversify the sources of energy supply and to increase energy storage capacities due to correspondingly higher shares of fluctuating renewable energy.
- The demand for hydrogen and hydrogen derivatives will increase even sooner. It is therefore important to consider all technological possibilities for climate-friendly hydrogen production in Bavaria.
- Hydrogen imports must be ensured much more quickly in the medium-term to cover domestic demand and to not inhibit the ramp-up of the hydrogen economy. This will also foster sufficient diversification of the energy supply.
- More ambitious and consistently implemented measures are needed for the construction and expansion of hydrogen infrastructure in order to guarantee hydrogen imports and supply as early as possible.
- Uncertain and highly dynamic developments influence forecasts on the availability of hydrogen derivatives, hydrogen technologies as well as their prices.

The significantly different energy policy situation has a particular influence on the forecasted demand for hydrogen and SynFuels in chapter 3.2. This also affects the actions that can be deduced from this to ensure demand and the ramp-up of the transport infrastructure. It should be examined whether the recommended actions and milestones can be brought forward in time.

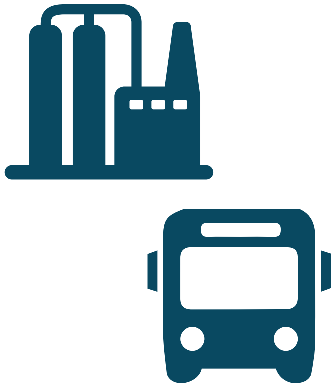
Table of contents

Executive Summary

Bavaria set the ambitious goal of being climate neutral by 2040. This means that the Free State of Bavaria is pursuing a more ambitious path than the German Federal Government or the European Union. It is certain that this goal cannot be achieved without the use of hydrogen across all sectors. The implementation of a hydrogen economy is associated with considerable efforts and has to be started immediately due to partly very long planning and investment cycles. This means: Setting the Bavarian course is an urgent task. On the one hand in order to achieve the climate targets that the Bavarian State has set itself and, on the other hand, to take advantage of the economic opportunities arising from the upcoming transformation. The intention of the Bavarian Hydrogen Roadmap is to identify perspectives and concrete needs for action as well as to contribute to accelerating the ramp-up of the Bavarian hydrogen economy.

Hydrogen consumption

The Bavarian demand for hydrogen is expected to increase faster compared to other federal states due to the State's more ambitious climate targets. The mobility and the conversion sector will be responsible for the biggest shares of this demand. The latter includes the petrochemical industry (refineries) as well as electricity and heat generation. However, a significant increase in hydrogen demand is also expected in the industrial and in the heat sector. In the industrial sector, hydrogen and its derivatives, such as methane, are mainly used to provide process heat. The use of hydrogen as a raw material, for example in the production of green steel or green basic chemicals such as methanol or ammonia, currently plays a rather small role in Bavaria. Overall, the demand for hydrogen and synthetic energy sources will increase to 33-75 TWh by 2040[1]. By 2030, hydrogen consumption will double from about 5 TWh today to about 10 TWh.



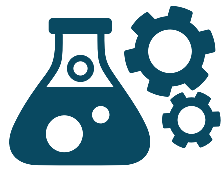
Hydrogen supply

The capacities for producing green hydrogen via electrolysis are rather low due to the low potential of renewable energy in Bavaria. In order to be able to meet the rapidly growing demand for hydrogen, Bavaria will have to rely on imports of hydrogen and hydrogen derivatives in the long term. The new German Federal Governement set a significantly more ambitious target for ramping up renewable energies in its coalition agreement. This will also create new opportunities for the production of green hydrogen in Bavaria. By 2030, at least 1 GW of electrolysis capacity must be installed in Bavaria (2025: 300 MW) to meet the assumed additional demand for hydrogen. Especially regarding a decentralized hydrogen supply, the use of hydrogen from biomass can also make a decisive contribution. At the same time, it should be assessed to what extent blue or turquoise hydrogen can play a role during a transition phase in the ramp-up of the hydrogen economy. In addition to Bavarian hydrogen production, the process of establishing a connection to the European Hydrogen Backbone must be accelerated in order to ensure a baseload supply for the most important consumers from 2030 onwards.

[1] It is difficult to make a clear distinction between elemental hydrogen and hydrogen-based synthetic energy carriers. For many applications, factors such as existing infrastructure, area of application, or prices determine the proportional allocation between hydrogen and synthetic energy carriers.

Business location
The transformation of global economies towards climate neutrality offers great opportunities for the export-oriented Bavarian economy. There are already numerous companies in Bavaria that are active in the broad field of hydrogen. Other companies have recognized the incipient transformation of the economy and are looking for ways to contribute their existing know-how to sustainable markets that are fit for the future. The hydrogen economy offers excellent starting points, e.g. for Bavaria's very important industrial sectors, such as (special) mechanical engineering, energy technologies, process and electrical engineering as well as mobility applications. In total, well over 40 percent of Bavarian employees in the manufacturing sector work in industries that are potentially relevant for hydrogen technologies – this corresponds to about nine percent of the total number of employees in Bavaria.

Science location
Bavaria's universities and higher education institutes are among the most innovative ones in Europe, and in many disciplines, they are also among the global leaders in research. This outstanding expertise also extends to the very broad field of hydrogen research. Bavaria is particularly well positioned in the field of electrolysis technology and (chemical) hydrogen storage and conversion. This good position is to be further strengthened and expanded.



Regulatory framework
Many hydrogen technologies fail to enter the market not because of a lack of technological maturity, but because of the unfavorable regulatory framework. In order for climate-friendly hydrogen to become competitive in the near future, the regulatory framework must be adjusted. This includes, for example, reducing the production costs of sustainable hydrogen (e.g. by lowering state-induced parts of the electricity price), making climate-damaging behavior more expensive (e.g. through an appropriate CO_2 price) and partially offsetting the initially expected differential costs between climate-friendly and climate-damaging technology (e.g. Carbon Contracts for Difference). In this regard, Bavaria has very little scope for action. Despite these regulatory limitations, the Free State can and will contribute in a constructive way to political decision-making processes at federal and EU level.

Demonstration projects
Demonstration projects are an excellent instrument for creating visibility for hydrogen technologies. It helps to further develop technologies, which are not econimically viable under the current regulatory framework. Bavaria should continue investing in research and development of hydrogen technologies and, furthermore, place and accompany Bavarian players in the best possible way in the competition for national and European funding. The targeted support of individual demonstration projects enables regional spill-over effects and can help to further establish hydrogen technologies in Bavaria.

German summary

Bayern hat sich das ehrgeizige Ziel gesetzt, bis 2040 klimaneutral zu sein. Damit verfolgt der Freistaat einen ambitionierteren Pfad als der Bund oder die Europäische Union. Klar ist: Ohne den Einsatz von Wasserstoff in allen Sektoren ist dieses Ziel nicht zu erreichen. Der Einstieg in die Wasserstoffwirtschaft ist mit erheblichen Anstrengungen verbunden und muss aufgrund der zum Teil sehr langen Planungs- und Investitionszyklen unmittelbar beginnen. Das heißt: In Bayern müssen zeitnah die richtigen Weichen gestellt werden, um einerseits die selbst gesteckten Klimaziele zu erreichen und andererseits die wirtschaftlichen Chancen der anstehenden Transformation zu nutzen. Die bayerische Wasserstoff-Roadmap soll Perspektiven und konkrete Handlungsbedarfe aufzeigen und dazu beitragen, den Hochlauf der bayerischen Wasserstoffwirtschaft zu beschleunigen.

Wasserstoffverbrauch

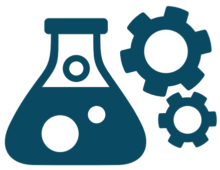
Es ist zu erwarten, dass der Wasserstoffbedarf aufgrund der ambitionierten Klimaziele in Bayern schneller steigt als in anderen Bundesländern. Die Sektoren mit dem größten Bedarf werden sowohl der Mobilitäts- als auch der Umwandlungssektor sein, der zum einen die petrochemische Industrie (Raffinerien) und zum anderen die (zentrale) Strom- und Wärmeerzeugung umfasst. Doch auch im Wärme- und Industriesektor ist mit einem erheblichen Anstieg des Wasserstoffbedarfs zu rechnen. Im Industriesektor werden Wasserstoff und dessen Derivate, wie Methan, vorwiegend zur Bereitstellung von Prozesswärme genutzt. Der Einsatz von Wasserstoff als Rohstoff, beispielsweise bei der Produktion von grünem Stahl oder grünen Grundchemikalien wie Methanol oder Ammoniak, spielt in Bayern aktuell eher eine kleine Rolle. Kumuliert wird der Bedarf an Wasserstoff und synthetischen Energieträgern bis 2040 auf 33 bis 75 TWh ansteigen[1]. Bis 2030 wird sich der Verbrauch von heute etwa 5 TWh auf etwa 10 TWh verdoppeln.

Wasserstoffversorgung

Die Kapazitäten zur Erzeugung von grünem Wasserstoff durch Elektrolyse sind aufgrund des geringen Potenzials erneuerbarer Energie in Bayern eher gering. Um den schnell wachsenden Wasserstoffbedarf decken zu können, wird Bayern langfristig auf den Import von Wasserstoff und Wasserstoffderivaten angewiesen sein. Durch die deutlich ambitionierteren Ausbauziele für erneuerbare Energien, die die neue Bundesregierung im Koalitionsvertrag formuliert hat, werden sich auch für die Erzeugung grünen Wasserstoffs in Bayern neue Chancen ergeben. Bis 2030 müssen in Bayern mindestens 1 GW Elektrolysekapazität installiert werden (2025: 300 MW), um den unterstellten zusätzlichen Wasserstoffbedarf decken zu können. Vor allem in der dezentralen Wasserstoffversorgung kann auch der Einsatz von Wasserstoff aus organischen Reststoffen einen entscheidenden Beitrag leisten. Gleichzeitig sollte auch evaluiert werden, inwieweit blauer oder türkiser Wasserstoff in einer Übergangsphase eine Rolle beim Hochlauf der Wasserstoffwirtschaft spielen können. Neben der Wasserstoffproduktion im Freistaat selbst muss der Anschluss Bayerns an das europäische Wasserstoff-Backbone beschleunigt werden, um eine grundlastfähige Versorgung der wichtigsten Verbraucher ab 2030 sicherzustellen.

[1] Eine klare Trennung zwischen elementarem Wasserstoff und wasserstoffbasierten synthetischen Energieträgern ist schwer zu ziehen. Bei vielen Anwendungen entscheiden Faktoren wie vorhandene Infrastruktur, Einsatzgebiet oder Preis über die proportionale Aufteilung zwischen Wasserstoff und synthetischen Energieträgern.

Wirtschaftsstandort
Die Transformation der globalen Volkswirtschaften hin zur Klimaneutralität ist mit großen Chancen für die exportorientierte bayerische Wirtschaft verbunden. Bereits heute existieren in Bayern zahlreiche Unternehmen, die sich im breiten Feld Wasserstoff engagieren. Andere Unternehmen haben die bereits beginnende Transformation der Wirtschaft erkannt und suchen nach Möglichkeiten, das bestehende Know-how in nachhaltige, zukunftsfähige Märkte einzubringen. Die Wasserstoffwirtschaft bietet hier hervorragende Anknüpfungspunkte z.B. für die im Freistaat sehr bedeutenden Industriebereiche (Sonder-)Maschinenbau, Energie-, Verfahrens- und Elektrotechnik sowie Mobilitätsanwendungen. In diesen potenziell für Wasserstofftechnologien relevanten Wirtschaftszweigen sind deutlich über 40 Prozent der bayerischen Beschäftigten des verarbeitenden Gewerbes tätig – das entspricht etwa neun Prozent der gesamten Beschäftigten in Bayern.



Wissenschaftsstandort
Die bayerischen Universitäten und Hochschulen gehören zu den innovativsten Hochschulen Europas und sind in vielen Bereichen auch global der Spitzenforschung zuzuordnen. Diese hervorragende Expertise erstreckt sich auch auf das sehr breite Feld der Wasserstoffforschung. Besonders im Bereich der Elektrolysetechnologie und der (chemischen) Wasserstoffspeicherung und -konversion ist Bayern sehr gut aufgestellt. Diese gute Position soll weiter gestärkt und ausgebaut werden.

Regulatorischer Rahmen
Der Markteintritt vieler Wasserstofftechnologien scheitert nicht an mangelnder technologischer Reife, sondern an den unvorteilhaften regulatorischen Rahmenbedingungen. Damit klimafreundlicher Wasserstoff zeitnah wettbewerbsfähig wird, muss der regulatorische Rahmen angepasst werden. Dazu zählt zum Beispiel, dass die Produktion von klimafreundlichem Wasserstoff günstiger (z.B. durch Reduzierung der staatlich induzierten Bestandteile des Strompreises), klimaschädliches Verhalten teurer (z.B. durch einen angemessenen CO_2-Preis) und die anfänglich erwartbaren Differenzkosten zwischen klimafreundlicher und klimaschädlicher Technologie teilweise ausgeglichen werden (z.B. Differenzkontrakte). Der Gestaltungsspielraum für Bayern ist dabei sehr gering. Dennoch kann und wird sich der Freistaat konstruktiv in politische Entscheidungsprozesse auf Bundes- und EU-Ebene einbringen.

Demonstrationsprojekte
Demonstrationsprojekte sind hervorragende Instrumente, um Wasserstofftechnologien, die unter den aktuellen regulatorischen Rahmenbedingungen nicht wirtschaftlich sind, ins Feld zu bringen und gleichzeitig weiterzuentwickeln. Bayern sollte auch weiterhin in die Forschung und Entwicklung von Wasserstofftechnologien investieren und die bayerischen Akteure darüber hinaus im Wettbewerb um nationale und europäische Fördermittel bestmöglich platzieren und begleiten. Die gezielte Unterstützung einzelner Demonstrationsprojekte ermöglicht regionale Spill-over-Effekte und kann helfen, Wasserstofftechnologien auch in Bayern weiter zu etablieren.

1. Introduction

Why is hydrogen an indispensable element for a climate-neutral economy?

Bavaria is committed to the goal of the Paris Climate Agreement to limit global warming to well below two degrees. Bavaria aims to be climate neutral by 2040 – five years earlier than Germany. This implies a considerable restructuring of the entire Bavarian energy system (including electricity, heating, mobility, industry, etc.).

In order to defossilize the energy system, many processes can be operated directly with renewable electricity. However, for a variety of applications and processes the use of hydrogen or its derivatives, such as ammonia, synthetic methane or methanol, is a reasonable or the only sustainable alternative. For some applications, such as in the chemical and petrochemical industry, the use of elemental hydrogen (H_2) is often the only alternative. In "green" steel production, hydrogen is indispensable as it serves as a reducing agent for the sustainable production of green steel. In other areas, hydrogen technology competes with other technologies – examples of this are road-based mobility or the provision of space heating. In most sectors, a coexistence of different technologies is expected due to different boundary conditions.

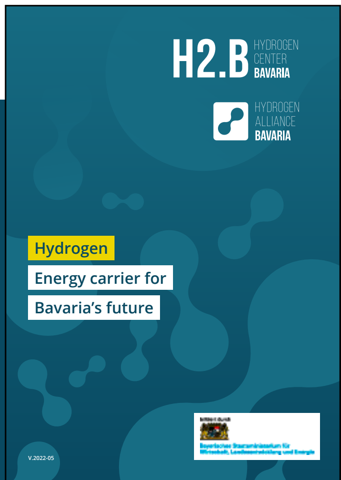
In the course of a global energy transition and the development of a worldwide hydrogen economy, new export markets for hydrogen technologies will emerge. This holds great potential for value creation in Bavaria. The prospect of attractive, long-term stable jobs in Bavaria can make a valuable contribution to the broad acceptance of ambitious climate policies. In this context, Bavarian companies can not only contribute to the reorganization of the domestic economy, but can also help to establish climate-neutral value chains worldwide.

The transformation of the Bavarian society and economy towards climate neutrality by 2040 involves considerable efforts and must begin quickly due to the sometimes very long planning and investment cycles. However, the conversion holds considerable opportunities: The Free State of Bavaria has an excellent position in many areas along the hydrogen value chain. These areas must be promoted in a targeted manner. At the same time, it is of great importance to give an honest evaluation of the areas in which the Bavarian economic and research landscape still needs to catch up.

The Hydrogen Center Bavaria (H2.B) plays an important role in this transformation process: It provides specifically compiled information, supports companies, associations and institutions in the formation of project consortia and brings together Bavarian hydrogen players in regional and international networks. The Hydrogen Alliance Bavaria, coordinated by H2.B, makes a valuable contribution to these activities. The alliance offers a platform where companies, research institutions and associations can network and inform each other. The Alliance, which consists of more than 250 partners in May 2022, has contributed to this roadmap through surveys and bilateral exchanges.

Information brochure about H2.B and the Hydrogen Alliance Bavaria

Bavarian Hydrogen Strategy (executive summary in English)



Why do we need a hydrogen roadmap for Bavaria now – and how does it fit into the national and international "roadmap landscape"?

The *Position Paper of the Bavarian Hydrogen Alliance about the Bavarian hydrogen economy* and the *Bavarian Hydrogen Strategy* (both published in May 2020) outlined the first perspective and vision for the development and design of a Bavarian hydrogen economy. The Hydrogen Roadmap Bavaria is intended to pick up on these impulses and to draw a current as well as future picture of Bavaria as a business and science location for hydrogen. Furthermore, an estimation of possible hydrogen consumption in Bavaria will be made and, derived from this, important milestones for the rollout of hydrogen technologies will be outlined.

The "hydrogen world" is currently in a state of quick and dynamic developments. This presents many players with the challenge of constantly realigning themselves and having to make decisions based on uncertain and highly variable forecasts. The results of a survey among the partners within the Hydrogen Alliance Bavaria showed that not only new players in the hydrogen economy wish more and external strategic orientation points. Even though the Hydrogen Alliance does not represent the Bavarian economy overall, it nevertheless unites a comprehensive selection of active hydrogen players in the Free State. Some of these players have been involved in the development, production and use of hydrogen and hydrogen technologies for several years to decades. These experienced actors also strongly base their decisions on political guidance such as roadmaps and strategies. The need for a "roadmap" for the upcoming decisions and strategic evaluations is therefore likely to be high throughout the entire Bavarian economy.

The Hydrogen Roadmap Bavaria fits well into the existing roadmap and strategy landscape of the federal states, the Federal Government and the European Union. In the future, Bavaria sees itself predominantly as a hydrogen importer and thus forms the complement to the northern German states, which place a strong focus on the production of the energy carrier. At the same time, Bavaria can establish itself as a hub for imports of hydrogen and hydrogen derivatives from northern Germany and South or Souch-East Europe.

The opportunities and challenges described at the federal level in the national hydrogen strategy apply to Bavaria to an even greater extent: Bavaria has a strong industrial character. Above all, mechanical and process engineering as well as the automotive and automotive supply industry are of outstanding economic importance. Bavaria is known as an excellent science location – also and especially for the hydrogen sector. Bavaria, like the Federal Republic of Germany, is a technology exporter, but at the same time a net energy importer. According to current scenarios and studies, both will have to cover a large part of its primary energy requirements through imports also in the future.

The Hydrogen Roadmap Bavaria is intended to analyse these aspects and to derive guidelines with regard to both a secure supply of sustainable hydrogen and future opportunities for Bavarian players.

...of the surveyed partners in the Hydrogen Alliance Bavaria base their business decisions strongly to very strongly on political roadmaps.

2. Status quo and strengths of the Bavarian science & economy

In which fields is hydrogen already used in Bavaria?

Currently, about 55 TWh of hydrogen are used for various applications in Germany every year. In Bavaria, the annual consumption amounts to about 5 TWh. The petrochemical industry accounts by far for the largest share – the refineries in the Ingolstadt area and in Burghausen are among the largest consumers. In addition, there are a variety of industrial consumers in the Free State, for example flat glass manufacturers or semiconductor producers, that use hydrogen as a protective gas in their production processes. At universities and other scientific institutions, hydrogen is used in minimal quantities for research purposes.

Large consumers such as refineries produce the hydrogen they need directly on site in their own production facilities. In some cases, hydrogen produced in other production steps can be used as well. However, the majority is obtained by steam reforming of natural gas (SMR – Steam Methane Reforming). Smaller consumers are mainly supplied by trucks from gas suppliers. A pipeline network that exchanges hydrogen over a large area – i.e., outside individual production sites or networks – between different sources and sinks does not yet exist in Bavaria.

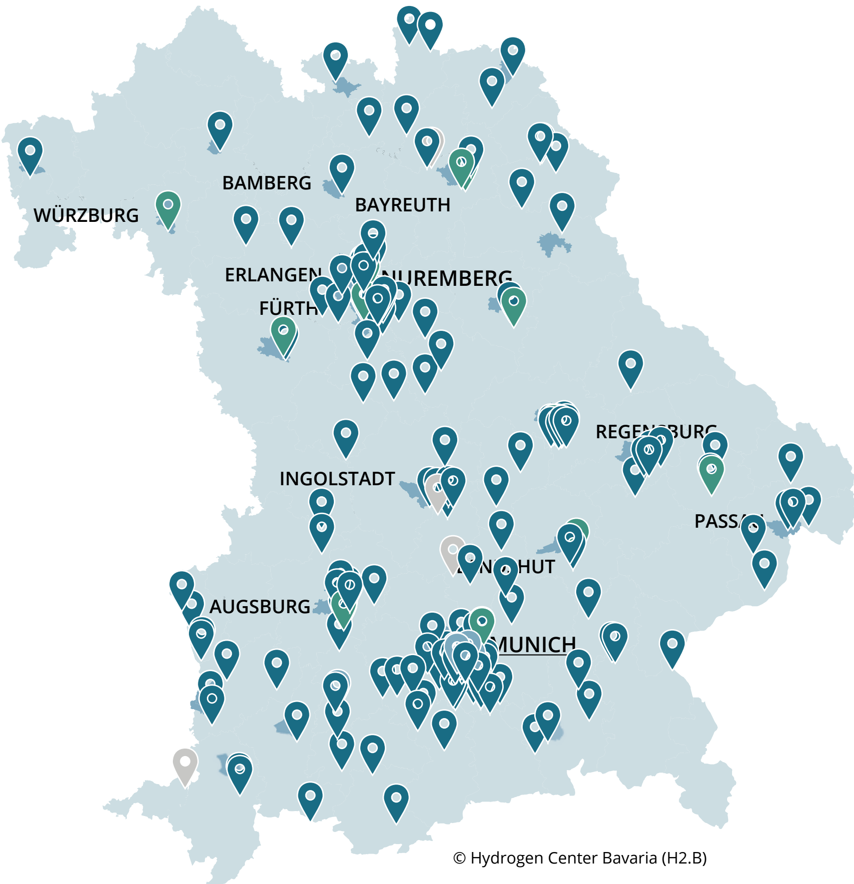
Which climate-neutral hydrogen projects already exist in Bavaria?

Several research and demonstration projects in the field of hydrogen already exist in Bavaria. In recent years, the number and scope of planned and approved projects have increased considerably. The figure on the right shows a selection of the research and demonstration projects funded in the Free State of Bavaria.

Partners in the Hydrogen Alliance Bavaria as of 04/2022

257 Partners in the Hydrogen Alliance Bavaria

- **209** companies
- **19** universities & research institutions
- **22** associations & clusters
- **7** other (public) facilities



© Hydrogen Center Bavaria (H2.B)

HyLand[2] hydrogen regions and IPCEI[3] project drafts in Bavaria

HyStarters

- A District of Kulmbach
- B District of Eichstätt
- C Industrial and business park “Interfranken“
- D City of Munich
- E Ostallgäu – Municipality of Fuchstal, City of Kaufbeuren, District of Ostallgäu

HyExperts

- F District of Wunsiedel im Fichtelgebirge
- G District of Neustadt an der Waldnaab
- H “IN2H2“ – City of Ingolstadt
- I District of Passau
- J Region of Ulm/Neu-Ulm (Baden-Württemberg & Bavaria)
- K “HyAllgäu“ – District of Oberallgäu
- L District of Lindau (Bodensee)

HyPerformers

- M “HyBayern“ – Districts of Landshut, Ebersberg, Munich, City of Landshut

IPCEI project drafts

- P1 SOFC (Bosch)
- P2 “BayH2“ (Bayernoil, Vattenfall)
- P3 “Green Hydrogen @ Blue Danube“ (Hydrogenious & partners)
- P4 H_2-Fahrzeug (BMW)
- P5 “RHYME“ (Wacker Chemie)

---

[2] “HyLand – Hydrogen Regions in Germany“ is a competition issued by the German Federal Ministry for Digital and Transport (BMDV) and launched in 2019, with the aim of identifying and promoting the most innovative and promising regional concepts.

[3] With the “Important Projects of Common European Interest - IPCEI“, the German federal and state governments are funding large-scale industrial projects that decisively advance the development of the hydrogen economy in Germany and Europe and thus make an important contribution to the energy transition. A total of 62 projects were selected in Germany, which will now be confirmed by the EU.

What competencies do Bavarian companies have in the field of hydrogen?

Bavaria is one of Europe's most powerful economic regions and has a strong industrial character. Measured in terms of turnover, the Bavarian economy accounts for around 22 percent of German mechanical engineering and almost 27 percent of German automotive and automotive parts production. Other important industrial sectors for Bavaria are the manufacturing of chemical products, metal products and electrical equipment.

Measured in terms of in-house investment in research and development, almost 51 percent of Bavarian products are considered to be research-intensive. This share is significantly higher than the German average and emphasizes Bavaria's status as high-tech location supported by the distinctive and innovative academic research landscape.

Cutting-edge technologies make an important contribution to the high export share of Bavarian products. In 2020, almost 54 percent of the revenues of Bavarian companies were generated abroad. The total sales of Bavarian companies amounted to almost 350 billion euros, making the Free State the front-runner among all German states.

The international orientation and the focus on cutting-edge technology are important prerequisites for a successful role in a global hydrogen value chain. With its high level of expertise in (special) machine engineering, energy, process and electrical engineering as well as in mobility applications, the Bavarian industry already covers numerous components and requirements of the emerging hydrogen economy. These economic sectors, which are potentially relevant for hydrogen technologies, employ well over 40 percent of the Bavarian workforce in the manufacturing sector, which corresponds to about nine percent of the total Bavarian workforce.

A relevant number of partners in the Hydrogen Alliance is represented in these fields of activity. On the one hand, the participating Alliance partners from industry are those who see hydrogen technologies as the core of their entrepreneurial activities. These companies have often only emerged in recent years. On the other hand, there are established industry players that are looking for new business areas within the hydrogen value chain that fit well their existing skills. This enables them to use existing experience for the transformation of the economy.

The close technological proximity to the entire hydrogen process chain enables the Bavarian industry to use long-standing know-how and important parts of the portfolio for new, innovative hydrogen products. It is therefore logical that individual Bavarian companies are in a leading position in the field of hydrogen technologies today. This applies particularly to hydrogen production, the manufacturing of valves and fittings, and hydrogen logistics.

The competencies of Bavarian players also include the production of hydrogen-based chemical products as well as carriers that simplify the transport and handling of green energy. This is also shown by the strong participation in international hydrogen projects, in which Bavarian companies are primarily active in the areas of hydrogen production, conversion and transport.

In comparison, application technologies are less strongly represented. Nevertheless, some Bavarian companies already offer innovative products for hydrogen applications. However, these are currently often still produced in comparatively small quantities and are partly focused on a very specific market sector. In terms of a broad and sustainable market entry of hydrogen technologies, the necessary quantities for an attractive price and sufficient availability are missing. Due to the relatively limited product portfolio, some user requirements cannot yet be met.

The challenges to be overcome are often not related to technical feasibility. One of the biggest obstacles is the lack of industry standards and norms that enable greater modularity,

Dr. Stefan Gossens
Vice President Hydrogen Strategy, Schaeffler AG

» *We consider the future topic of hydrogen as a unique growth opportunity. Therefore, we are establishing a competence center for hydrogen at the Herzogenaurach site where we develop and produce components such as bipolar plates for fuel cells and electrolyzers.* «

cross-company product development and easier scaling of production. The so-called Hydrogen Technology and Application Center (WTAZ) in the town of Pfeffenhausen, will address this problem in the future. The WTAZ if funded within the framework of the site competition of the BMDV (Federal Ministry for Digital and Transport; formerly BMV) for a Hydrogen Technology Innovation and Technology Center (ITZ). At the same time, various Bavarian players have announced to scale up their production capacities and the series production of hydrogen products "made in Bavaria".

The federal and state governments are already working on incentives to increase the market uptake of hydrogen technologies. In Bavaria, for example, the focus lies on promoting a hydrogen filling station infrastructure for commercial vehicles. At the same time, however, the availability of sufficient quantities of green hydrogen must be ensured.

In the short term, regional initiatives in particular will be able to make a decisive contribution here. However, this will only be possible if a corresponding domestic market for renewably produced hydrogen – and thus for renewable energies from all sources – can be created. Apart from planning and projecting wind power and photovoltaic plants, Bavarian players are particularly active in the field of the energetic use of biomass or organic residues. Nevertheless, Bavarian companies also play a strong role in the development and planning of projects for the generation of renewable energies from wind and sun.

What competencies does Bavaria have as a research location in the field of hydrogen?

Bavarian universities and colleges are among the most innovative ones in Europe and are represented in the global top research in individual fields. Outstanding expertise also exists in the field of hydrogen technologies – this should be further expanded, as already outlined in the H2.B Position Paper and the Bavarian Hydrogen Strategy.

In order to smoothen and accelerate the path from (academic) technology and product development to a market-ready product, the exchange between academic and private-sectorresearch and development should be intensified. However, due to its relevance for the transformation processes of the energy transition for society as a whole, the socio-economic view must also remain an important component of the Bavarian research strategy.

The central technologies of the hydrogen economy, namely electrolysis and fuel cell technology, are a focus of Bavarian research activities in the field of hydrogen as well. This is the result of an analysis of the research priorities and project participations of universities, colleges and research institutes. The primary goal is cost reduction over the entire life cycle: Both a lower power-related precious metal usage as well as a standardized, efficient and large-scale production process for the individual system components promote a lower, lifetime related system price (TCO). In addition to the actual electrolysis or fuel cells, this also includes all components that contribute to the function and integration of the hydrogen production and use – for example gas compressors, measurement and control technology as well as power electronic components.

Another relevant research topic – in addition to the electrochemical production and use of hydrogen – is the use of waste and residual materials as well as biomass. The intensive research work of various Bavarian institutes has already led to the foundation of several start-ups in this field. One important focus lies on researching different ways of breaking down the often heterogeneous starting products. Another focus is the consideration of different approaches to convert the resulting, mostly gaseous mixture of substances into different energy sources or basic chemicals. Great importance is attributed to integrating existing infrastructures and operating the plants as part of an energy supply system that is no longer exclusively demand-driven.

In this area, there are close thematic links to PtL or PtX processes. These processes are used to produce liquid or gaseous energy carriers and platform chemicals and are thus excellently suited to synchronize energy consumption across sectors, time and space. The accompanying research is concerned with different synthesis routes and inexpensive catalyst materials that can also be used in dynamic operation.

Highly efficient, decentralized electricity and heat generation, based on renewable energy stored in gaseous or liquid fuels (so-called SynFuels or BioFuels), can contribute to relieving the electricity infrastructure. Research into the development and integration of combined heat and power plants (CHP plants) for particularly efficient reconversion into electricity is gaining momentum. In addition to combustion engines, PEM fuel cells and SOFCs, so-called high-temperature solid oxide fuel cells, already play an important role today.

Possibilities for storing elemental hydrogen include compressed, cryogenic compressed and liquefied hydrogen. Bavarian players are researching both new materials and manufacturing processes that enable high-performance, cost-effective and large-scale production of pressure tanks. A particular focus is being placed on lightweight composite tanks that are to be used in mobility applications.

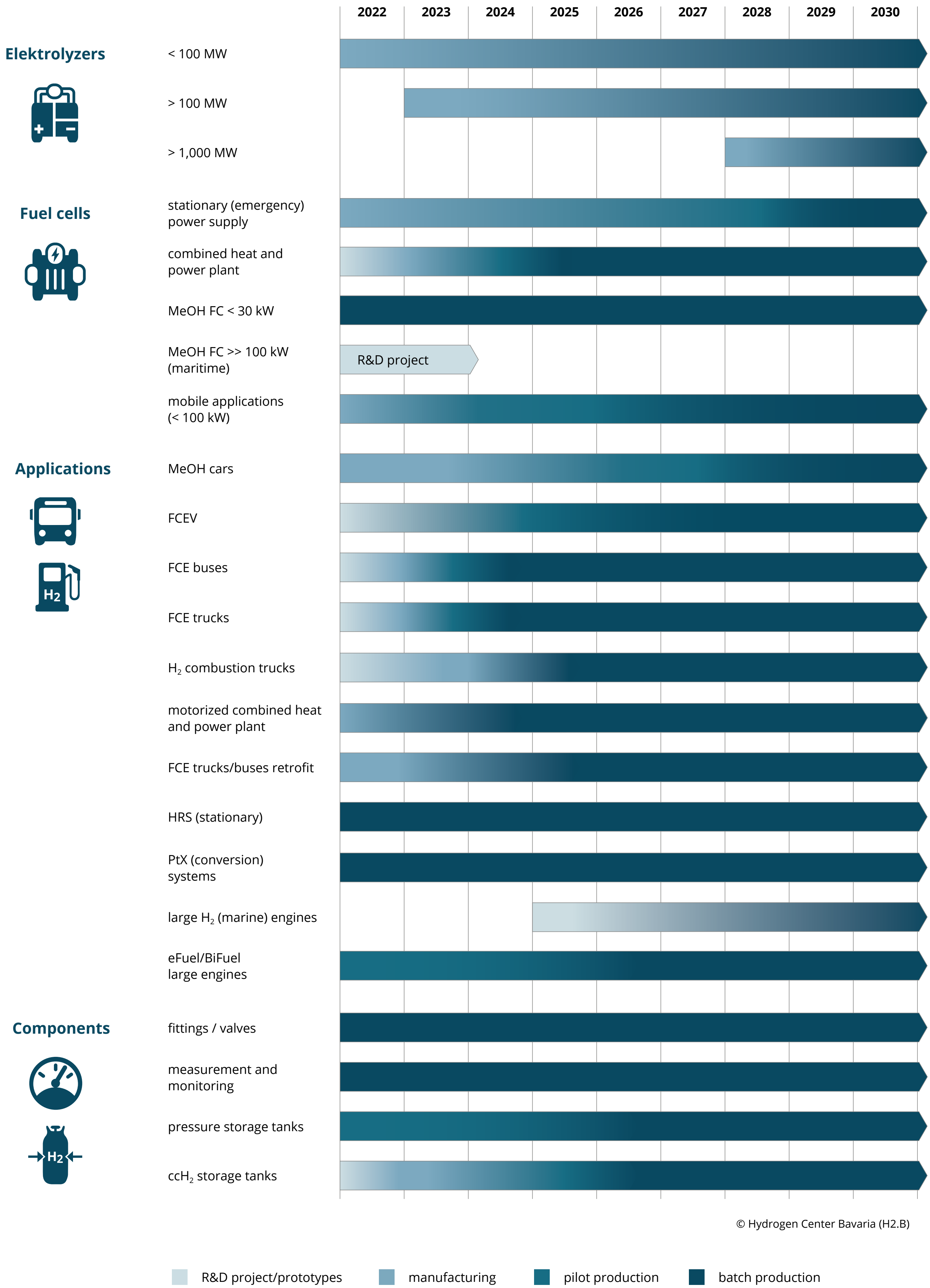
Another possibility to transport and store hydrogen in large quantities is offered by so-called liquid organic hydrogen carriers (LOHC). Using LOHC, hydrogen can be bound chemically at the point of energy supply and released again when required. To be able to reliably control and efficiently use this process chain, Bavarian players from science and industry are researching inexpensive and durable catalyst materials as well as the intelligent integration of storage and release systems into existing processes in the energy, chemical and hydrogen industries. Possible applications exist in various sectors. LOHC technology can, for example, be used to store large quantities of hydrogen in existing fuel tanks, e.g. for refueling hydrogen vehicles. Current projects are also investigating the provision of hydrogen on board of large vehicles such as ships and trains.
Bavarian research organizations already cover –and some have done so for many years – a broad spectrum of topics along the hydrogen process chain. Bavarian universities and research institutes enjoy a high reputation worldwide, particularly in the fields of electrolysis and hydrogen storage and conversion. In addition to the existing intensive efforts in the field of combined heat and power generation, research into hydrogen applications is also gaining importance. This is necessary because, in international comparison, there is a need for Bavaria to catch up in individual areas of hydrogen utilisation technologies.

© Georg Pöhlein

Prof. Dr. Karl Mayrhofer
Director, Helmholtz Institute Erlangen-Nürnberg for Renwable Energies (HI ERN)

»*Bavaria already has established first unique and sustainable research infrastructures. This success story must be further developed in a targeted and focused manner in order to be decisively involved in the worldwide implementation.*«

Development status and availability of hydrogen technologies from Bavaria



3. Potentials of a future Bavarian hydrogen economy

In which sectors should hydrogen be increasingly used?

Hydrogen is a versatile energy carrier that can be used in many sectors. In some areas, such as in the chemical and petrochemical industry, there is no alternative to the use of hydrogen because it is an indispensable component of basic chemical materials and products. Currently, these sectors predominantly use grey hydrogen which will have to be replaced by climate-friendly hydrogen in the future.

In other sectors, such as the mobility sector, there are some alternatives to the use of hydrogen and its derivatives. However, hydrogen can show its strength as a green fuel with a high energy density wherever direct electrification via overhead line or battery is technically not possible or economically not viable.

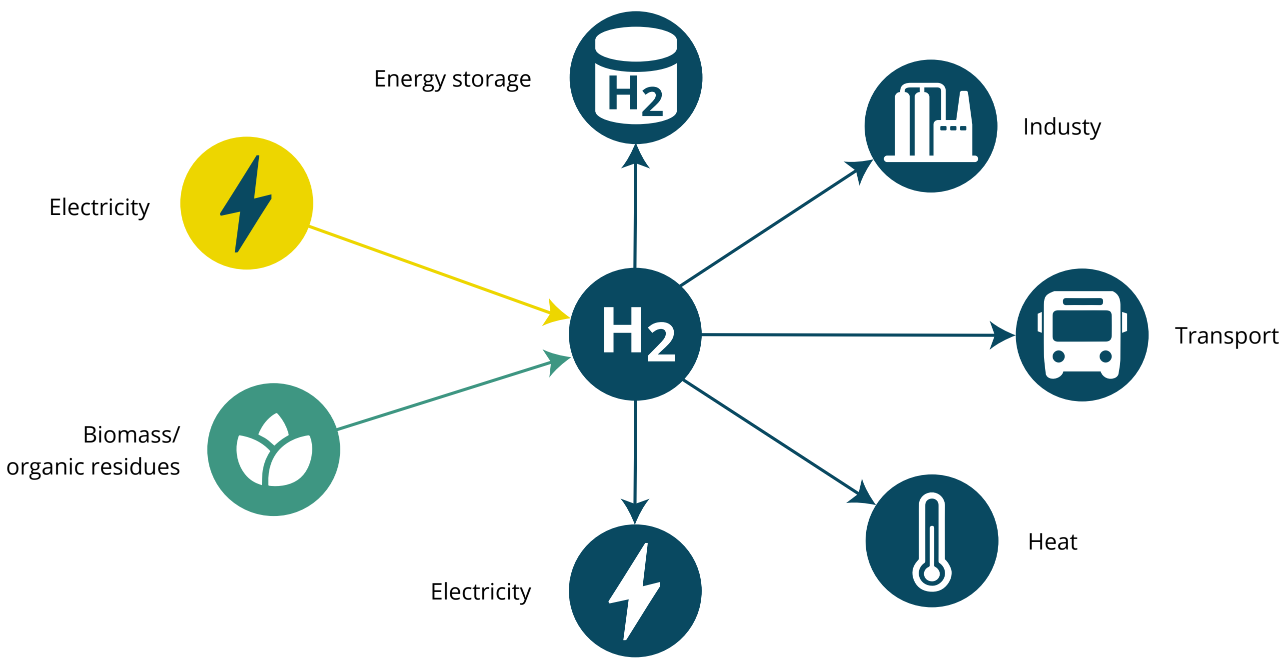
This applies, for example, to parts of air and sea traffic, but also to large parts of road-bound heavy-duty transport. Here, hydrogen based solutions are favorable if a high availablity of vehicles, long ranges and the transport of high payloads are required. In the passenger car segment, the use of hydrogen and fuel cell technology can make a notable contribution to climate neutrality, too. Several of the world's leading car manufacturers have already included fuel cell cars in their portfolios, and others have announced their intention to do so.

Some of the know-how that has made Bavarian companies global market leaders in the field of combustion engines could also be transferred to fuel cell vehicles. Bavaria must therefore have an economic interest in participating in the future value creation of this growing market.

Hydrogen will also play a decisive role in seasonal energy storage in the future. With the increasing share of fluctuating renewable energies in the energy mix in Bavaria, Germany and Europe, the importance of demand-driven, sustainable electricity and heat generation is also growing. Uncertainty effects can be reduced by a flexibilization of demand or intra-European energy trade (grid expansion), but not completely avoided. Therefore, hydrogen-based solutions such as combustion engines and fuel cells will be needed for demand-responsive electricity and heat production in Bavaria.[4]

There are various options for the provision of domestic space heating and hot water in a climate-neutral energy system, which have specific advantages and disadvantages depending on the application. Heat pumps are generally characterized by very high efficiency. However, a one-sided focus on electrical heating by heat pumps leads to considerable challenges in terms of practical feasibility. Increasing the deployment of electrical heating solutions requires a significant effort in modernizing the existing building infrastructure. However, the required annual renovation rate of nearly 2 % was not accomplished in preceding years. This means that chemical energy sources will still be needed for the foreseea-

Possible applications of hydrogen



ble future. The highly seasonal nature of the heating market can also be served more easily by hydrogen, which is easy to store, compared to electricity- based technologies.

It is impossible to foresee every technology and infrastructure development. Thus, excluding specific (hydrogen) technologies in a political top-down approach should be avoided. Only in this way, economies of scale, which lead to a reduction in production and transport costs, can be used and a system-optimal coexistence of different technologies can be made possible. In this context, debates narrowed down to technical and physical efficiencies are misleading. The analysis of complex real world systems must be complemented by the dimensions of economic and macroeconomic efficiency.

The Bavarian economy is an export-driven economy. The strategic focus should not be placed exclusively on possible applications within Bavaria or Germany. Many applications that are seen as second-best solutions in Germany can be a decisive building block in the transformation of the respective economies in other regions of the world. For example, the comparatively simple integration of hydrogen or its derivatives into existing infrastructures favors the adaptation of the technologies in developing and emerging countries.

Other technological approaches, such as the provision of domestic space heating, are particularly interesting in countries where hydrogen is available very cheaply and where very cold winters prevail or a particularly preceivable seasonality make the use of heat pumps difficult.

In order to become a technology leader, Bavaria must quickly develop a strong domestic market at an early stage that also takes these applications into account. With its more ambitious climate targets, Bavaria has the chance to become a demonstrator for a sustainable hydrogen economy.

How could hydrogen consumption in Bavaria develop in the future?

The demand for hydrogen in Bavaria will increase significantly in the future. From today's perspective, it is difficult to say in which sectors and processes hydrogen will be used and to what extent. However, it is possible to estimate general trends and develop corridors of the future hydrogen demand.

In general, it can be stated that the hydrogen demand of an energy system increases disproportionately as the CO_2 reduction demand rises. This is due to the fact that hydrogen technologies are used where the CO_2 abatement costs are particularly high. In climate-neutral scenarios, which assume limited availability or a high price for negative emissions, there is a particularly high demand for hydrogen and its derivatives.

Bavaria has announced net climate neutrality for the year 2040 and is thus setting itself more ambitious goals than Germany or the EU. To achieve these goals, the Free State of Bavaria must start much earlier with replacing the processes that are particularly difficult to defossilize ("hard-to-abate") . Thus, Bavaria needs to set the course for a climate-neutral hydrogen economy earlier.

The following chapters will give corridors which outline the minimum and maximum hydrogen demand until 2040. The corridor boundaries are based on existing studies for Germany, but they consider the specific conditions of the location of Bavaria. Respective estimates concern the four sectors **industry**, **transport**, **buildings** and **conversion**.

The charts show not only the demand for hydrogen, but also for synthetic fuels, which are generally based on hydrogen. The advantage of most of these synthetic fuels is the possibility to use existing infrastructures for transport and application. However, the production of SynFuels is generally more expensive since at least one additional process step is required after the hydrogen production. Due to unavoidable in-process losses and the extraction of the required reaction partner (e.g. CO_2) in pure form, more renewable energy must be used to store the same amount of energy.

For some applications, however, synthetic hydrocarbons can offer long-term advantages not only because of their good system integration. For example, intercontinental aviation is expected to rely on liquid hydrocarbon fuel for a long time. Whereas this is due to the high energy density required for long haul aviation, chemical and petrochemical industries will use liquid hydrocarbons, since carbon is the most important building block of their products. In other areas, where theoretically both solutions (hydrogen and SynFuels) can be used, the distribution of alternatives may vary - for example, depending on widely differing prices or the existing infrastructure for hydrogen.

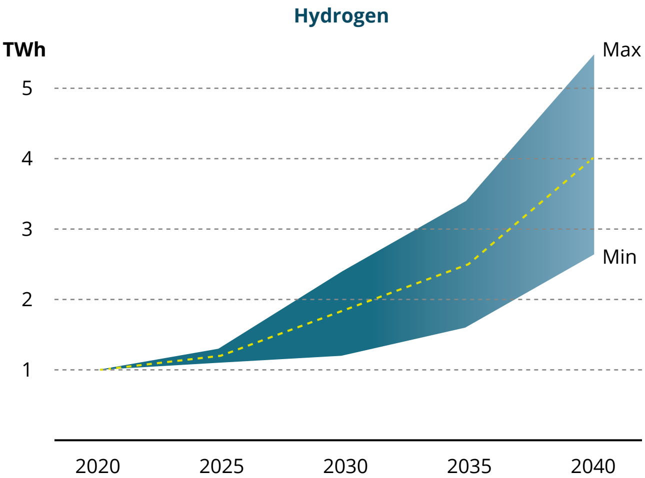
[4] In its current guideline study (dena-Leitstudie Aufbruch Klimaneutralität), the German Energy Agency dena states a necessary capacity of 59 GW for controllable gas-fired power plants for a climate neutral German energy system.

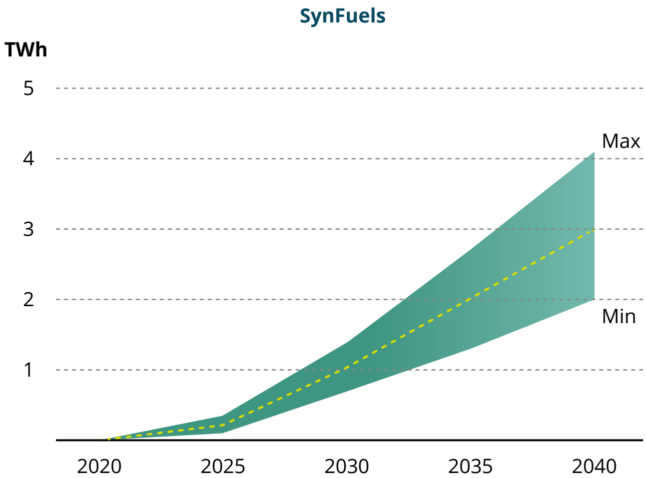
In the **industry sector**, the future demand for hydrogen results from both applications in which the gas is used to provide process heat and processes in which hydrogen is required as a raw material. However, the petrochemical industry is not included in the industry sector, but in the **conversion sector**.

Applications in which significant quantities of hydrogen are already used as raw material today, such as ammonia or methanol production, do currently not play a major role in Bavaria. Nevertheless, tthere are a few pioneering projects, especially in the chemical industry, which are likely to lead to a higher consumption of hydrogen in the respective areas. In addition, there are already several consumers who use hydrogen in their production processes for example for hydrogenation processes or the generation of a reducing protective atmosphere. In the area of process heat supply, there are currently no significant consumers of elemental hydrogen or synthetic fuels.

However, the demand will develop very dynamically in the future. Hydrogen and its derivatives such as synthetic methane will increasingly be used in the future, especially in processes that require very high temperatures and for which heating with burners is favorable over electirical heating or if there is no possibility to electrify the heating process. The production of cement, glass, lime or paper and cardboard can serve as examples for processes carried out in decentralized manner throughout Bavaria. Due to the high energy input required, these processes currently use high shares of fossil fuels such as natural gas.

Derived hydrogen and SynFuel demand in the industry sector





Dr. Peter Gigler
Head of Corporate Sustainability, Wacker Chemie AG

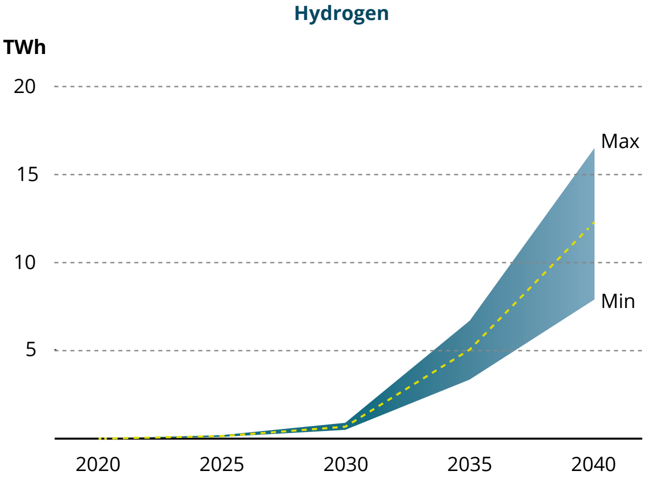
Climate neutrality requires the defossilization of chemical processes and products. Here, the use of CO_2 as a raw material will play a central role. By means of green hydrogen, as planned in the RHYME Bavaria project, renewable methanol can be produced and fossil resources can be replaced. To drive this transformation forward, we need an early connection to a hydrogen network through which we can obtain green hydrogen at internationally competitive prices.

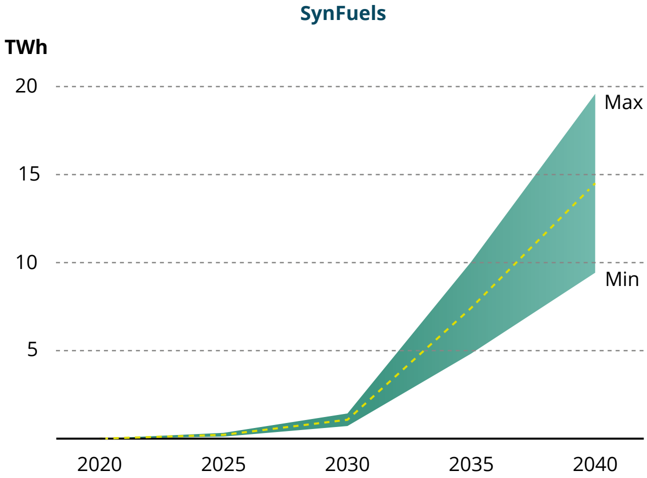
Transport

In the **transport sector**, hydrogen is used directly, either in a fuel cell or a heat engine (e.g. engine or turbine). It can also be used to produce synthetic fuels. Due to their higher energy density, such liquid hydrocarbons are particularly interesting for the operation of heavy vehicles that travel long distances. These include, for example, aircraft or ships.

But SynFuels can also play an important role for the road-based transport in Bavaria. According to forecasts, around 75 percent of the vehicles in Germany will still be equipped with combustion engines in 2030. The use of SynFuels in road transport can therefore make a significant contribution to achieving the target of climate neutrality by 2040.

Derived hydrogen and SynFuel demand in the transport sector





Conversion

In addition to the production of electricity from hydrogen, the **conversion sector** primarily includes the petrochemical industry, which is by far the largest consumer and producer of hydrogen in Bavaria today.

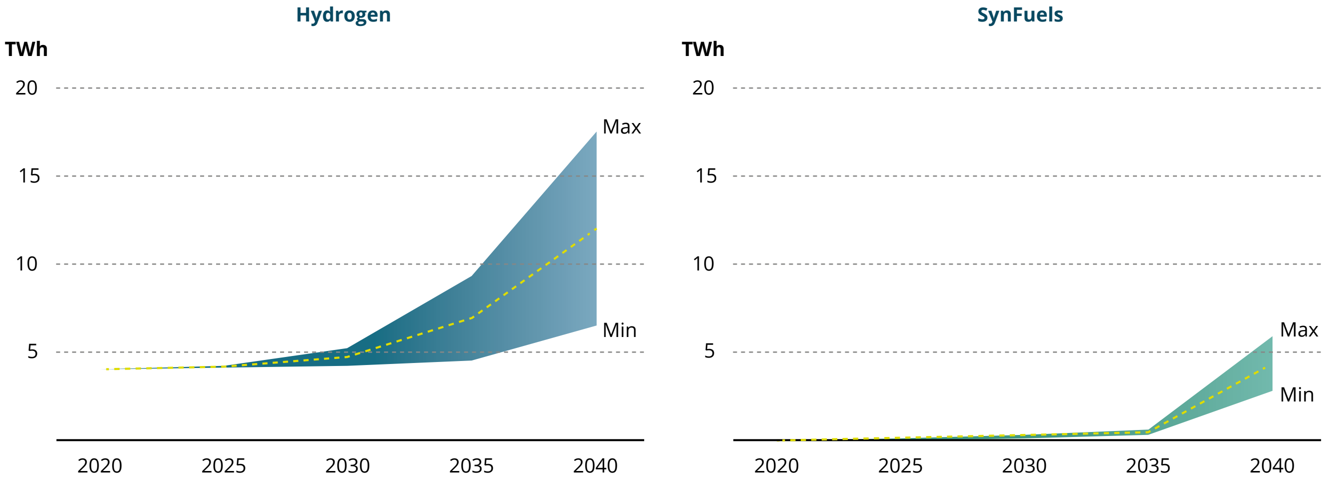
The future role of refineries is largely unclear. In the short and medium term, the greenhouse gas intensity of conventional fuels can be significantly reduced by using climate-friendly hydrogen. In the long term, however, the role of refineries is uncertain: Basic chemicals and fuels could increasingly be produced abroad due to the lower production costs for hydrogen and carbon.

Other scenarios assume a broader import of green hydrocarbons such as naphtha, which, as a drop-in feedstock, can be integrated in today's refinery processes comparatively easy. The further hydrogen-intensive processing could continue to take place in Bavaria, but with gradually declining production volumes. This can be attributed to the fact that the demand for liquid hydrocarbons will decrease sharply throughout Germany, but also globally. The dena guideline study for a climate-neutral Germany, for example, indicates a demand of only about 138 TWh of liquid (synthetic) hydrocarbons. The largest share of this is attributable to air traffic (122 TWh).

In 2018, on the other hand, around 900 TWh of liquid hydrocarbons such as gasoline, diesel, kerosene and heating oil were still consumed. The study assumes that in a lower-bound scenario the refining of these products will be phased out by 2040. The upper limit is a scenario in which hydrogen consumption of four TWh remains roughly constant. Should the Bavarian refinery sites expand the production of synthetic fuels, the demand for hydrogen or carbon-containing synthetic feedstocks could rise considerably above the range shown, depending on the process management.

Hydrogen will also be of great importance for electricity production in Bavaria in the future. An increasing flexibility in electricity demand and a more intelligent electricity distribution in better developed electricity grids in Europe will help to absorb the strongly increasing share of volatile electricity generation. Nevertheless, the need for storage will increase significantly with the renewable power generation capacities. Hydrogen can be stored relatively cheaply, especially in gaseous form or as a liquid derivative, in (pressure) tanks and in parts of the existing gas and distribution network. This flexibility, combined with low operating costs, makes hydrogen and its derivatives especially suitable for seasonal and strategic storage for power and heat generation.

Derived hydrogen and SynFuel demand in the conversion sector

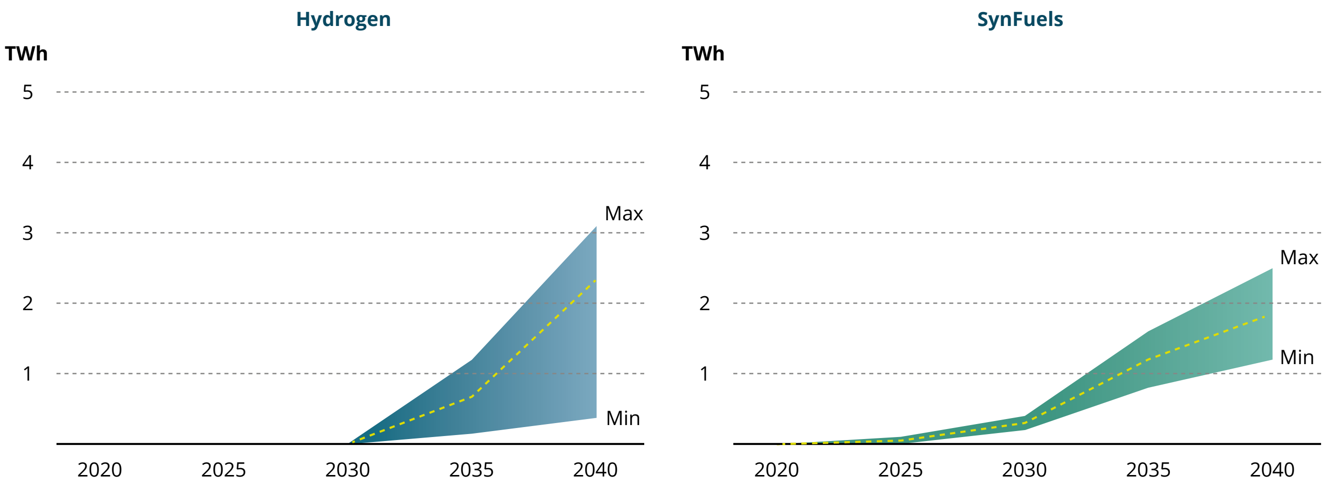


Buildings

Hydrogen can also contribute to reducing greenhouse gas emissions in the **building sector**. When and to what extent hydrogen will be used to generate space heating and hot water depends strongly on the development of hydrogen availability, the hydrogen price, the infrastructure for electricity, district heating, natural gas and hydrogen as well as the actual renovation rates.

Only if the ambitious renovation rate of just under two percent per year is achieved on a permanent basis, which is equivalent to doubling the current renovation rates, hydrogen or synthetic energy carriers like methane would become less important in the provision of space heating. If these rates are not achieved, the use of hydrogen or its derivatives is mandatory in order to defossilize the existing heating and hot water systems.

Derived hydrogen and SynFuel demand in the building sector

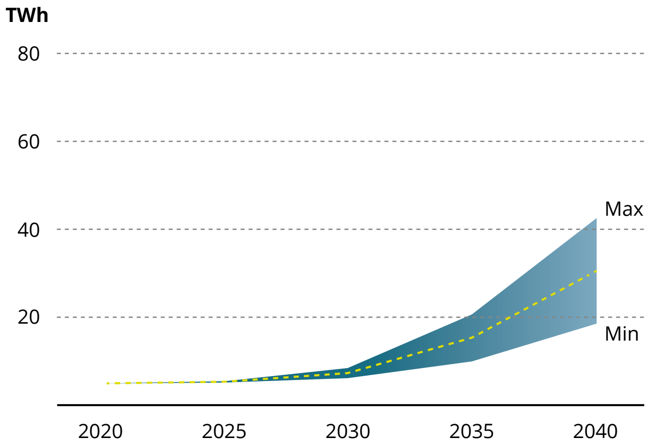


Cumulative demand

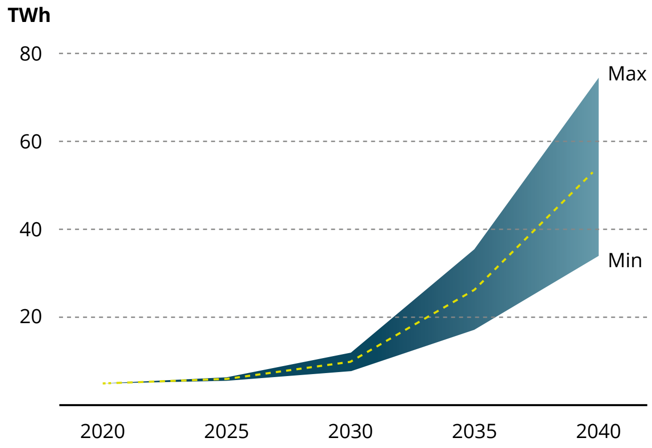
In Bavaria, the cumulative demand for hydrogen and synthetic products could amount to about 33-75 TWh per year by 2040. The transport sector will have the largest share with 17-36 TWh, followed by the conversion sector with 9-23 TWh, which is currently the largest consumer with about 4 TWh. In the industrial sector, hydrogen and hydrogen derivatives are mainly used for the generation of process heat. The demand for hydrogen and synthetic energy sources in this sector will develop only slowly for the time being – nevertheless, according to calculations, it will double to about 10 TWh by 2040. It is assumed that consumption in the refineries will not change substantially. In contrast, demand in all other sectors will increase continuously.

The demand for elemental hydrogen will have increased to 17-43 TWh/a in the target year of greenhouse gas neutrality 2040. Here, too, the conversion and mobility sectors will be the largest consumers. A significantly higher increase in hydrogen demand is already forecasted for the period starting from 2030.

Cumulative hydrogen demand



Cumulative hydrogen and SynFuel demand



How can the hydrogen demand be met during the ramp-up phase and beyond?

As pointed out in the previous chapter, the Bavarian demand for hydrogen will increase significantly in the years ahead. Renewable electricity generation in the Free State does not offer the potential for large-scale hydrogen production by electrolysis. Bavaria is an importer of electrical energy – the negative balance is likely to increase further with the last nuclear power reactors shut down in 2022.

An electrolysis capacity of between 1.4 and 2.4 GW_{el} would be required (assumption of electrolyzer efficiency: 0.7; possible full load hours: 3,000-5,000) to produce merely the current annual consumption of about five TWh of hydrogen. For comparison: The maximum electrical load in Bavaria is currently about 12.5 GW. Even the planned expansion of the transmission grid will not be sufficient to provide the necessary power for large-scale domestic hydrogen production – especially since hydrogen-based energy transport in pipelines is in any case considerably more cost-effective than the transport of electrical energy via high voltage lines.

In the future, Bavaria's demand for hydrogen will therefore have to be covered to a large extent by imports from the rest of Germany, other European countries and from countries with very good conditions for renewable energies outside of Europe. At present, however, there is neither sufficient infrastructure nor production capacity for the large-scale import of hydrogen.

In the medium term, hydrogen distribution within Germany and Europe is to take place primarily via an efficient pipeline network connecting the most important hydrogen sources and sinks. To determine the future demand and supply structure, the market survey "Hydrogen production and demand" WEB (in German "Wasserstoff Erzeugung und Bedarf") realized by the transmission system operators (TSO) has identified potential projects for the generation and consumption of hydrogen.

The results are included in the scenario framework of the Gas Network Development Plan 2021-2023 and are shown in aggregated form on page 23 for the year 2032. In total, a cumulative demand of 476 TWh in 2050 was mentioned in the market survey. Due to the design of the survey, these values are associated with considerable uncertainties. Nevertheless, they are within the range of common energy system modellings and give a first impression of the spatial distribution of future sources and sinks.

Stefanie Jacobi
Hydrogen Project Development, Deputy Head of Grid Strategy & Innovation, bayernets GmbH

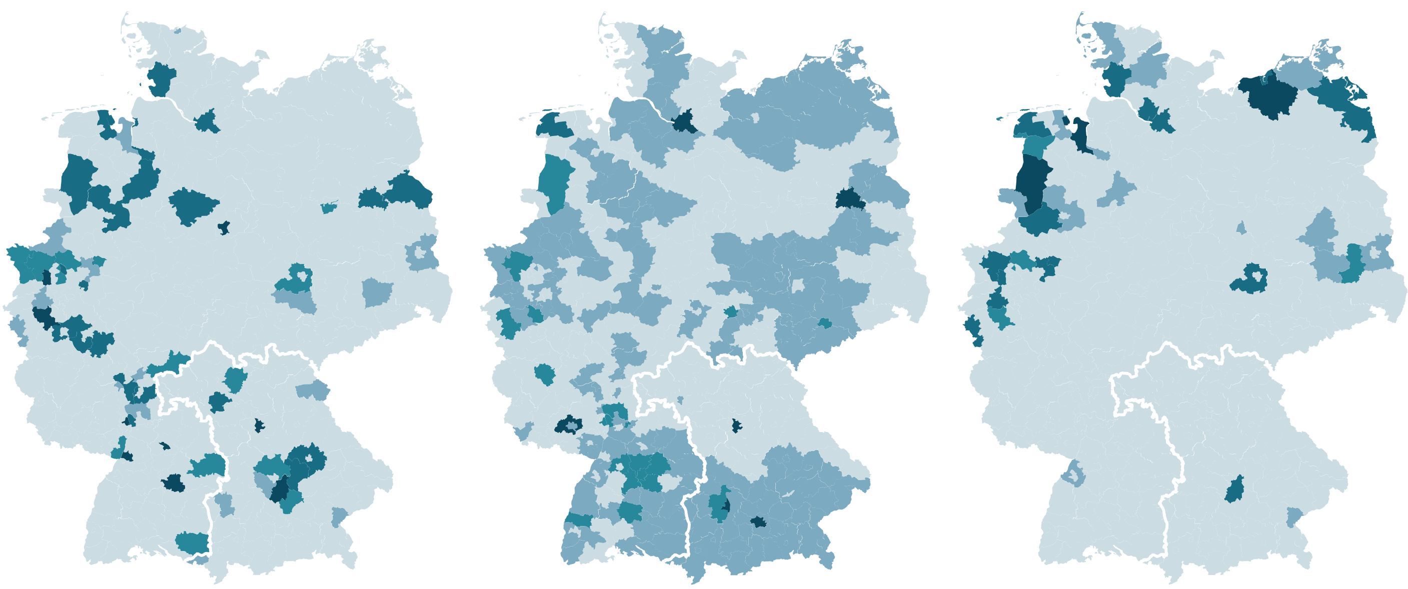
» *The integration of hydrogen production and consumption into a supra-regional hydrogen transport network is a key building block for the ramp-up of the hydrogen economy in Bavaria. This is confirmed by the results of the market survey "Hydrogen production and demand" of the German transmission system operators: The Bavarian hydrogen production is far from sufficient to meet the needs of Bavarian hydrogen customers. For the Bavarian industry, networking with potential hydrogen sources in northern Germany and abroad is essential.* «

The reported projects for hydrogen consumption lie within the corridor shown on page 21, although direct comparability is not possible. It is clear that the required output volume considerably exceeds the planned feed-in volume. In addition, it is evident that the hydrogen demand is not exclusively focused on industrial centers but is in part strongly decentralized.

The first concepts for a German and European backbone network internd southern Germany and thus Bavaria not to be connected before 2035. Recent concepts of the German transmission system operators, however, show a connection of important industrial sites in the northern part of Upper Bavaria already by 2030. By 2035, the hydrogen demand (without SynFuels) should already amount to 9-21 TWh per year. Should the Free State have to supply itself with hydrogen until it is connected to a German or European pipeline network[5] in 2035, an average hydrogen demand of 16.5 TWh would be equivalent to electrolysis capacity of 5-8 GW_{el} is required (assumption of electrolyzer efficiency: 0.7; possible full load hours: 3,000- 5,000). It is foreseeable that the additional load for the power grid in Bavaria cannot be realized.

Hydrogen supply and demands by 2032 according to the market enquiry WEB "Hydrogen production and demand"

H_2 supply projects (injections) | **H_2 demand public utilities / regional suppliers (withdrawals)** | **H_2 demand projects (withdrawals)**



Absolute quantities at county level:

less than 0.1 TWh | 0.1 to less than 0.5 TWh | 0.5 to less than 1 TWh | 1 to less than 5 TWh | more than 5 TWh

Source: Own illustration based on the scenario framework of the Gas Network Development Plan 2022-2032, FNB Gas e.V.

[5] Repurposed pipelines are capable of transporting up to 13 GW depending on diameter and pressure.

Actions to meet the hydrogen demand in Bavaria

The connection of Bavaria to a European hydrogen network is essential. In addition to this connection, further distribution must be enabled across Bavaria. This is of special importance, as currently, most industrial natural gas customers are not connected to the transport/transmission grid but to the distribution network. The consumption figures given in this roadmap can only serve as a first indication of the development of Bavarian hydrogen demand. However, the general trend indicates that the Bavarian hydrogen demand will significantly exceed the possible production volumes. Various measures must be taken in order to reliably meet the demand for hydrogen during ramp-up of the Bavarian hydrogen economy and to enable the transition to a climate-neutral society.

- **Hydrogen backbone network**
  Accelerating Bavaria's connection to the European Hydrogen Backbone (EHB) must become a priority in order to ensure sufficient supply to the most important consumers no later that 2030.

- **Determination of hydrogen demand**
  A detailed and regionally broken-down determination of hydrogen demands of the individual sectors should be carried out in a timely manner to further specify the demand forecast in this roadmap.

- **Expanding renewable energy capacities**
  The expansion of renewable energy capacities and the transmission grids must be accelerated. This is a basic requirement in order to provide sufficient energy and power to produce hydrogen by electrolysis in Bavaria.

- **Hydrogen production ramp-up**
  Domestic hydrogen production must be ramped up. In addition to hydrogen from electrolysis, the use of biomass or organic residues or other climate-friendly variants such as blue hydrogen should also be evaluated. This could be especially interesting for locations where the production of electrolysis hydrogen is not possible without major adaptations due to a lack of infrastructure. Especially when producing turquoise and blue hydrogen, possible lock-in effects have to be evaluated and avoided.

- **Check existing plants**
  It should be examined under which conditions the existing production plants for grey hydrogen could continue to be used on a transitional basis. The transition phase should be kept as short as possible and the greatest possible reduction in emissions should be achieved e.g. by carbon capture and utilization procedures (CCU).

- **Use hydrogen derivatives**
  The import of hydrogen by means of hydrogen carriers such as LOHCs, but also ammonia or methanol, which do not depend on a hydrogen pipeline network, should be accelerated and scaled up in a timely manner.

- **Using existing hydrogen sources**
  Existing hydrogen resources such as by-product hydrogen from chlor-alkali electrolysis plants, must be further developed and used consistently.

Rudolf Dieterich
Renewables, Bayernoil Raffineriegesellschaft mbH

» *Bayernoil calls for a connection of the refinery to the European Hydrogen Backbone already until 2029, as only then and in this way, the base-load-capable supply of their sites can be secured for the defossilization of hydrogen supply and the production of synthetic fuels.* «

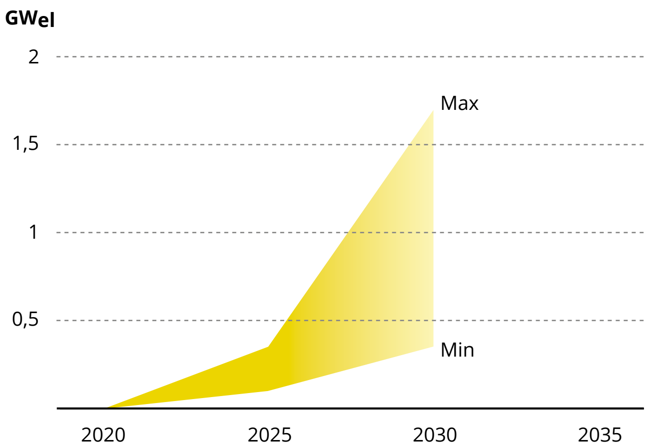
If it is assumed that current hydrogen consumption will continue to be covered by SMR plants for the time being and that the connection to the European Hydrogen Backbone can already be ensured by 2030, the need for additional Bavarian hydrogen generation is reduced considerably to 1.2-3.5 TWh.

Depending on the assumption of possible full load hours, between 0.3 and 1.7 GW_{el} would be required (assumption of electrolyzerefficiency: 0.7; possible full load hours: 3,000-5,000). The necessary capacities should be built primarily in locations where the largest consumers are expected in the future and where the necessary infrastructure already exists. Suitable sites include chemical and petrochemical industries and power plants. Due to the expected economies of scale, it makes economic sense to predominantly build up capacity at these locations. Apart from that, enabling hydrogen supply in more remote areas must not be neglected since their connection to a national or european hydrogen network is mostly – if ever – foreseen at a much later stage.

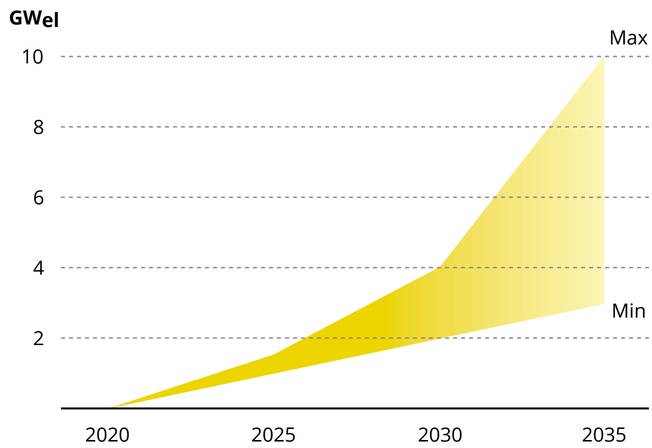
Based on the assumption that the connection to a pipeline network will not take place until 2035 and that the current producers of grey hydrogen will switch to green, electrolytically produced hydrogen by 2030, the electrolysis demand will increase to 3-10 GW in 2035.

In both scenarios, the demand for hydrogen to be produced regionally is significant. It is therefore important to consider all technological possibilities for climate-friendly hydrogen production in Bavaria.

Demand for electrolysis power with connection to EHB by 2030



Demand for electrolysis power with connection to EHB by 2035



Which milestones can and should be achieved by 2025 and 2030?

In the future, hydrogen will be used throughout various sectors. In order to create planning certainty for the stakeholders involved, some important milestones should describe the possible path to a hydrogen economy that meets Bavaria's climate goals.

The production of Bavarian green hydrogen has already begun. However, compared to the dimensions required for climate neutrality, the total capacity of the realized plants is still very low. The plants mainly serve local demand and some of them have more of a research project character. To bring climate-friendly hydrogen into use on a large scale in Bavaria, the availability of the energy carrier must be considerably increased. In the short term, this can only be achieved through hydrogen production within the Free State. At the same time, Bavaria must be connected to the EHB and the import of hydrogen derivatives such as ammonia, methanol, naphtha or LOHCs must be prepared.

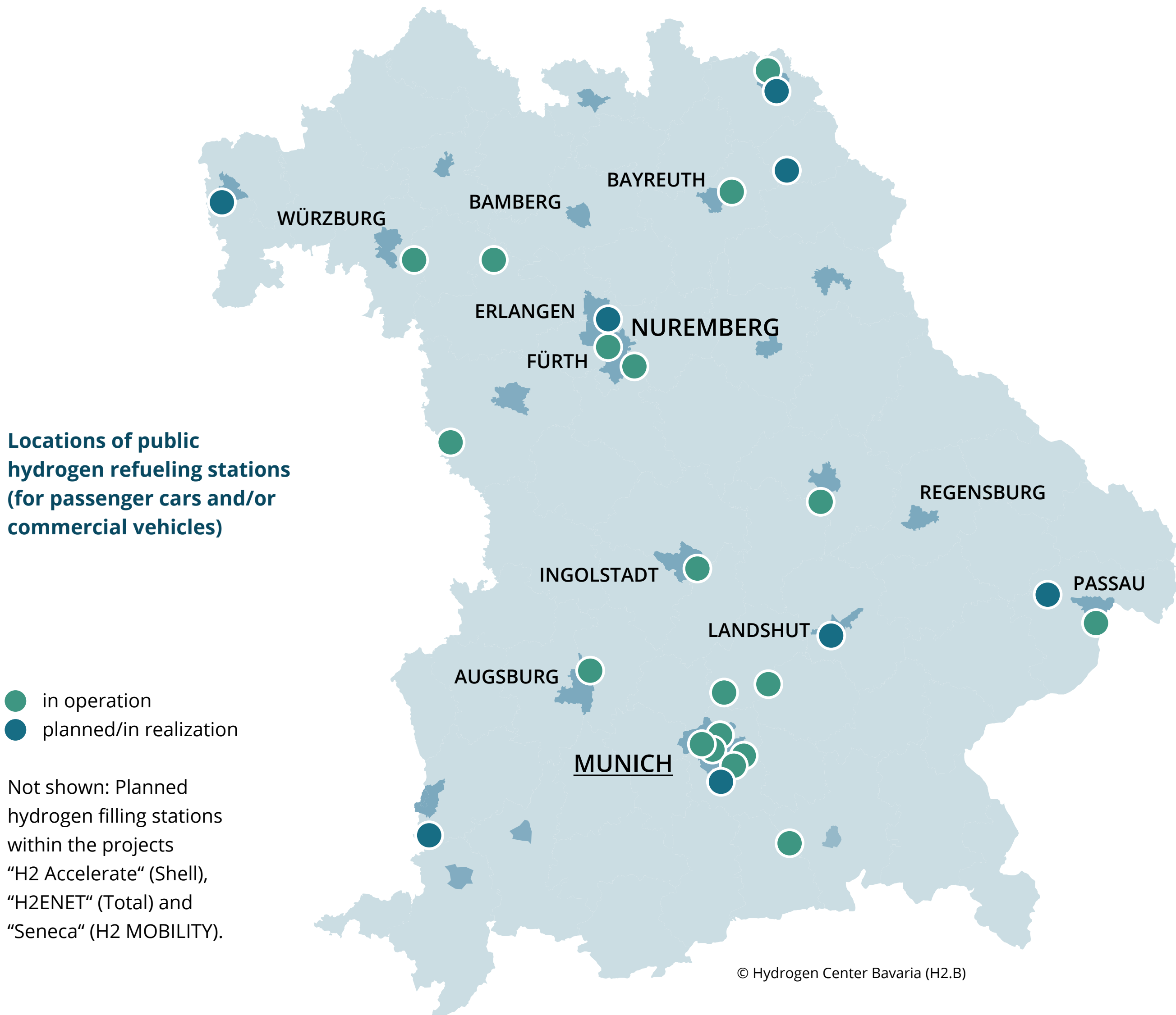
Bavaria's largest hydrogen consumers must be connected to a European backbone by 2030 - otherwise it will be difficult to achieve climate neutrality by 2040. At the same time, the wide-spread expansion of the hydrogen network (distribution networks) must be driven forward.

Bavaria-wide, the potential of by-product hydrogen is to be exploited, made usable and connected with hydrogen sinks. Here, existing chlor-alkali electrolysis capacities in Bavaria are to be mentioned above all.

A good way to make hydrogen technologies accessible to a broader public is to use them in local public transport. For this reason, the number of hydrogen-powered vehicles in Bavaria should be increased significantly.

To this end, the number of hydrogen refueling stations, especially for commercial vehicles, must be further increased. In addition to funding instruments at federal level, the Bavarian funding program for the development of a hydrogen filling station infrastructure is an important instrument for achieving this goal.

Locations of public hydrogen refueling stations (for passenger cars and/or commercial vehicles)



Not shown: Planned hydrogen filling stations within the projects "H2 Accelerate" (Shell), "H2ENET" (Total) and "Seneca" (H2 MOBILITY).

Milestones for Bavaria

...until 2025

Hydrogen production
- Installation of at least 300 megawatts of electrolysis capacity, additional construction of renewable electricity generation plants on the same scale
- Initiation of industrial scale projects to produce hydrogen from biomass
- Advance industrial projects for blue and turquoise hydrogen production
- Consistent use of hydrogen sources, in which the gas occurs as a by-product of the process

Distribution
- Advancing pioneering projects for the import of hydrogen derivatives
- Establishment/conversion of first regional hydrogen distribution networks as starting points of the hydrogen economy

Application
- Putting 500 hydrogen buses for the public transport system into service
- Putting 500 hydrogen trucks into service
- Widespread establishment of hydrogen refueling stations
- Implementation of first projects for the provision of process heat with climate-friendly hydrogen or its derivatives on an industrial scale

...until 2030

Hydrogen production
- Installation of 1,000 megawatts of electrolysis capacity, additional construction of renewable power generation plants on the same scale

Distribution
- Successful connection to the European Hydrogen Backbone (EHB) network
- Upscaling the import of hydrogen derivatives
- Installation/repurposing of further regional hydrogen distribution networks and connection of these centers

Application
- Wide use of hydrogen for (high temperature) process heat supply in industry
- Successive switch to hydrogen-based fuels in central power generation
- Wide use of hydrogen CHP plants for decentralized power and heat supply
- Upscaling the use of hydrogen in the mobility sector

Which demonstration projects can be derived from this?

Due to inappropriate regulatory framework conditions, many hydrogen applications are currently not commercially viable. Demonstration projects are a target-orientated way of bringing these technologies into the field and at the same time further increasing the maturity of the technologies.

- **Reduce inhibitions and strengthen the home market**
  The short-term goal must be to reduce the investment costs of the facilities and to accelerate the implementation of the projects. Technical feasibility is an obstacle in very few cases, if anything, it is the availability of individual products, for example of fuel cell vehicles.

  The domestic market is both an important technology showcase and a real world laboratory for companies. On site, technologies can be further developed and used in operation. In addition to this, these sites can be used to advertise Bavarian products and the innovative strength of Bavarian companies.

- **Maintaining and expanding technology leadership**
  Even independently of a strong domestic market, a large part of Bavaria's value creation in a global hydrogen economy can be achieved through the development, sale and export of technology products. Accordingly, Bavaria as a hydrogen location should continue to be shaped particularly innovation-friendly by promoting both academic and non-academic research and development.

  Due to the support and network of the H2.B, the stakeholders of the Bavarian hydrogen economy should find the best prerequisites to continue the development of leading technologies along the entire hydrogen process chain. As far as possible, cross-sectoral offers should be created in order to make meaningful use of the diversity of technological competences represented in Bavaria.

Based on the production potential of hydrogen and the forecasted demand in Bavaria, general recommendations for a targeted research and technology promotion can be derived:

- The potential for renewable energies in Bavaria is limited. In addition to the production of green hydrogen from electrolysis, further hydrogen sources should therefore be developed. For this reason, the development of alternative H2 production technologies should be given greater consideration. This equally includes the production of hydrogen from biomass/organic residues as well as the production of hydrogen from (synthetic and biogenic) methane. In all cases, emission reduction must be ensured on a life cycle basis.

- In the future, the amount of hydrogen transports will increase. This concerns on the one hand the transport of large quantities of hydrogen and its derivatives to Bavaria and on the other hand the distribution to filling stations, industrial customers and other consumers in the area. The Free State should consider both dimensions in its strategic planning and advocate for better framework conditions at federal level.

- The development of hydrogen applications should be further supported. The mobility sector, together with (special) mechanical engineering and electrical engineering, is of particular importance for Bavaria. Accordingly, the Free State should campaign at the federal level for the creation of favorable framework conditions for the development of hydrogen products and climate-friendly plants and processes throughout Germany. Federal funding should be complemented in a targeted manner by accompanying Bavarian funding programs to support the transformation of industry and electricity/heat generation towards greenhouse gas-neutral processes.

Dr.-Ing. Ulrich Mach
General manager, blueFLUX Energy AG

» *Organic residues are regionally available in large quantities. Through circular economy in combination with new technologies, these residues are turned into raw materials and offer great potential for the decentralized production of sustainably produced hydrogen and thus to the development of a hydrogen infrastructure.* «

4. Current challenges and necessary actions for a Bavarian hydrogen economy

What are the fundamental obstacles that the Bavarian industry sees in the ramp-up of the hydrogen economy?

For the development of the Bavarian Hydrogen Roadmap, the partners of the Hydrogen Alliance Bavaria were asked about the greatest challenges in the ramp-up of the hydrogen economy. It was striking that both, the technological maturity of the related technologies as well as the lack of public acceptance, were rarely seen as a decisive challenge. In contrast, the lack of a roadmap made by political decision-makers and, above all, an unsuitable regulatory framework were mentioned by far more frequently.

Actions for the ramp-up of the hydrogen economy

...on a national and international level

In order to overcome these hurdles and to speed up the ramp-up of the hydrogen economy, H2.B proposes a catalogue of measures. A large part of the measures is not the sole responsibility of the Free State of Bavaria, but must be decided at national and European level. Nevertheless, Bavaria can and should play a constructive role in political decision-making processes.

These include among others:

- Reduction of state-induced levies on the electricity price, for example reduction of the electricity tax to the European minimum
- Introduction of proofs of origin for climate-friendly hydrogen
- Strategic decision for the use of other generation technologies besides green hydrogen, for example blue, turquoise or orange alternatives
- Introduction of incentive and compensation mechanisms to promote climate-friendly investments, e.g. contracts for difference
- Rapid expansion of the European/national pipeline network for hydrogen (partly by repurposing existing pipeline routes)
- Ensuring the availability of hydrogen refueling stations along Europe's main roads – or at least highways – as part of the implementation of the Alternative Fuels Infrastructure Directive (AFID – 2014/94/EU)

...in Bavaria

The Free State of Bavaria also has possibilities to promote the hydrogen economy in Bavaria:

- Massively accelerated expansion of renewable energy capacities
- Further development of tailor-made funding programs for Bavaria as science and business location
- Information and participation of citizens and businesses to create acceptance
- Preparation of detailed studies on future hydrogen demand and production potential in Bavaria
- Strengthening the education and training of professionals
- Initiation of public procurement of hydrogen vehicles

5. Conclusion and prospects

Due to the ambitious goal of climate neutrality by 2040, Bavaria must also take on a pioneering role in the development of the hydrogen economy. The Bavarian science and business location is very well positioned for this task. Since the planning and investment cycles for both infrastructure measures and the climate-friendly conversion of industry are very long, it is important to involve the companies concerned as quickly as possible.

However, it is also clear that the players involved need planning security – which is why the strategic course must be set at an early stage. The strategy process in Bavaria must be driven forward in order to be able to react to future developments and to continue to critically accompany the transformation of the Bavarian economy. This Roadmap is intended to provide central recommendations for action in this process.

Contact / Imprint

Hydrogen Center Bavaria (H2.B) / Zentrum Wasserstoff.Bayern (H2.B)
Fürther Straße 250
90429 Nuremberg, Germany
Phone: +49 (0) 911 5302 99236
info@h2.bayern
www.h2.bayern/en

Follow us on our social media channels and get the latest information on hydrogen-related topics and events:

/company/h2bayern

Publisher: Hydrogen Center Bavaria (H2.B) / Zentrum Wasserstoff.Bayern (H2.B)
Authors: Philipp Runge, Stefan Dürr, Dr. Fabian Pfaffenberger, Prof. Dr. Veronika Grimm, Prof. Dr. Peter Wasserscheid

Responsible for the content:
Dr. Fabian Pfaffenberger, Fürther Straße 250, 90429 Nuremberg, Germany
Layout: zur.gestaltung, Nuremberg
Photos: H2.B, bayernets GmbH, blueFlux Energy AG, Kurt Fuchs,
Giulia Iannicelli, Georg Pöhlein, Schaeffler AG, StMWi Bayern
Illustrations: Hydrogen Center Bavaria (H2.B) / Zentrum Wasserstoff.Bayern (H2.B)
As of May 2022 (partially updated in October 2022 and translated in January 2023)

Glossary

BioFuels	Gaseous or liquid fuels produced on the basis of renewable raw materials (biological fuels).
Blue hydrogen	Hydrogen produced from fossil fuels. The resulting CO_2 emissions are captured as completely as possible and then stored or reused.
ccH$_2$	Deep cooled and compressed (Compressed Cryogenic Hydrogen)
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
Defossilization	Stopping the emission of carbon dioxide from the combustion of fossil raw materials. Remaining emissions (e.g. end-of-life emissions), must be compensated by negative emissions
EEG	Renewable Energy Sources Act – often synonymous with the associated levy set by law to support renewable electricity generation plants
EHB	European Hydrogen Backbone
FCE	Fuel Cell Electric
FCEV	Fuel Cell Electric Vehicle
Grey hydrogen	Hydrogen produced by steam reforming – or partial oxidation of fossil hydrocarbons. Methane (CH_4) and water (H_2O) are converted into hydrogen and CO_2
Green hydrogen	Hydrogen that is generated by water electrolysis using regenerative energy
Climate-friendly hydrogen	Hydrogen, which produces significantly reduced greenhouse gas emissions compared to the reforming or partial oxidation of fossil hydrocarbons without storage or further use of the resulting emissions
CHP	Combined heat and power generation
LH$_2$	Deep cooled and thus liquified hydrogen
LOHC	Liquid Organic Hydrogen Carriers (LOHC) – organic compounds that can bind and release hydrogen by chemical reaction
MeOH	Methanol
Orange hydrogen	Hydrogen obtained by thermochemical or biological conversion processes produced from biomass or organic residues
SMR	Steam Methan Reforming
SynFuels	Synthetically produced gaseous or liquid fuels (Synthetic Fuels)
TSO	Transmission system operator – operator of the gas transmission networks
Turquoise hydrogen	Hydrogen produced from fossil fuels. The solid carbon, generated during the production process, can be landfilled or reused

www.h2.bayern