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Hydrogen projects in Germany: A comparison of studies and practical implementation

Alisa Riebartsch

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Tikkarinne 9
80200 JOENSUU
+358 13 260 600 (switchboard)

Author
Alisa Riebartsch

Title
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Abstract
This thesis supports the project, “Green Hydrogen Economy and Renewable Energy”, run by Karelia University of Applied Science in Finland. Background information on hydrogen is introduced, along with studies on the most relevant green hydrogen projects in Germany that can be used for benchmarking. The projects are analysed based on different attributes. At least a comparison is made between practical green hydrogen projects and theoretical scientific literature.

This thesis employs a quantitative research method. Scientific books, e-books and articles are used to provide background information about hydrogen and as references for scientific literature. Information about green hydrogen projects is gathered from the available material on websites and online newspapers.

The results of the comparison with the scientific literature show that the CO_2 reduction amounts of the projects are in line with, or even higher than, those in the literature. Another conclusion is that two types of electrolysis have been developed in order to be used in industrial production. These include alkaline water electrolysis and proton membrane exchange electrolysis. All the projects involving hydrogen which were reviewed use these types of electrolysis.

Zusammenfassung
Diese Arbeit unterstützt das Projekt „Green Hydrogen Economy and Renewable Energy“, das von der Karelia University of Applied Science in Finnland durchgeführt wird. Es werden Hintergrundinformationen zum Thema Wasserstoff geliefert und die wichtigsten grünen Wasserstoffprojekte in Deutschland zu Vergleichszwecken untersucht. Analysiert werden diese Projekte anhand von besonderen Merkmalen. Zum Schluss wird ein Vergleich zwischen den praktischen Projekten und der theoretischen wissenschaftlichen Literatur gezogen.

Eine quantitative Forschungsmethode wird in dieser Arbeit verwendet. Wissenschaftliche Bücher, Elektronische Bücher und wissenschaftliche Artikel werden verwendet, um Hintergrundinformationen zum Thema Wasserstoff zu liefern und um einen Vergleich mit der wissenschaftlichen Literatur vorzunehmen. Informationen über grüne Wasserstoffprojekte werden von Webseiten und aus Online-Zeitungen zusammengetragen.

Die Ergebnisse des Vergleichs mit der wissenschaftlichen Literatur zeigen, dass die CO_2-Reduktionswerte der Projekte mit denen in der Literatur übereinstimmen oder sogar höher sind. Ein weiteres Ergebnis ist, dass zwei Arten der Elektrolyseure so weit entwickelt sind, dass sie in der industriellen Produktion eingesetzt werden können. Es handelt sich um die Alkalische Elektrolyse und die Protonen-Austausch-Membran Elektrolyse. Alle untersuchten Wasserstoffprojekte nutzen diese Elektrolyseverfahren.

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Abbreviations

AEM	anion-exchange membrane
AWE	alkaline water electrolysis
BMFTR	Federal Ministry of Research, Technology and Space
BMWK	Federal Ministry for Economic Affairs and Energy
CAPEX	capital expenditures
IPCEI	Important projects of Common European Interest
LHV	Lower Heating Value
OPEX	operating expenses
PEM	proton exchange membrane
SMR	steam methane reforming
SOEC	Solid Oxide Electrolysis Cell

1 Introduction

In June 2020, the German government passed the National Hydrogen Strategy for green hydrogen. The government intends to advance the hydrogen economy with a number of steps. It has been resolved that Germany will extend the power grid by 1800 km until 2027/2028 and must have a hydrogen capacity of 10 gigawatts in 2030. Furthermore, the use of hydrogen in various sectors such as industry, heavy vehicles, and air and sea transport are set to increase by 2030. Moreover, Germany has set itself the target of becoming a leading provider across the entire hydrogen value chain by 2030. For this purpose, the necessary framework conditions are to be created. The national hydrogen strategy of Germany puts forward Germany's commitment to global responsibility, with the goal of attaining climate neutrality by 2045 according to the Paris Agreement. Hydrogen must become economically competitive in order to enable the hydrogen market to grow rapidly. There must be strong and sustainable demand so that hydrogen is produced locally. The plan states that hydrogen can and must be an integral component of energy transformation and a promise of success. Hydrogen is a precious basis for industries. It is important that industries in the future must utilize green hydrogen to substitute current old, non-climate-friendly applications with new green hydrogen applications.
In this manner, science and professionals must develop. (Federal Ministry of Economic Affairs and Energy ,2020; BMWK, 2023)

In times of climate change, hydrogen can help to fill a gap together with the switch to renewable energy. It can be an assistance for renewable energy and therefore great assistance in the question of how to stop climate change. Hydrogen and electricity can complement and help on another. Renewable energy could produce electricity, and hydrogen could store and deliver it. Hydrogen could be the solution to storing an excess of renewable energy such as wind and solar power. In this way, hydrogen could smooth out the daily and seasonal fluctuations of this renewable energy system. Power-to-X technologies, which convert electricity into other forms, are growing and so are hydrogen technologies. Hydrogen is an interesting chemical material because it can be produced from any fossil fuel or renewable energy source. So, hydrogen is very flexible and can be phased into our existing energy system. Another advantage is that it produces no harmful emissions when it is used. The only by-product is water. Hydrogen has even more advantages over fossil fuels. Hydrogen is the most abundant element in the universe with the highest energy density per unit mass, it is non-toxic, non-irritating, environmentally neutral, odorless, tasteless, invisible, non-explosive in the open air, non-radioactive and non-carcinogenic. All in all, hydrogen could be a very useful and important technology in the future. That's why the German government created the National Hydrogen Strategy and supports the hydrogen economy in Germany. (Busby, 2005; Geitmann & Auguste, 2022)

This thesis aims to support a hydrogen project in Finland. The European Union has set targets for the creation of a hydrogen economy by 2030 and with the European region, Finland also set targets. The EU's plan is to produce 10 million tons of green hydrogen per year. Finland aims to produce 10% of this amount. Therefore, Finland's goal is to produce one million tons per year by 2030. To achieve this, the North Karelia region in Finland has decided to become carbon neutral by 2030 and hydrogen production or utilisation has been seen as one of the ways to implement the green transition. This project, run by the Karelia University of Applied Sciences, should help North Karelia achieve this goal. The project is called 'Green Skills for Hydrogen Economy and Renewable Energies'. The project aims to identify the educational content needs of the region’s educational organizations and the skills and training needs of the North Karelian workforce and new operators. It also aims to clarify the role of different actors and organizations, build a training path for them, create a business-oriented investment plan for the region, and connect actors involved in education and research. Competence strengths in different areas are explored through benchmark trips. The project implements the North Karelia Regional Program POKAT 2025, the North Karelia Smart Specialization Strategy, the North Karelia Climate and Energy Strategy, the Just Transition Finland (JTF) policy of the Reforming and Skilled Finland (2021–2027) program, and the North Karelia Regional Just Transition Plan. (Karelia University for Applied Sciences, 2024)

This thesis should support the project “Green Skills for Hydrogen Economy and Renewable Energy” by benchmarking from German projects, help to understand why hydrogen projects are so important and give an overview of the most relevant green hydrogen projects in Germany. It should also be a comparison between practical hydrogen projects and theoretical literature. The thesis includes background information on hydrogen, categorizes the most relevant hydrogen projects, compares them with literature and provides recommendations for action derived from the results.

2 Hydrogen fundamentals

2.1 Possible applications and value chain of hydrogen

Hydrogen already has many practical applications. Most of these are in industries such as oil refineries and chemical plants. The production of ammonia and the refining of crude oil currently use the largest amounts of hydrogen. In the food industry, hydrogen is used to solidify edible fats and oils. Hydrogen is also used in the manufacturing of many commercial products. Examples include plastics, vitamins and cosmetics. Another use of hydrogen is the extraction of pure metals from their compounds and the generation of very high temperatures for arc welding and glass cutting. Hydrogen also reduces friction in rotating equipment and cools large generators, motors and frequency converters. (Busby, 2005; Geitmann & Auguste, 2022; Hebling et al., 2019)

But hydrogen is also being used outside these industries. Most of these technologies are still being improved and are niche products. Fuel cells could be used in electronic devices such as laptops, cameras and bicycles. In the future, fuel cells could also be used as back-up systems instead of diesel generators.

Domestic heating systems could be replaced by fuel cells. One scenario involves decentralized electricity and heat supply from green hydrogen via a pure hydrogen network. Another scenario could be the hydrogen admixture in the existing natural gas network. It's also being researched whether vehicles such as cars, buses and trucks will run on fuel cells in the future. (Busby, 2005; Geitmann & Auguste, 2022; Hebling et al., 2019)

At the moment there are very few hydrogen vehicles. But this could change and fuel cells, together with electric cars, could take over the market from internal combustion engines. Hydrogen is also the only known alternative fuel that could be used to replace kerosene in aircraft. But there is still a lot of research to be done in all these areas before hydrogen and fuel cells become an integral part of the market. On the other hand, space travel is the only transportation sector that has been using hydrogen for years. Hydrogen is used as a propellant for rockets, space shuttles and to supply energy and water on board. As a final application, ships, ferries and submarines could run on green methanol produced from hydrogen. Initial tests have already been carried out. (Busby, 2005; Geitmann & Auguste, 2022; Hebling et al., 2019).

Hydrogen has high potential for industry, transport and electricity sectors. In order to stop climate change, the energy system needs to phase out fossil fuels and move towards a sustainable energy circular economy. Hydrogen can be an important technology for greenhouse gas neutrality as it has the ability to reduce fossil fuels from industry, transport and electricity sectors. Furthermore, hydrogen has high storage and transportability. This makes it even more powerful. More about this in chapter 2.4. (Busby, 2005; Geitmann & Auguste, 2022; Hebling et al., 2019)

2.2 Hydrogen colors and production

2.2.1 Hydrogen colors

The main focus of this thesis is on green hydrogen. Green hydrogen is produced using renewable energy and electrolysis technology. But there are different ways how hydrogen can be produced and with which energy. At the moment, hydrogen is most of the time not produced with renewable energy. The following is a brief introduction to the colors of hydrogen and the ways in which hydrogen can be produced. (Hartmut, Golze, Hirscher & Felderhoff, 2023; Minic, 2012)

- Grey hydrogen uses heat to split natural gas into hydrogen and CO_2.CO_2 is released unused into the atmosphere. This process is called steam reforming.
- Blue hydrogen is also made by steam reforming, but the CO_2 is captured and not released into the atmosphere.
- If hydrogen is produced by thermal methane cracking, the process is called methane pyrolysis and turquoise hydrogen is produced. This process is done using renewable energy and produces solid carbon. It is not allowed to burn solid carbon here.
- Red and pink hydrogen are both hydrogens produced by nuclear energy. Just the process is different.
- If the energy to produce hydrogen comes from the electricity grid and the hydrogen is produced by electrolysis, it is called yellow hydrogen.
- The last color is white hydrogen. It is produced by chemical processes whose main purpose is not to produce hydrogen. (Hartmut, Golze, Hirscher & Felderhoff, 2023; Minic, 2012)

2.2.2 Hydrogen production

In the following some processes will be explained in more detail. Today, a small amount of hydrogen is produced by electrolysis of water. Several types of cells are used. The solid oxide electrolysis cell, the alkaline electrolysis cell and the polymer electrolyte membrane cell. These cells operate at temperatures between 76.85-296.85 degrees Celsius. This process involves high concentrations of electrolytes and catalysts. The efficiency is between 50% and 80%, if it does not take into account that the production of electricity for electrolysis is inefficient. If this is considered, efficiency drops to 30% to 45% or even lower if renewable energy is used. (Hartmut et al., 2023; Minic, 2012)

Water thermolysis is a thermal separation of water at a temperature of 2526.85 degrees Celsius. This temperature is too high for practical applications. Research is currently underway to find catalysts that can lower the temperature. The aim is to use water thermolysis in solar concentrators to produce hydrogen by direct use of thermal energy. When hydrogen is produced directly from solar energy, the process is called photocatalytic water splitting. The photocatalyst captures solar energy and uses it to dissociate water. There are two main types of catalysts. Photoelectrochemical and photobiological catalysts. One process that is more efficient than water dissociation is called the sulfur-iodine cycle. It produces hydrogen at a lower temperature of 426.85 degrees Celsius. Sulphur and iodine can be recovered and reused, so they are not consumed. It's usually combined with concentrating solar power systems to produce hydrogen using solar energy (Hartmut et al., 2023 & Minic, 2012).

There are also processes that use fossil fuels to produce hydrogen. The most common method is steam methane reforming (SMR) of methane or natural gas. At a temperature of 726.85-1026.85 degrees Celsius, water vapor reacts with methane to produce large amounts of syngas, which is used to produce hydrogen through a reaction of water and carbon monoxide. This process produces a lot of CO_2 waste. Other methods of producing hydrogen from fossil fuels are partial oxidation, plasma reforming, and coal gasification. These will not be discussed in detail as the focus of this work is on green hydrogen produced by renewable energy. (Hartmut et al., 2023; Minic, 2012)

Another interesting production of hydrogen is biohydrogen production. These are biological productions to produce hydrogen on an industrial scale, such as biomass gasification and steam reforming with biomass instead of hydrogen (biomass pyrolysis). Other processes use biological organisms that convert sunlight into hydrogen through their metabolic processes. This can be done with unicellular algae, cyanobacteria, photosynthetic bacteria and dark fermentative bacteria. Hydrogen produced by biological organisms has an efficiency of 10% with solar energy conversion. The challenges are the slow rate of hydrogen production and cost-effective production. Different bacteria that absorb light in different spectral regions could help make the process more efficient. Biomass could have a positive impact on pollution. However, the main limitation is the availability of land for biomass production. There is not enough space for industrial-scale production. (Hartmut et al., 2023 & Minic, 2012)

2.3 Hydrogen storage, transport and safety

2.3.1 Current storage systems

There are different ways of storing hydrogen, depending on its physical state. Hydrogen holds more energy by weight than any other fuel. But it contains less energy per unit volume than other fuels. That's why it has to be compressed or liquid. It can be stored in compressed gas tanks and in vacuum-insulated cryogenic containers. In addition, the use of fossil fuel network infrastructure and storage can be used. If hydrogen is in gaseous form, pressurized gas tanks can be implemented. As the pressure within a pressurized gas tank increase, the capacity for hydrogen storage also rises, consequently making the tank heavier. Pressures of 200 to 700 bars can be generated in the tanks. The problem with high pressure is that about 15% of the energy is lost in the process. (Busby, 2005; Geitmann & Auguste, 2022)

The second option is vacuum insulated cryogenic tanks. This allows hydrogen to be stored in liquid form. The advantage of this technology is that the energy density is higher compared to compressed gas tanks, so the tank can be smaller to store the same amount of energy. Hydrogen needs very low temperatures to become liquid, around -253 degrees Celsius. That's why cryogenic tanks need to be well insulated. Most tanks are made of stainless steel, which can work at very low temperatures and is a good material for storing liquid hydrogen. But even with very good insulation, heat can get into the tank and a small amount of hydrogen can evaporate. Because of this, and because liquefaction requires a lot of energy, more than compression, it takes 30 to 35% of the energy content of hydrogen to use this process. The operating pressure for the vacuum insulated cryogenic tanks is 1.2 to 3.5 bar. (Busby, 2005; Geitmann & Auguste, 2022)

2.3.2 Future storage possibilities

Other hydrogen storage technologies are currently being researched, such as metal hydrides, chemical hydrides, carbon materials and caverns. The connection between metals and hydrogen is called metal hydrides. There are different metals that can absorb hydrogen. These metals can store a large volume of hydrogen, more than the volume of liquid hydrogen could store. There are different ways of storing hydrogen as metal hydrides. It works with metals like palladium, magnesium or lanthanum. Other methods store hydrogen using intermetallic compounds, multiphase alloys or light metal hydrides. When hydrogen is absorbed, it gives off heat. Heat is also required to release hydrogen. This heat could be supplied by a fuel cell. The metals with the highest storage capacity require high temperatures. Research is being done on new alloys that work at lower temperatures and can store high energy densities. (Busby, 2005; Geitmann & Auguste, 2022)

Research is also being conducted on liquid chemical hydrides such as sodium borohydride and carbazole. In the future, there may be carbon materials that can store hydrogen in nanotubes. These two types require further research, which is why they are not explained in more detail here. Another realistic technology for storing hydrogen could be in caverns. This method is still used to store fossil fuels. Now, it is needed to find a way to change the use of fossil fuel storage to hydrogen storage in caverns. Salt caverns could also be created to store hydrogen. (Busby, 2005; Geitmann & Auguste, 2022)

2.3.3 Transport

Transporting and distributing hydrogen requires more equipment before it becomes convenient to use. It is more difficult than transporting fossil fuels. Hydrogen contains almost three times more energy by weight than petrol. But the mega joules per liter are ten times higher in petrol than in compressed hydrogen and four times higher than in liquid hydrogen. There are four options for managing transport to the different storage technologies. (Busby, 2005; Geitmann & Auguste, 2022)

Hydrogen can be transported as a gas in trailers, as a liquid in trailers, as a gas in pipelines and as a liquid in pipelines. Hydrogen is most commonly transported today as a compressed gas in loads of cylinders or in a single large tube trailer by truck or train. Trailers on trucks can also be used for storage. The problem with this method of transport is that there is not enough space in the loads and in the tube trailers for the quantities that will be needed in the future. The volume of hydrogen on a truck can be more than six times larger if it is transported as a liquid. Due to the different temperatures of cold hydrogen and the outside temperatures, the trailers must withstand significant thermal stresses. But this transport technology is being improved, so liquid hydrogen could also be transported by train and ship. (Busby, 2005; Geitmann & Auguste, 2022)

Pipeline transport is the most efficient method. However, a pipeline for hydrogen in either gas or liquid form must meet different requirements. Special steel is required, such as stainless steel. Because of the lower density of hydrogen, the pipelines must be gas tight. The pipeline must also endure the high pressure of hydrogen in gas form. If hydrogen is transported as a liquid, the steel must be very stable to withstand the low temperatures and the temperature difference between the inside and outside of the pipeline. There are two major hydrogen pipeline systems in Germany. One system is between Cologne, Leverkusen, Düsseldorf and the Ruhr Area. This system is 240 km long and can handle pressures from 20 to 100 bars. The second hydrogen pipeline is in the industrial area of Leuna, 100 km long and has a 24-bar system. The pipeline system connects the towns of Meresburg, Leuna, Böhlen, Bitterfeld and Rodleben near Dessau. (Busby, 2005; Geitmann & Auguste, 2022)

2.3.4 Safety

All energy sources have a certain risk potential. Hydrogen is not more dangerous than other fuels. The only difference is in the handling. Hydrogen reacts with oxygen. The entry of additional energy, akin to a spark, into this mixture of substances must be prevented. A dangerous scenario could be the release of hydrogen. This can be solved by intensive ventilation or absorption from the air. If oxygen gets into the fuel tank, a dangerous situation can arise. It could lead to detonation. It's important that the upper ignition limit is not exceeded. The energy required for hydrogen to explode is ten times lower than for other fuels. So, working with hydrogen is only slightly more dangerous than working with other fuels in terms of explosions. In its gaseous form, hydrogen is not toxic to humans. It is only when there is less oxygen that people can become breathless. Short-term skin contacts with liquid hydrogen for up to one second are usually not dangerous. The heat of the skin causes the liquid hydrogen to evaporate. If the skin contact lasts longer than one second, it can lead to cold burns. If liquid hydrogen leaks out, it will evaporate due to the heat of the ground. At the same time, the ground will freeze. This means that hydrogen can't seep into the ground and poses a danger to the environment. (Geitmann & Auguste, 2022)

In summary, there are risks for accidents by working with hydrogen. Accidents could be fires and explosions. Intensity and consequences for these accidents depend on the amount of hydrogen leaked, the conditions in the process, the ignition point and if the hydrogen ignites immediately or with a delay. In addition, it can come to hydrogen leakage and hydrogen explosion inside the compressor space, leaking during tank change and leaking within the transport container. (Tukes, 2024)

2.4 Outlook for green hydrogen production costs, hydrogen production costs and electrolysis costs

2.4.1 Outlook for green hydrogen production costs

The following diagram, taken from a paper by the German Federal Parliament and re-drawn in English, illustrates the projected production costs of hydrogen for the years 2019, 2030 and 2050. Grey, blue and green represent the different types of hydrogen. An expected drop in electrolysis costs is reflected in the bright green pillar, which shows the projected cost of green hydrogen. A black line displays the range of changes in production costs. (Federal parliament, 2020)

In 2020, the year of the study, the price of green hydrogen was 15-18 ct/kWh, which was twice the price of blue hydrogen and three times the price of grey hydrogen. But the cost trends of green hydrogen show that in the coming years it might acquire a better position in the marketplace. That is due to the reduction in electrolysis and CO_2 tax prices in grey and blue hydrogen.
It can be possible that the cost of electrolysis will decline from €500–1,500/kW in 2020 to $200/kW (€185.02) in 2030. As indicated from the diagram, by 2050, the cost of green hydrogen will either be equal to, or even less than, the cost of grey or blue hydrogen. Blue or grey hydrogen prices cannot be reduced due to CO_2 charges, so green hydrogen can be made less expensive in the future, but grey and blue hydrogen will become more expensive. Steady gas prices are assumed during the period mentioned in the diagram. (Federal parliament of Germany, 2020)

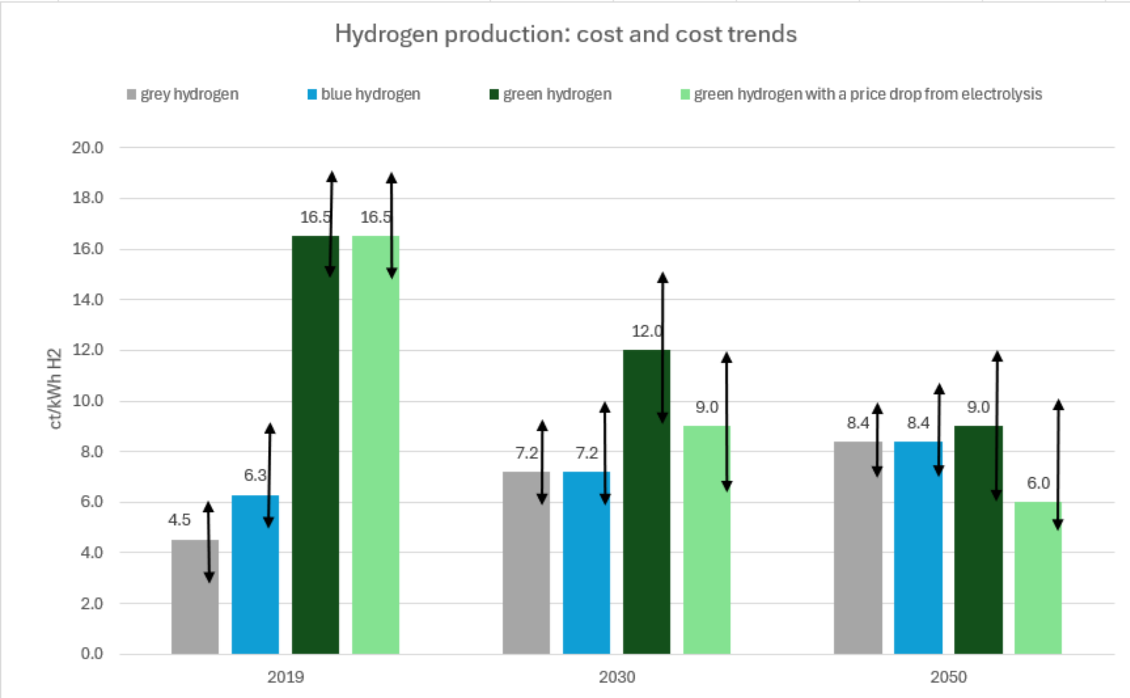

Figure 1: Hydrogen production costs (Federal parliament of Germany 2020)

2.4.2 Hydrogen production costs

For more accurate figures, there are numbers from 2023. The production technologies involved are grid electrolysis, reforming with carbon capture, renewable hydrogen connected directly to an electricity generation source, and SMR. These different production technologies incur different costs. The following is an overview of these costs in Germany in 2023.

- The cost of CAPEX (capital expenditures) for grid electrolysis are €2.76 /kg. Grid fees cost is €1.44 /kg in 2023. Other OPEX (operating expenses) costs are €0.11/kg. Grid electrolysis taxes are €1.79 /kg. The wholesale electricity cost is €3.13 /kg.
- For reforming with carbon capture, the CAPEX in 2023 is €0.43/kg. The CO_2 costs of this technology are €0.82/kg. The natural gas costs are €2.79/kg, and the other OPEX costs are €0.13/kg.
- The CAPEX costs for renewable hydrogen produced using a renewable electricity generation source are €4.50/kg. Using this technology, the electricity costs are €4.20/kg. In 2023, Germany did not levy any grid fees or taxes on this technology. Other OPEX costs are €0.18 /kg.

- The final technology to consider is SMR. Here, the CAPEX is €0.26/kg in 2023. CO_2 costs are €0.60/kg and natural gas costs are €2.60/kg. For SMR technology, the other OPEX costs are €0.09 /kg. (European Hydrogen Observatory, 2023)

Table 1: Total costs for different technologies

Total costs for different technologies (€/kg)		Year
Technology	Cost	2023
Grid electrolysis	CAPEX	2.76 €
	Grid Fees	1.44 €
	Other OPEX	0.11 €
	Taxes	1.79 €
	Wholesale electricity costs	3.13 €
Grid electrolysis total costs		**9.22 €**
Reforming with carbon capture	CAPEX	0.43 €
	CO2 costs	0.82 €
	Natural gas costs	2.79 €
	Other OPEX	0.13 €
Reforming with carbon capture total costs		**4.16 €**
Renewable hydrogen directly connected to a renewable electricity generation source	CAPEX	4.50 €
	Electricity costs	4.20 €
	Grid fees and taxes	0.00 €
	Other OPEX	0.18 €
Renewable hydrogen directly connected to a renewable electricity generation source total costs		**8.87 €**
SMR	CAPEX	0.26 €
	CO2 costs	0.59 €
	Natural gas costs	2.60 €
	Other OPEX	0.09 €
SMR total costs		**3.55 €**

2.4.3 Electrolysis costs

Since this thesis focuses on green hydrogen, the next paragraph briefly describes the cost of electrolysis in Europe from 2024 in more detail. There are two types of electrolysis: Alkaline water electrolysis and proton exchange membrane (PEM) electrolysis. For alkaline water electrolysis, the total CAPEX was €2310/kW in Europe. These costs are split into €323.4/kW stack costs. This includes equipment, engineering, procurement and installation of the stack. €693/kW are balance of plant costs. This includes the equipment, engineering, procurement and installation of the rectifier and transformer connected directly to it, as well as gas/liquid separation, water/lye feeding and gas purification. The other utilities cost includes the equipment, engineering, procurement and installation of high-voltage transformers, water treatment equipment, cooling systems, hydrogen compression systems, control systems and other services. The costs for other utilities are €693/kW. Other CAPEX costs for the alkaline water electrolysis are €600.6/kW. These costs include land and grid fees, insurance, permits, feasibility studies, contingencies and engineering-procurement-construction (EPC) management. The OPEX amount is €46.2/kW/year. Electricity is excluded here. (European Hydrogen Observatory, 2024)

The stack costs for a PEM-electrolysis are €562.72/kW in Europe in 2024. The balance of plant costs is €646.8/kW, while the other utilities cost €693/kW and the other CAPEX costs are €600.6/kW. The OPEX for the PEM electrolysis is €50.1/kW/year. The total cost of PEM electrolysis in Europe in 2024 is €2503/kW. (European Hydrogen Observatory, 2024)

Table 2: Electrolysis costs 2024 (Hydrogen Observatory 2024)

Year	Category cost	Subcategory cost	Technology	Value (EUR/kW)	Value (EUR/kW/year)
2024	CAPEX	Stack	Alkaline	323.4	
2024	CAPEX	BoP	Alkaline	693	
2024	CAPEX	Other utilities	Alkaline	693	
2024	CAPEX	Other CAPEX	Alkaline	600.6	
2024	**Total CAPEX**		**Alkaline**	**2310**	
2024	OPEX		Alkaline		46.2
2024	CAPEX	Stack	Proton Exchange Membrane	562.716	
2024	CAPEX	BoP	Proton Exchange Membrane	646.8	
2024	CAPEX	Other utilities	Proton Exchange Membrane	693	
2024	CAPEX	Other CAPEX	Proton Exchange Membrane	600.6	
2024	**Total CAPEX**		**Proton Exchange Membrane**	2503	
2024	OPEX		Proton Exchange Membrane		50.06232

3 Methodological choices of the thesis

This thesis is quantitative research about different green hydrogen projects in Germany. Quantitative research is typically used to gain an in-depth understanding of a topic. In this case, green hydrogen projects in Germany. It is used to explore new topics and understand complex issues. Quantitative research can provide depth, detail, nuance and context to the research topic, which may be too complex to be easily covered by qualitative research. (Hennink, Hutter & Bailey, 2020)

In this thesis the literature for background research is provided by academic books, e-books and academic articles. The main part of the thesis, the data collection on green hydrogen projects in Germany, is provided by internet references. IPCEI (Important projects of Common European Interest) projects and German leading projects in the field of green hydrogen are analysed as well as the connected projects to the IPCEI projects. Some information can be found on the main website of the project. The rest of the information is available on other websites and online newspapers.

The different projects in the production, transport, storage and research categories provide a good overview of the current situation. The focus is on production projects funded by IPCEI. Which stands for 'Important Projects of Common European Interest'. Therefore, these projects are highly relevant to Germany. Pipeline projects connected to the chosen production projects, which are also funded by IPCEI, provide an overview of hydrogen transport projects. There is one storage project that is also connected to a production project and, with this, a relevant German hydrogen project. These categories provide an overview of hydrogen projects in Germany and demonstrate the interconnected nature of many projects. The German leader projects are research projects that will help Germany develop its hydrogen economy. Here, an overview of the various hydrogen research projects is presented. A comparison is made between projects in the same categories. Several projects from the same categories are analysed, so that the research is reliable. Books and e-books as well as internet resources such as scientific articles are used for the final comparison.

4 Relevant hydrogen projects in Germany

4.1 Hydrogen production projects

Several green hydrogen production projects are being developed in Germany. Most of them are still in the planning stage. Very few are producing hydrogen on a small scale. This thesis focuses on the most relevant green hydrogen projects in Germany. The following projects are all IPCEI projects from the H_2-Infra-Wave for this reason. IPCEI stands for 'Important Projects of Common European Interest'. These projects, located in different EU member states, contribute the economy to grow, create new jobs and support the process of a green transition. Each project must have spill-over effects to impact the entire value chain. This is why IPCEI projects are large. Several projects work together to form one large IPCEI project. In total, there are four IPCEI H_2-waves. The H_2-Infra-Wave is the third. This wave covers a large part of the hydrogen value chain, supporting the development of green hydrogen production alongside transport infrastructure such as pipelines and hydrogen storage projects. Funding for the projects comes from European member states. In Germany, 70% of the funding comes from the German Government more specifically from the Federal Ministry for Economic Affairs and Energy (BMWK) and 30% from the federal state in which the companies involved in the IPCEI projects are located. It is not the costs of the projects that are being funded, just the financing gaps. The following is an overview of the IPCEI projects from H_2-Infra-Wave, which plans to produce green hydrogen in Germany. (European Commission; BDO Österreich 2025; Federal Ministry for Economic Affairs and Energy)

The projects are analysed in the following categories: use of produced hydrogen, capacity in MW, CO_2 reduction, production amount, commissioning year, electrolysis type, funding amount, general project investment, and utilised heat, if this information is available. Utilised heat refers to the waste heat generated in the electrolysis process and utilised. In general, it is challenging to find all the information about these categories. Project websites do not provide much information. Newspapers are required to provide further information. Articles about the projects in different newspapers tend to be similar. In addition, the information from the internet is the same on German and English websites. All of the production projects are part of larger scale projects. This chapter focuses on production projects. The following chapter explains the larger scale projects in more detail.

4.1.1 H_2-ERO

'H_2-ERO' the first project, is located in Rostock-Laage. There, hydrogen is produced for the regional hydrogen network. The project plans to build an alkaline water electrolysis plant with a capacity of 100 MW. Commissioning is planned for 2027, at which time the project members expect to produce 7,500 tons of hydrogen per year. This project could reduce CO_2 emissions by 100,000 tons every year with this amount of green hydrogen. The utilised heat is 145 GWh per year, which will be supplied to the regional heating network. The project was funded with €137,363,430 by BMWK and the federal state of Mecklenburg-Western Pomerania and the total investment for the entire project is €213,000,000. (H2APEX 2024)

This project is an IPCEI project and part of a larger project called 'doing hydrogen'. The aim of the 'doing hydrogen' is to strengthen the region of eastern Germany in terms of a hydrogen economy. This project connects hydrogen producers, gas network operators and consumers. The northern part of eastern Germany should be the center of hydrogen production and import, and H_2-ERO is part of this. More partner companies of the project are focusing on the pipeline network in the southern part of East Germany, so that they can transport the produced hydrogen to the regions of Berlin, Eisenhüttenstadt and Leipzig-Leuna. These pipeline systems are called Flow and Green Octopus. (H2APEX 2024)

Table 3: H_2-ERO

project	H_2-ERO
use	regional hydrogen network
capacity MW	100 MW
CO_2 reduction	100,000 tons/year
production amount	7,500 tons/year
commissioning	2027
heat utilised	145 GWH/year, goes to regional heating network
electrolyser type	alkaline water electrolysis
amount of funding	€167,363,430 by BMWK and federal state Mecklenburg-Western Pomerania
investment	€213,000,000
pipeline	doing hydrogen Flow-pipeline

4.1.2 HyTech Hafen Rostock

In general, the main projects for producing green hydrogen are located in the north of Germany. Rostock has two IPCEI production projects. The second project is ‘HyTech Hafen Rostock’. This project has a capacity of 100 MW, and it is being investigated if this can be increased in the future. It is expected to produce 6,500 tons of hydrogen per year from 2027 onwards. The plan is to use this amount of hydrogen in a way that benefits regional consumers, such as those in the maritime and industrial sectors in the port city. Hydrogen production projects in a port city can be highly efficient. Green energy can come from onshore and offshore wind farms, and hydrogen consumers are located close to the production site. Import infrastructure for future imports is directly available in a port city. Produced heat can be fed directly into the local district heating network. (RWE 2025; rostock EnergyPort cooperation; Windmesse 2021; TRACTEBEL-eNGie 2023; eNergie de 2025)

Green hydrogen is produced by the project through the use of alkaline water electrolysis. The project received funding of €199,000,000 from BMWK and the federal state of Mecklenburg-Western Pomerania. The total investment in this project is €380,000,000. As this second project is in the same city as the previous one, it is also connected to the larger hydrogen project and the Flow pipeline system. Part of the hydrogen produced is fed into the Flow-pipeline system while the rest is transported to a trailer filling station where it is used by local consumers. Information about the amount of CO_2 reduction is not available. (RWE 2025; rostock EnergyPort cooperation; Windmesse 2021; TRACTEBEL-eNGie 2023; eNergie de 2025)

Table 4: HyTech Hafen Rostock

project	HyTech Hafen Rostock
use	regional consumption
capacity MW	100 MW
CO_2 reduction	
production amount	6,500 tons/year
commissioning	2027
heat utilised	district heating network
electrolyser type	alkaline water electrolysis
amount of funding	€199,000,000 by BMWK and federal state Mecklenburg-Western Pomerania
investment	€380,000,000
pipeline	doing hydrogen Flow-pipline

4.1.3 Elektrolysekorridor Ostdeutschland

‘Elektrolysekorridor Ostdeutschland’ is located in the east of Germany as well. In this project, the electrolysis has a capacity of 185 MW and is expected to produce 17,000 tons of hydrogen per year, with operations set to begin in 2027. The electrolysis capacity is divided between two locations in Mecklenburg-Western Pomerania and Brandenburg. Due to its cross-regional nature, this project is building a corridor between these two regions. This explains the name of the project. Another advantage of this project is the ability to refine excess energy directly at the point of generation. The produced hydrogen will be used in the hydrogen network and the local value chain. A valuable contribution to regional development is made by this project, as was the case with previous ones. (ENERTRAG 2024; ROSTOCK PORT 2024)

This project can reduce 135,000 tons of CO_2 per year. Information on the type of electrolysis used in this specific project is not available. Nevertheless, another project that the company ENERTRAG is involved in uses an alkaline water electrolysis system. This project might also be used for this type of electrolysis. Information about the specific amount of funding for this project is unavailable, but the federal state of Mecklenburg-Western Pomerania has received a total of €540,000,000 funding from the BMWK and the federal state government. Projects included in this funding are HyTech Hafen Rostock, doing hydrogen, Grüner Wasserstoff aus Rostock and the Elektrolysekorridor Rostock. The general investment for the ‘Elektrolysekorridor Ostdeutschland’ project is €94,000,000 and, like the previous projects, it is involved in the project doing hydrogen, where the produced hydrogen can then be transported via the Flow pipeline. The amount of heat utilised is unavailable. (ENERTRAG 2024; ROSTOCK PORT 2024)

Table 5: Elektrolysekorridor Ostdeutschland

project	Elektrolysekorridor Ostdeutschland
use	hydrogen network, local value chain
capacity MW	185 MW
CO_2 reduction	135,000 tons/year
production amount	17,000 tons/year
commissioning	2027
heat utilised	
electrolyser type	alkaline water electrolysis (used by ENERTRAG in another project)
amount of funding	€540,000,000 by BMWK and federal state Mecklenburg-Western Pomerania for entire region Mecklenburg-Western Pomerania
investment	€94,000,000
pipeline	doing hydrogen pipline Flow

4.1.4 H_2P

Project ‘H_2P’ is located in Emden. The region of Emden has significant onshore and offshore wind energy production. It is well connected to hydrogen transport and storage infrastructure. In addition, there is a possibility that green hydrogen could be imported in future. This is the reason why this project has a high capacity of 320 MW. In terms of capacity, this is the largest of all the production IPCEI projects in Germany. The project can produce 26,000 tons of hydrogen every year with a proton exchange membrane electrolysis. Commissioning is expected to begin in 2028. The produced hydrogen can be used in industry and transport. It can reduce CO_2 emissions by 1,000,000 tons every year. The specific investment for this project is unavailable, but it is part of a larger project called Clean Hydrogen Coastline, for which the total investment is €800,000,000. The specific funding for the H_2P project is unavailable. Clean Hydrogen Coastline is funded with €500,000,000 by the BMWK and the federal states of Lower Saxony and Bremen. The H_2P project's connected pipeline is part of the larger Clean Hydrogen Coastline project and is known as the H_2-Pipeline Nordwest. This larger project includes projects focusing on the entire hydrogen value chain. The information regarding the used heat is not accessible. (EWE 2024)

Table 6: H_2P

project	H_2P
use	industry, transport
capacity MW	320 MW
CO_2 reduction	1,000,000 tons/year
production amount	26,000 tons/year
commissioning	2028
heat utilised	
electrolyser type	proton exchange membran electrolysis
amount of funding	€500,000,000 by BMWK and federal state Lower Saxony/Bremen for entire Clean Hydrogen Coastline project
investment	€800,000,000 entire Clean Hydrogen Coastline project
pipeline	H_2-pipline infrastructure Nordwest by project Clean Hydrogen Coastline

4.1.5 Hamburg Green Hydrogen Hub

'Hamburg Green Hydrogen Hub' one of the first projects worldwide that aims to decarbonise an entire port city. The city of Hamburg wants to switch from using coal to using renewable energy and green hydrogen in the future. To achieve this, the project aims to decarbonise the entire Hamburg port industry by focusing on industry and transport. Part of an old coal power plant in Moorburg is to be dismantled and replaced with 100 MW electrolysis in the port of Hamburg. The old infrastructure from the coal plant can be used and converted to produce green hydrogen. From 2027 onwards, this proton exchange membrane electrolysis will be able to produce 10,000 tons of hydrogen per year. The project aims to reduce CO_2 emissions by 1,000,000 tons every year. The project has received €154,115,690 in funding. It is funded by the BMWK and the federal state of Hamburg. The total investment for this project is €400,000,000. The Hamburg Green Hydrogen Hub has a connected pipeline project. This project is another Hamburg initiative called 'HH-WIN'. A 60 km pipeline will connect industries in Hamburg with the hydrogen production facility. This guarantees a distribution network. Some of the produced hydrogen can be transported by trailer. Information's about the heat utilised is unavailable. (HGHH 2024; Welt 2024; Hamburger Energiewerke 2024)

Table 7: Hamburg Green Hydrogen Hub

project	Hamburg Green Hydrogen Hub
use	industry, habour
capacity MW	100 MW
CO_2 reduction	1,000,000 tons/year
production amount	10,000 tons/year
commissioning	2027
heat utilised	
electrolyser type	proton exchange membran electrolysis
amount of funding	€154,115,690 by BMWK and federal state Hamburg
investment	€400,000,000
pipeline	HH-WIN (60 km Hamburger hydrogen industrie net)

4.1.6 Lingen Green Hydrogen

In the east of Germany is the project 'Lingen Green Hydrogen' located. Lingen is an industrial site with a refinery. Starting in 2027, a 100 MW electrolysis is producing 11,000 tons of hydrogen per year. This hydrogen will be used by industries in Lingen. The in green hydrogen produced in future should replace 20% of the grey hydrogen currently used by the refinery. Increasing the electrolysis capacity to 150 MW could be a viable option in the second step. Theoretically, expansion of the electrolysis to 500 MW will be possible in the future. In that case, the produced hydrogen would not just be for the industries in Lingen and the surrounding area. It could also be used as a synthetic fuel. The required electricity could be obtained from offshore wind farms. Which are available not far away in the North Sea. The proximity to the sea is the reason why most hydrogen production projects are located in the north. (Niedersächsisches Wasserstoff-Netzwerk; bp Deutschland 2024; RWE; STADT LINGEN EMS)

This project is expected to reduce CO_2 emissions by 80,000 tons per year. Currently, tests are being conducted to determine the most suitable type of electrolysis for this project. The choice is between proton exchange membrane electrolysis and alkaline water electrolysis. The project was funded by BMWK and the federal state of Lower Saxony. The total amount is €145,000,000. Information on the exact costs of the investment is not available. 'Lingen Green Hydrogen' is connected to 'Get H2-Nukleus'; future information on this project are explained in the next chapter. This project features a 130 km pipeline connecting Lingen and Gelsenkirchen. Lingen Green Hydrogen uses this pipeline to transport produced hydrogen to other industries. Information on the heat utilised is unavailable. (Niedersächsisches Wasserstoff-Netzwerk; bp Deutschland 2024; RWE; STADT LINGEN EMS)

Table 8: Lingen Green Hydrogen

project	Lingen Green Hydrogen
use	industry in Lingen
capacity MW	100 MW
CO_2 reduction	80,000 tons/year
production amount	11,000 tons/year
commissioning	2027
heat utilised	
electrolyser type	proton exchange membran electrolysis, alkaline water electrolysis (test)
amount of funding	€145,000,000 by BMWK and federal state Lower Saxony
investment	
pipeline	Get H_2 -Nukleus pipeline (130 km Lingen-Gelsenkirchen)

4.1.7 Get H2-Nukleus

The IPCEI project 'Get H2-Nukleus' forms part of the larger 'Get-H2' project. This project is a large initiative that bundles production projects with transportation infrastructure. Get H2-Nukleus is the first phase of the project. A 300 MW electrolysis in Lingen should produce 21,000 tons per year. Lingen has many industrial consumers. Consequently, the produced hydrogen will be used primarily within the local industrial sector. The project will start in 2027 and could reduce CO_2 emissions by 210,000 tons every year. The next step is to build a 130 km pipeline between Lingen and Gelsenkirchen. Most of this pipeline system will be converted from fossil gas. Another part will be newly constructed. As this project is working together with Lingen Green Hydrogen, the electrolysis type is being tested here as well. Both proton exchange membrane electrolysis and alkaline water electrolysis are being tested. The IPCEI funding for this project amounts to €492,000,000 from BMWK and the federal state North Rhine-Westphalia. This project is set to receive a mid-three-digit million-pound investment from RWE, one of the partner companies. The project is also connected to the entire Get-H2 pipeline system. Information on the utilisation of heat is not available. (GETH2; RWE; OGE 2025)

Table 9: Get H2-Nukleus

project	Get H2-Nukeus
use	industry
capacity MW	300 MW
CO_2 reduction	210,000 tons/year
production amount	21,000 tons/year
commissioning	2027
heat utilised	
electrolyser type	proton exchange membran electrolysis, alkaline water electrolysis (test)
amount of funding	€492,000,000 by BMWK and federal state North-Rine-Westphalia
investment	mid-three-digit million amount
pipeline	Get H2 pipeline

4.1.8 Green Motion Steel

‘Green Motion Steel’ is another production project in North Rhine-Westphalia. It is located in the Ruhr area, in the Marl chemical park, which is another industrial area in North Rhine-Westphalia. Marl is the starting point of Germany's largest hydrogen network. The production of hydrogen in the chemical park and the surrounding area is mainly intended for industrial and transport use. The goal of this project is to establish an integrated value chain in the region. This involves constructing a 120 MW proton exchange membrane electrolysis. From 2027 onwards, it will produce 18,400 tons of hydrogen per year. (Air Liquide 2025; NRW.ENERGY 4CLIMATE 2024; WIRTSCHAFT NRW 2024)

The project aims to reduce CO_2 emissions by 249,000 tons per year. The IPCEI project has received €178,000,000 in funding from the BMWK and the federal state of North Rhine-Westphalia. Information about the exact investment amount is not available. However, North Rhine-Westphalia's investment in IPCEI production hydrogen projects amounts to €800,000,000. There are two IPCEI production projects in this region: Green Motion Steel and Get H2, which includes the Get H2-Nukleus project. The company responsible for planning this project is Air Liquide. This company already owns a hydrogen pipeline system, the H2-long-distance line, which can be used to transport the produced hydrogen. The existence of this pipeline system is what makes this project so special. Another option is the planned EU pipeline Backbone. Information about the utilised heat is unavailable. (Air Liquide 2025; NRW.ENERGY 4CLIMATE 2024; WIRTSCHAFT NRW 2024)

Table 10: Green Motion Steel

project	Green Motion Steel
use	industry, traffic
capacity MW	120 MW
CO_2 reduction	249,000 tons/year
production amount	18,400 tons/year
commissioning	2027
heat utilised	
electrolyser type	proton exchange membran electrolysis
amount of funding	€178,000,000 by BMWK and federal state North-Rine-Westphalia
investment	€800,000,000 in entire North-Rine-Westphalia
pipeline	H2-long-distance-line from Air Liquide, Backbone pipeline (EU)

4.1.9 HydroHub Fenne

'HydroHub Fenne' is the final IPCEI production project. With a capacity of 55 MW, it is the smallest of all the IPCEI production projects. The project is placed at an energy nodal point in Saarland and is part of the Grand Region Hydrogen initiative. It is a collaboration between Germany, France, and Luxembourg. Producers and consumers are located nearby, as it is a district heating network. Existing infrastructure can be utilised, eliminating the need for significant modifications. The project aims to utilise the produced hydrogen for industrial and mobility applications within the Saarland region of Germany, the Grand East region of France and Luxembourg. From 2028 onwards, it is planned to produce 8,200 tons of hydrogen per year. The amount of CO_2 reduction is not available. In the future, the heat produced will be supplied to the district heating network. A proton exchange membrane electrolysis is used by the project. The project was funded by BMWK and the federal state of Saarland with funding of €102,415,794. The total investment is €150,000,000. The plan is for the produced hydrogen to be transported via the mosaHyc pipeline system, which is intended to connect three countries. Another pipeline system already exists in the area. Therefore, the project is only partially dependent on the planned pipeline system mosaHyc. (iquny 2024; creos 2025; stadt+werk 2024)

Table 11: HydroHub Fenne

project	HydroHub Fenne
use	industry, mobility
capacity MW	55 MW
CO_2 reduction	
production amount	8,200 tons/year
commissioning	2028
heat utilised	goes to district heating network
electrolyser type	proton exchange membran electrolysis
amount of funding	€102,415,794 by BMWK and federal state Saarland
investment	€150,000,000
pipeline	mosaHyc

These projects are very diverse. The electrolysis is intended for different uses and has a different capacity. The range is from 55 MW to 320 MW. The CO_2 reduction amount varies, ranging from 80,000 to 1,000 tons per year. CO_2 reduction amount is connected to the hydrogen production amount. Production amounts vary from 6,500 to 26,000 tons per year. The largest electrolysis capacity produces the largest amount of hydrogen in these projects. More detailed information's on how the hydrogen plants will operate, for example, the running times are unavailable. Commissioning is expected to take place in either 2027 or 2028. The electrolysis types are alkaline water electrolysis or proton exchange membrane electrolysis. Funding amounts range is from €10,241,579 to €49,200,000. The total investment cost ranges are from €94,000,000 € to €380,000,000. The figure below shows a comparison of the capacity of the projects and their production amounts. The table below provides a comprehensive overview of all production projects using the total project numbers. If there is no specific number available for a project, it is not included.

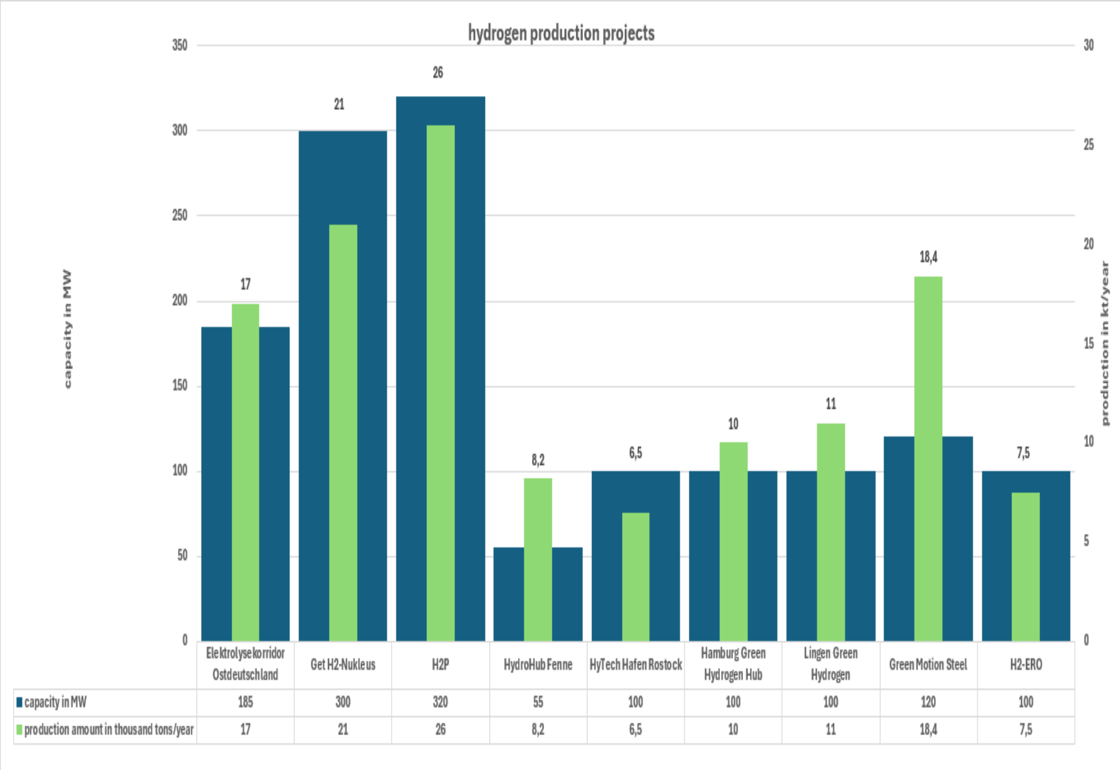

Figure 2: Comparison between capacity and production amount

Table 12: Green hydrogen production projects

project	capacity in MW	CO_2-reduction	production amount	funding amount	investment amount	year of comission
H_2-ERO	100 MW	100,000 tons/year	7,500 tons/year	€167,363,430	€213,000,000	2027
Green Motion Steel	120 MW	249,000 tons/year	18,400 tons/year	€178,000,000		2027
Lingen Green Hydrogen	100 MW	80,000 tons/year	11,000 tons/year	€145,000,000		2027
Hamburg Green Hydrogen Hub	100 MW	1,000,000 tons/year	10,000 tons/year	€154,115,690	€400,000,000	2027
HyTech Hafen Rostock	100 MW		6,500 tons/year	€199,000,000	€380,000,000	2027
Hydro Hub Fenne	55 MW		8,200 tons/year	€102,415,794	€150,000,000	2028
H_2P	320 MW	1,000,000 tons/year	26,000 tons/year			2028
Get H2-Nukleus	300 MW	210,000 tons/year	21,000 tons/year	€492,000,000		2027
Elektrolyse-korridor Ost-deutschland	185 MW	135,000 tons/year	17,000 tons/year		€94,000,000	2027

4.2 Large scale hydrogen projects including hydrogen pipeline and hydrogen cavern projects

This chapter provides a more detailed explanation of the larger projects connected to the IPCEI production projects. These are large-scale combined hydrogen projects. This means that they include both hydrogen production and infrastructure projects. It focuses on the pipeline systems of these projects. In addition, it explains the pipeline projects that are connected to IPCEI production projects but not to the larger hydrogen projects. Both pipeline projects are funded by IPCEI. One cavern project, which forms part of a larger hydrogen project and is funded by IPCEI, is used as an example of a hydrogen storage project. This chapter contains more information on the cavern project. The projects are analysed in the categories: type of project, use, included projects, CO_2 reduction, entire pipeline scale, scale pipeline funded by IPCEI, year of commissioning, IPCEI funding amount and total investment.

4.2.1 doing hydrogen

There are three large-scale projects associated with the IPCEI production projects. The first is 'doing hydrogen'. The aim of this project is to establish a strong hydrogen economy in eastern Germany. The project covers the federal states of Mecklenburg-Western Pomerania, Brandenburg, Berlin, Saxony and Saxony-Anhalt. Production, transportation, storage and consumer projects are all included. ‘Zukunftsnetz Nordwest’ is a partner project that is building a district heating network in Berlin. The north-west of Berlin will be connected to the supra-regional hydrogen transport infrastructure. This will enable the city of Berlin to use green hydrogen as the basis for heat and electricity, helping it to become climate neutral by 2040. Another partner is Concrete Chemicals. There, the project intends to utilise CO_2 produced during concrete manufacturing and process it further with green hydrogen from the Elektrolysekorridor Ostdeutschland project to produce green synthetic fuel. Both Elektrolysekorridor Ostdeutschland and H_2-ERO are project partners. (doing hydrogen)

The ONTRAS H2-Sartnetz pipeline project partners are building a 575 km infrastructure pipeline that will connect production and consumption points in Mecklenburg-Western Pomerania, Brandenburg, Berlin, Saxony and Saxony-Anhalt. This pipeline system already exists. It just needs to be adapted for hydrogen transportation. The rest of the pipeline system is under construction with the aim of connecting Salzgitter, Eisenhüttenstadt, Poland, the Czech Republic and Denmark in the future. Doing hydrogen has cooperation with the pipeline project 'Flow-making hydrogen happen'. This project plans to build a 1,630 km hydrogen pipeline between Rostock, Lubmin, Schwedt, Berlin, Leipzig, Leuna, Erfurt, Ludwigshafen and Stuttgart, connecting a large part of Germany. International connections can be constructed via the European Hydrogen Backbone pipeline system. The main part of this pipeline system already exists. Similar to the preceding venture, it needs to be adapted for hydrogen usage. The project is due to be commissioned in 2030. The following picture shows the pipeline system in Germany, with the blue line showing the hydrogen Flow-pipeline. The solid blue lines show the converted pipeline systems. The dashed blue line shows the new hydrogen pipeline system. This cooperation project has a total pipeline length of 2.205 km. (ONTRAS H2-Startnetz; Flow)

Figure 3: Pipeline infrastructure in Germany with pipeline system Flow (Rohrleitungsbau-verband 2023)

The hydrogen project can reduce CO_2 emissions by 2,030,000 tons every year. IPCEI has fund 618 km of pipelines. The total amount of funding is €446,908,423,66 by BMWK and the federal states of Mecklenburg-Western Pomerania, Brandenburg, Berlin, Saxony and Saxony-Anhalt. The total investment is €1,300,000,000. (3R 2024; doing hydrogen)

Table 13: doing hydrogen

project	doing hydrogen
type	combined hydrogen project
use	connection of hydrogen markets
included projects	Zukunftsnetz Nordwest, H_2-ERO, Elektrolysekorridor Ostdeutschland, Concrete Chemicals ONTRAS H2-Startnetz, Flow
CO_2 reduction	2,030,000 tons/year
entire pipeline scale	2205 km
scale pipeline IPCEI	618 km
commissioning	2030
IPCEI funding	€446,908,423.66 by BMWK and federal states Mecklenburg-Western Pomeria, Brandenburg, Berlin, Saxony, Saxony-Anhalt
investment	€1,300,000,000

4.2.2 Get-H2

'Get-H2' is another large-scale project. The initiative involves building the core of Germany's hydrogen transport infrastructure, starting in the federal states of North Rhine-Westphalia and Lower Saxony. The entire hydrogen value chain is covered by this project. Pipeline systems and electrolysis are planned. Consumers of green hydrogen, such as refineries, steel industries and heavy goods traffic, will be connected to the hydrogen pipelines. Hydrogen storage is also included. Three phases are planned for this initiative. Phase one is the Get H2-Nukleus project. This phase involves connecting the RWE Epe-H_2 cavern storage facility. It has been included in the IPCEI projects as well. 70,000,000 m^3 of hydrogen can be stored in this cavern. Commissioning is planned for 2027. Until then, the existing cavern system needs to be expanded and another cavern, previously used for storing natural gas, needs to be converted for hydrogen storage. A pipeline system needs to be constructed to connect the cavern to the above-ground facilities. The IPCEI funding is €127,528,437 by BMWK and the federal state of North Rhine-Westphalia and the total investment for this project is €300,000,000. (GETH2 2024; RWE 2025; H2.NRW; top agrar 2024)

Table 14: RWE Epe-H_2

project	RWE Epe-H_2
scale	70,000,000 m^3
commissioning	2027
IPCEI funding	€127,528,437 by BMWK and federal state North Rine-Westphalia
investment	€300,000,000

The second phase of the Get-H2 initiative involves converting existing gas pipelines for hydrogen use, enabling the transportation of hydrogen to the Vlieghuis import point in the Netherlands. This will establish a connection to the HYNETWORK hydrogen network in the Netherlands. HYNETWORK connects Germany, the Netherlands, France, Belgium and the port of Rotterdam, which is the main import point. The IPCEI project Lingen Green Hydrogen is also part of this phase. The least ambitious step in this phase is the construction of a new hydrogen pipeline to connect Dorsten and Hamborn, as well as the industrial area in the Ruhr area. In the third phase, the Salzgitter AG company should be connected to the pipeline system. An existing system will be converted for the use with hydrogen. (GETH2)

The entire pipeline system is expected to be ready for commissioning by 2030. An annual reduction in CO2 emissions of 16,000,000 tons can be achieved through a switch in the connected industries within this hydrogen network. The pipeline system is 1,294 km in total, with 316 km funded by IPCEI through the BMWK and the federal states of North Rhine-Westphalia and Lower Saxony. The project receives €224,239,383. Information on the total investment amount for this project is not available. On the whole, Germany should have a hydrogen core-network of 9,700 km by 2032. It includes the pipeline systems from Get-H2 and all other pipeline projects. Moreover, Get-H2 has some partner projects. A distribution network will be connected to the Get H2 hydrogen network in Westmünsterland. In the future, local green hydrogen producers, industries, and hydrogen fuel stations will be able to connect to it. Near the Marl chemical park, another partner is planning to build a hydrogen fuel station alongside hydrogen transport infrastructure for trains and trucks. Additionally, the TransHyDE leader project is connected to Get-H2. Further information about the German leader projects can be found in the next chapter. The pictures below show the Get-H2 hydrogen infrastructure and the hydrogen core network in Germany. In figure 3 the dashed green lines show the new pipelines. The solid lines show the converted pipeline systems. The table below contains information about the Get H2 project. (GETH2; Niedersächsisches Ministerium für Umwelt, Energie und Klimaschutz 2024; Die Landesregierung Nordrhein-Westfalen 2024; Federal Ministry of Research, Technology and Space 2025)

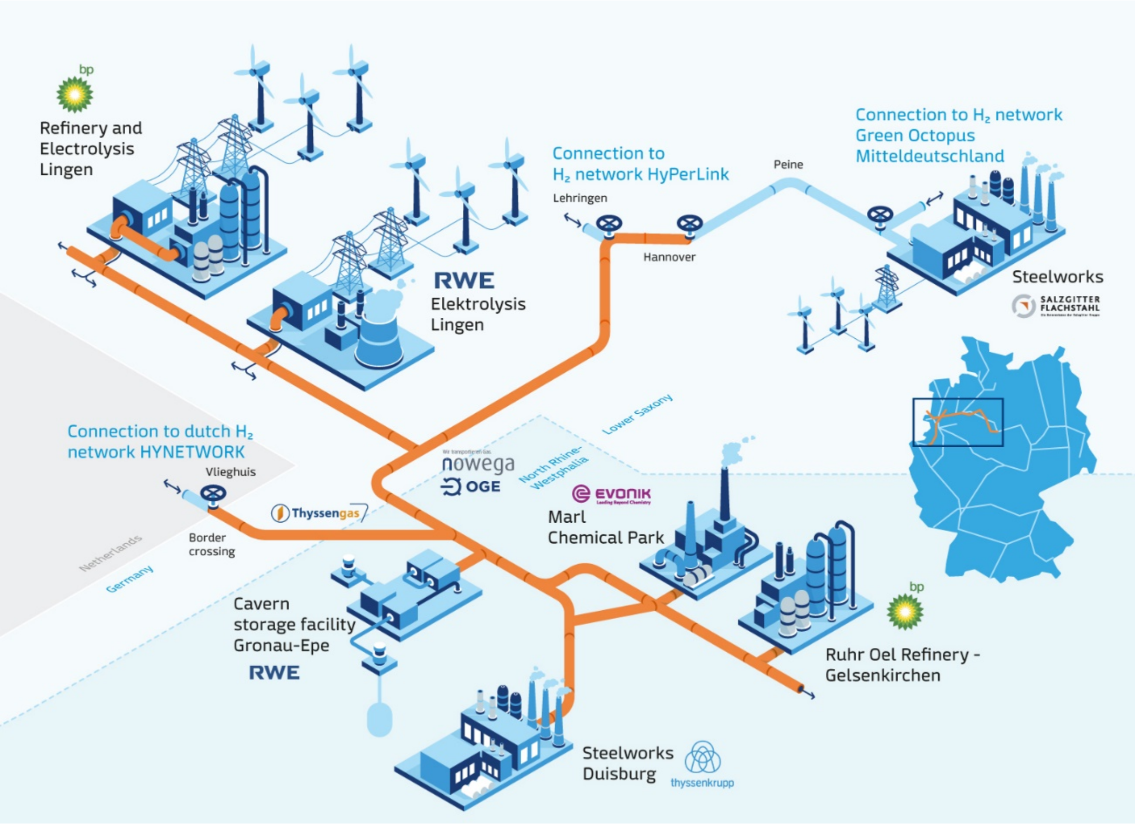

Figure 4: Get H2 infrastructure (GETH2)

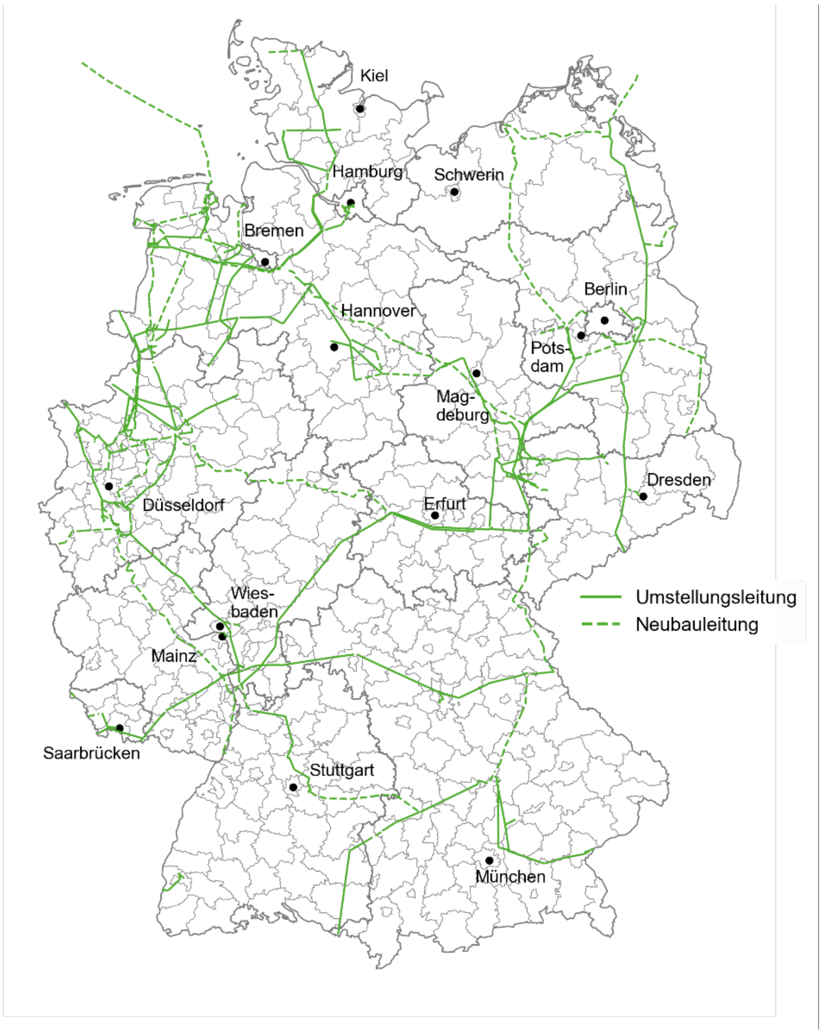

Figure 5: Hydrogen core-network Germany (GETH2 2023)

Table 15: Get H2

project	Get H2
type	combined hydrogen project
use	connection between production and industry
included projects	distributing network Westmünsterland, hydrogen fuel station and transport infrastructure in Marl
CO_2 reduction	16,000,000 tons/year
entire pipeline scale	1294 km
scale pipeline IPCEI	316 km
commissioning	2030
IPCEI funding	€224,239,383 by BMWK and federal states North Rine-Westphalia, Lower Saxony
investment	

4.2.3 Clean Hydrogen Coastline

‘Clean Hydrogen Coastline’ is the third major initative. Four projects from Clean Hydrogen Coastline are funded by IPCEI. The H_2P production project in Emden is one of them. Another is the hydrogen storage project in Huntorf. From 2027 onwards, 70 GWh of hydrogen can be stored here. This involves repurposing a salt cavern originally used for natural gas storage for hydrogen storage. The project involves connecting the hydrogen storage to the H_2-core network and the European Hydrogen Backbone pipeline systems. A 50 MW electrolyser in Bremen is funded by IPCEI. The green hydrogen produced should be used for industry and transport. In addition, a connection to the HyPerLink hydrogen pipeline network is planned. The fourth IPCEI-funded project is H_2Coastlink. H_2Coastlink comprises four pipeline sections. Pipeline sections one and two have been funded. These two pipeline sections are 56 km long. In total, the H_2Coastlink project plans to commission a pipeline with a length of 293 km by 2027. These four projects are funded with an amount of €500,000,000 by BMWK and the federal states of Lower Saxony and Bremen. The total investment for these four projects is €800,000,000. (EWE 2024; Niedersächsisches Wasserstoff-Netzwerk; GTG Nord)

Other projects connected to the Clean Hydrogen Coastline initiative include the H2-Allianz Osnabrück project, which involves building an electrolysis plant with a capacity of 15 MW to produce copper products using green hydrogen. Moreover, a hydrogen fuel station is planned so that project partners can use the green hydrogen. Another project is HyCux. Here, a 2 MW electrolyser produces green hydrogen at the port of Cuxhaven. This hydrogen is supplied in compressed form in fuel containers on a supply ship. The ship's propulsion system is converted to run on hydrogen. This means that it can now operate emission-free. The HyCAVmobil research project helped to plan the storage project in Huntorf. The company behind this project proved on a small scale (500 m^3) that it is possible to convert a natural gas cavern into a hydrogen cavern. This project was successful, and the larger hydrogen storage facility in Huntorf is now undergoing conversion. Another hydrogen production project is HyBit with a capacity of 10 MW. This green hydrogen is intended for a nearby steelworks.

Another part of the produced hydrogen will be used to decarbonise heavy transport in the region. In the future, this project will connect the electrolyser to a pipeline system and hydrogen storage facility. HyFri intends to use green hydrogen to power five hydrogen buses. The project also includes a hydrogen fuel station where the buses, as well as other H_2-cars and trucks, can get hydrogen. A similar project is underway in Oldenburg. There, a hydrogen refueling option has been added to a fuel station, that will serve four buses from the city of Oldenburg and other hydrogen vehicles. A total investment of €1,300,000,000 is planned for all Clean Hydrogen Coastline projects. Information about the CO_2 reduction of the entire project is not available. (EWE; H2 News 2021)

Table 16: Clean Hydrogen Coastline

project	Clean Hydrogen Coastline
type	combined hydrogen project
use	connection between production and industry, mobility
included projects	H_2P , H_2Coastlink, hydrogen storage in Huntdorf, 50 MW electrolysis Bremen, H2-Allianz Osnabrück, HyCux, HyCAVmobil, HyBit, HyFri, project from VWG Oldenburg
CO_2 reduction	
entire pipeline scale	293 km
scale pipeline IPCEI	56 km
commissioning	2027
IPCEI funding	€500,000,000 by BMWK and federal states Lower Saxony, Bremen
investment	€800,000,000 (IPCEI-projects) €1,300,000,000 (all projects)

4.2.4 HH-WIN

Two pipeline projects connected to IPCEI production projects are not included in a larger project. HH-WIN is the connected pipeline project to the Hamburg Green Hydrogen Hub. The goal is to connect Hamburg's industries with electrolysis. Future import of hydrogen is an option, because it is connection to European pipeline infrastructure. If there is sufficient demand, HH-WIN's scale can increase. Currently, the planned scale is 60 km. 40 km of this will be funded by BMWK and the federal state of Hamburg with €126,000,000. Natural gas pipelines in Hamburg and the surrounding area will be converted into hydrogen pipelines. Some new sections are planned as well. The section of the pipeline related to IPCEI will be ready for commissioning in 2027. The plan is to complete the rest of the pipeline system by 2031. This hydrogen pipeline infrastructure and Hamburg Green Hydrogen Hub will enable a reduction of 1,400,000 tons of CO_2 in Hamburg every year. The investment costs for HH-WIN are €200,000,000. (HAMBURGER ENERGIENETZ 2024; Welt 2024)

Table 17: HH-WIN

project	HH-WIN
type	pipeline project
use	connect industry in region
CO_2 reduction	1,400,000 tons/year
entire pipeline scale	60 km
scale pipeline IPCEI	40 km
commissioning	2027 part IPCEI, 2031 all
IPCEI funding	€126,000,000 by BMWK and federal state Hamburg
investment	€200,000,000

4.2.5 MosaHyc

'MosaHyc' is the second pipeline system. This pipeline is connected to the HydroHub Fenne IPCEI production project. MosaHyc's main purpose is to connect industries in the Grand Region. This region comprises Saarland (Germany), Grand Est (France) and Luxembourg. The pipeline system is 90 km long. 70 km of the pipeline already exist and will be converted for hydrogen use. The remaining 20 km will be newly constructed. The exact scale of the IPCEI-funded part is not available. The German part of the project has received funding of €44,000,000 from the BMWK and the federal state of Saarland. The commissioning date is 2027. 1,000,000 tons per year can be reduced by the pipeline project. The total investment is €117,000,000. (Grand Region Hydrogen; Ministerium für Wirtschaft, Innovation, Digitales und Energie Saarland 2024; creos 2025)

Table 18: mosaHyc

project	mosaHyc
type	pipeline project
use	connect industry in Germany, France, Luxembourg
CO_2 reduction	1,000,000 tons/year
entire pipeline scale	90 km
scale pipeline IPCEI	
commissioning	2027
IPCEI funding	€44,000,000 by BMWK and federal state Saarland (part Germany)
investment	€117,000,000

Overall, larger hydrogen projects include many smaller projects and require significant funding and investment. Moreover, all the included projects can achieve significant CO_2 reductions. The hydrogen core network is built together by all pipeline systems. The pipelines in this project range in length from 60 km to 2,205 km. Funding amounts depend on project scale and range from €44,000,000 to €500,000,000. The same applies to the investment amount. Larger projects receive larger amounts. These amounts range from €117,000,000 € to €1,300,000,000. The project involves different regions, most of which are in northern Germany. The CO_2 is reduced from 1,000,000 tonnes/year to 16,000,000 tonnes/year. The year of commissioning ranges from 2027 to 2031.

Table 19: Large-scale hydrogen projects

project	CO_2 reduction	entire pipline scale	investment amount	funding amount	year of commission
doing hydrogen	2,030,000 tons/year	2205 km	€1,300,00,000	€446,908,423.66	2030
Get H2	16,000,000 tons/year	1294 km		€224,239,383	2030
RWE Epe-H_2			€127,528,437	€300,000,000	2027
Clean Hydrogen Coastline		293 km	€1,300,000,000	€500,000,000	2027
HH-WIN	1,400,000 tons/year	60 km	€200,000,000	€126,000,000	2031
mosaHyc	1,000,000 tons/year	90 km	€117,000,000	€44,000,000	2027

4.3 Hydrogen research projects

This chapter focuses on the leading projects in Germany. These projects focus on various types of research related to green hydrogen. The projects are divided into three categories. H_2Giga focuses on producing hydrogen through electrolysis. H_2Mare research ways to produce green hydrogen directly at sea using wind power. The TransHyDE category works on various technologies for transporting hydrogen. The following is a brief overview of the various projects that fall under these categories. This overview is not intended to be exhaustive. It only showcases a selection of projects from each category to provide an insight into the diversity of these projects. The projects are analysed in terms of their type, topic of the project their funding, operational time and, if applicable, results. All green hydrogen leader projects are funded by the Federal Ministry of Research, Technology and Space (BMFTR).

4.3.1 SineWave

As part of H_2Giga, SineWave aims to increase the efficiency of PEM electrolysis by examining the different components involved. Another aspect of this process is identifying interfaces with industrial processes. For instance, green hydrogen produced by electrolysis could be used to produce methanol or ammonia directly. This project is developing digital solutions to make electrolysis systems safer. The project has received funding of €11,700,000 from BMFTR and will run from 01/06/2021 to 30/09/2025. No project results have been published yet. (Federal Ministry of Research, Technology and Space)

Table 20: SineWave

project	SineWave
leader project	H_2Giga
topic	optimising technology of PEM-electrolysis
funding	€11,700,000 by BMFTR
operational time	01/06/2021-30/09/2025
results	

4.3.2 ReNaRe

Another H_2Giga project is ReNaRe. The focus of this project is to develop technologies to recycle PEM- and high-temperature electrolysis. The goal is to reuse valuable and critical raw materials. Researchers and industry experts are working together on this project. After developing the recycling technologies, they are analysed in terms of sustainability and cost efficiency. The project is funded by the BMFTR to the tune of €8,600,000 and will run from 01/04/2021 to 30/09/2025. The project's results are not yet available. (Federal Ministry of Research, Technology and Space)

Table 21: ReNaRe

project	ReNaRe
leader project	H_2Giga
topic	sustainable recycling of electrolysis
funding	€8,600,000 by BMFTR
operational time	01/04/2021-30/09/2025
results	

4.3.3 H2Wind

The H_2Mare project, which is being conducted by H2Wind, involves researching on PEM electrolysis, on a process that should be able to work in conjunction with a wind power plant located directly on the sea. The components of this electrolysis are tested and modified in sea conditions. Additionally, the project is working on processing and providing water for the electrolysis. This will make electrolysis profitable directly at sea. The project is funded to the tune of €38,700,000 by the BMFTR and will run from 01/04/2021 to 31/03/2025. The project has already conducted research into processing salt water for electrolysis. The results of the tests show that seawater processing can be carried out over a wider temperature range than thought before. With a difference of 30 degree Celsius. (Federal Ministry of Research, Technology and Space)

Table 22: H2Wind

project	H2Wind
leader project	H_2Mare
topic	research on PEM-electrolysis direct connected to a wind turbin
funding	€38,700,000 by BMFTR
operational time	01/04/2021-31/03/2025
results	Research is carried out on the processing of salt water

4.3.4 OffgridWind

'OffgridWind' is a second H_2Mare project. In the future, a new electrolysis process could operate directly on the platform from a wind power plant at sea. This project is researching how the wind farm and the electrolysis can work together. In order to build an electrolysis unit on the platform, a larger platform, a new foundation and a transport system to the mainland would be required. These components are part of the research project as well. Some of the results of this project address the question of how the necessary power for electrolysis can be generated in situations without wind. The researchers concluded that a hybrid solution combining a hydrogen combustion engine and battery storage would be the most effective. The project is funded with €21,800,000 by the BMFTR and will run from 01/04/2021 to 31/03/2025. (Federal Ministry of Research, Technology and Space)

Table 23: OffgridWind

project	OffgridWind
leader project	H_2Mare
topic	research on a wind turbin plattform for electrolysis
funding	€21,800,000 by BMFTR
operational time	01/04/2021-31/03/2025
results	research on power in situations without wind

4.3.5 Get H2

'Get H2' is also involved in the TransHyDE research project. The project involves investigating the entire transport chain, including pipelines, hydrogen fuel stations and industrial consumers. The focus is on converting natural gas pipelines. The project involves developing procedures to clean and inspect the pipelines. They have already developed a technique to measure the quality of hydrogen in this research. The BMFTR funded this project with €11,620,000. The project will run from 01/04/2021 to 31/12/2025. (Federal Ministry of Research, Technology and Space)

Table 24: TransHyDE part of Get H2

project	Get H2
leader project	TransHyDE
topic	transport net of H_2 in gas form
funding	€11,620,000 by BMFTR
operational time	01/04/2021-31/12/2025
results	found technic to measure quality of H_2

4.3.6 Helgoland

Project ‘Helgoland’ is part of TransHyDE. The project involves researching and developing a transport chain between the island of Heligoland and the port of Hamburg for the liquid organic hydrogen carrier benzotoluene. The project re-searched how the utilised heat could be used to supply the island of Heligoland with heat. The project received funding of €13,700,000 from BMFTR and will run from 04/2021 to 12/2025. No results from this project have been published yet. (Federal Ministry of Research, Technology and Space)

Table 25: Helgoland

project	Helgoland
leader project	TransHyDE
topic	research on transport of H_2 by LOHC Benzyltoluol
funding	€13,700,000 by BMFTR
operational time	04/2021-12/2025
results	

4.3.7 AmmoRef

AmmoRef is a TransHyDE project focusing on extracting hydrogen from ammo-nia. A good transport infrastructure already exists for ammonia. Finding a way to extract hydrogen from ammonia would make long-distance imports easier. This involves high-pressure or low-pressure techniques. The project's research into a new, more efficient catalyst has yielded results. The catalyst is efficient due to a combination of two metals. The project was funded with €14,700,000 by the BMFTR and will run from 04/2021 to 12/2025. (Federal Ministry of Research, Technology and Space; Cristian-Albrechts-Universität zu Kiel 2024)

Table 26: AmmoRef

project	AmmoRef
leader project	TransHyDE
topic	get H_2 from ammonia
funding	€14,700,000 by BMFTR
operational time	04/2021-12/2025
results	developed a catalyst

4.3.8 AppLHy!

‘AppLHy!’ is the final research project to be selected. It is part of TransHyDE and focuses on liquid hydrogen (LH_2). The project focuses on the requirements and potential applications of liquid hydrogen, among other things. The effects of transporting liquid hydrogen are being researched as well. No results have been published yet. The project is funded by BMFTR with €15,200,000 and will run from 04/2021 to 12/2025. (Federal Ministry of Research, Technology and Space)

Table 27: AppLHy!

project	AppLHy!
leader project	TransHyDE
topic	imporve of transport, storage and use of LH_2
funding	€15,200,000 by BMFTR
operational time	04/2021-12/2025
results	

Leader projects tend to be smaller projects focusing on one topic. All of the projects will end in 2025. IPCEI projects require more time and have a later commissioning date. The funding amount is lower than that of IPCEI projects. The funding amount for the selected leader projects ranges from €8,600,000 to €38,700,000.

Table 28: Included research projects

project	leader project	funding amount	end of the project
SineWave	H2 Giga	€11,700,000	2025
ReNaRe	H2 Giga	€8,600,000	2025
H2Wind	H2Mare	€38,700,000	2025
OffgridWind	H2Mare	€21,800,000	2025
Get H2	TransHyDE	€11,620,000	2025
Helgoland	TransHyDE	€13,700,000	2025
AmmoRef	TransHyDE	€14,700,000	2025
AppLHy!	TransHyDE	€15,200,000	2025

4.4 Economic and political framework conditions

This section provides more detailed information about the value chains of these projects, their marketing strategies, the political framework conditions and an evaluation of the funding programme.

The IPCEI projects and large-scale hydrogen projects pay attention to a significant part of the value chain. With the large-scale projects, they include the entire value chain. Companies in the industry that produce electrolysers work together with hydrogen projects to produce green hydrogen with the help of these electrolysers. Some projects have maintenance contracts with electrolysis production companies. All these projects are located where green hydrogen is needed. In these industrial areas, consumers of green hydrogen are nearby. Pipeline infrastructure for natural gas is present in these areas. This existing infrastructure makes it easier to develop a hydrogen economy. Pipelines can be converted from transporting natural gas to transporting hydrogen. There is no long distance between producers and consumers of green hydrogen. Additionally, if the hydrogen project is located in a port city, there are options for importing and exporting via the sea. Being near the sea brings more advantages. Many offshore wind farms produce renewable energy there. This renewable energy can be used to produce green hydrogen. (Federal Ministry for Economic Affairs and Climate Action)

Green hydrogen projects and large renewable energy resources are close by, so energy doesn't need to be transported over long distances. There are plans to build more transport infrastructure to the south of Germany. But at first, it is an advantage that infrastructure elements for green hydrogen are nearby. Other infrastructure elements connected to the projects include fuel stations where hydrogen fuel tanks can be added, as well as hydrogen storage options such as salt caverns that were previously used for natural gas storage and has now been converted. District heating networks are included in some large-scale projects. All these elements form a complete value chain. Additionally, the research projects collaborate with scientific research companies and industries. This ensures that the final research is useful for the market and can be used by companies to improve the value chain. (Federal Ministry for Economic Affairs and Climate Action)

The marketing strategies align with the value chain. The projects aim to produce hydrogen on a large scale. This will enable industrial consumers to benefit from the production of green hydrogen. The projects are located in industrial areas, targeting steel industries, the chemical industry and refineries. Investments in transport infrastructure, such as pipelines, are part of the marketing strategy. With this infrastructure, the produced hydrogen can be transported to consumers. With a large-scale pipeline, more consumers can be connected to the hydrogen network in future and consume green hydrogen. This creates a supply and demand and allows a hydrogen economy to develop. (Federal Ministry of Research, Technology and Space 2021; Federal Ministry for Economic Affairs and Energy 2025)

Another part of the marketing strategy is to focus on large-scale areas within the transport sector. This means focusing on public transport, such as hydrogen buses, trains and ships, as well as trucks. There is a high demand for hydrogen in this area of transport, and it is easier to transport green hydrogen to fuel stations for public and heavy transport. It would be more difficult for individual consumers, such as those with hydrogen cars. More infrastructure would be needed, for example as fuel stations. Additionally, fuel cell technology is still in its infancy. Building partnerships with technology producers, green hydrogen production companies and consumers as part of hydrogen projects could be part of the marketing strategy. The fact that Europe wants to create a hydrogen economy, including Germany, makes green hydrogen more attractive. This, together with state funding for IPCEI projects and hydrogen technology research, paves the way for a hydrogen economy. (Federal Ministry of Research, Technology and Space 2021; Federal Ministry for Economic Affairs and Energy 2025)

Political framework conditions support a hydrogen economy and are responsible for founding programmes. The European Green Deal, which includes the goal of Europe becoming climate neutral by 2050 and reducing net greenhouse gas emissions by 55% by 2030 compared to 1990, is one of the reasons why Germany created the hydrogen strategy and is supporting hydrogen projects such as IPCEI projects and German leader projects in the field of hydrogen. These projects are politically initiated to establish a hydrogen economy. The European Commission must authorise every IPCEI project. Otherwise, member states are not permitted to fund these projects due to the prohibition of state aid. (Europe Commission; BDO Österreich 2025)

The advantages of IPCEI are that it has founded large-scale projects. Without IPCEI, these projects could not be realised due to the high investment costs. Large-scale green hydrogen projects are needed to realise a green hydrogen economy. Projects are only funded when they focus on the entire value chain. This focus is required for IPCEI projects, as well as for Germany's leading projects. Another advantage is the high level of funding. With this funding, the projects can achieve their goals. Overall, IPCEI funding amounts to €1,500,000,000 in Germany and €6,900,000,000 in Europe for the Hy2-Infra-Wave. Along with this substantial funding come high requirements. The process of obtaining funding is complex and time-consuming due to the authorisation procedure. Consequently, it is usually large companies that plan the projects and receive the funding. For smaller companies, the process is too complex. Nevertheless, IPCEI funding is worthwhile. Funding for the leader projects and IPCEI projects will help Germany reach its goal of setting up a green hydrogen market and, with it, a green hydrogen economy. (Federal Ministry for Economic

Affairs and Energy; Federal Ministry of Finance 2022; European Commission 2024)

5 Comparison of the hydrogen projects with scientific literature

This section compares practical green hydrogen projects with theoretical scientific literature. When comparing green hydrogen projects with scientific literature, there are three key figures to consider:

- The amount of CO_2 reduction achieved by the projects,
- The type of electrolysis used,
- The investment costs and the hydrogen production costs.

The comparison begins with the amount of reduced CO_2, continues with the types of electrolysis and emphasises the importance of investment costs and hydrogen production costs, as presented in recent studies.

5.1 CO_2 reduction

The meta-analysis of the climate impact reduction potential of hydrogen usage in nine power-to-X pathways compares, among other things, the production amount of green hydrogen with its CO_2 reduction potential. The paper states that producing one kg of H_2 from renewable energy or nuclear power could reduce CO_2 emissions between 5.68 kg and 24.96 kg. These figures were obtained using LCA (life cycle analysis) calculations with the GWP 100 indicator (Global Warming Potential indicator) established studies. See the table below. (Sillman, et al., 2024)

Table 29: CO_2 reduction potential of green hydrogen (Sillman, et al. 2024)

Impact reduction potentials of different PtX pathways per 1 kg of H_2 when using RE or nuclear to power H_2 production.

	H_2_required	Unit	Reference products	MIN, MAX [$kg_{CO2\text{-}eq}kg_{H2}^{-1}$]	MEAN [$kg_{CO2\text{-}eq}kg_{H2}^{-1}$]	No of LCA studies
PtHydrogen	1	kg_{H2}	H_2 From SMR; coal gasification	5.68–24.96	9.61; 22.96	11
PtSteel	0.051–0.059	kg_{H2}/kg_{Steel}	BF-BOF production route	21.4–38.96	31.97	2
Partial hydrogen injection	0.025	kg_{H2}/kg_{Steel}	BF-BOF production route	10.28–12.8	11.54	1
PtAmmonia	0.18–0.19	kg_{H2}/kgN_{H3}	Ammonia from natural gas	4.09–15.14	11.33	7
PtMethane	0.46–0.50	kg_{H2}/kg_{CH4}	Natural gas	1.28–6.8	3.91	9
Biogas upgrading	0.17–0.19	kg_{H2}/kg_{CH4}	Natural gas	9.52–15.35	12.43	2
PtSyngas	0.126	kg_{H2}/kg_{Syngas}	Syngas from natural gas or coal	No reduction potential −16.2	0.91; 8.11	2
PtMethanol	0.19–0.34	kg_{H2}/kg_{CH3OH}	Methanol from natural gas or coal	No reduction potential – 22.88	3.33; 8.92	11
PtFuel						
PtDiesel	0.30–0.64	kg_{H2}/kg_{Diesel}	Diesel	1.76–30.93	9.75	6
PtGasoline	0.48–0.64	$kg_{H2}/kg_{Gasoline}$	Gasoline	2.06–6.71	5.69	2
PtDME	0.23	kg_{H2}/kg_{DME}	Diesel (based on MJ)	5.03–8.49	6.37	2
PtJetfuel	0.20–0.64	$kg_{H2}/kg_{Kerosine}$	Kerosine	4.55–16,62	8.41	2
PtMethanol	0.22	kg_{H2}/kg_{CH3OH}	Diesel or Gasoline (based on MJ)	No reduction potential – 8.30	3.15	11
PtPlastics	0.50–0.58	$kg_{H2}/kg_{Plastics}$	Polypropylene from petrochemical factory	No reduction potential −7.02	2.46	2
PtFood	0,12–0,15	$kg_{H2}/kg_{Protein}$	Plant proteins; Other microbial proteins; Animal proteins	No reduction potential −347.52	-*	2
					Total	72

* Several different protein sources are present; thus calculating the mean value is unreasonable. The reduction potential is separately discussed.

This scientific data makes it possible to compare the amount of CO_2 reduced by green hydrogen production projects with the potential CO_2 reduction outlined in the scientific literature. Achieving climate neutrality is Germany's goal, and the key figure for CO2 reduction from the projects is crucial in this regard. To achieve this goal, Germany plans to invest in green hydrogen production projects, among other things. The table below shows that all IPCEI production projects with available CO_2 reduction data have matching values with the calculated CO_2 reduction in the scientific literature. Some projects even have a higher CO_2 reduction amount. The numbers are calculated by multiplying the production amount of green hydrogen from the projects in kg (see the project tables above) by the minimum and maximum amount of reduced CO_2 in kg. After this the numbers are changed back to the unit tons. As the amount of green hydrogen produced is required to enable comparison with the data from the scientific literature, it is only possible to compare the CO_2 reduction amount from projects that only include the production of green hydrogen. (Sillman, et al., 2024)

Table 30: Comparison of CO2 reduction from projects and scientific literature

project	CO_2 reduction project	CO_2 reduction literature	matching values
H_2-ERO	100,000 tons/year	42,600 tons/year-187,200 tons/year	yes
HyTech Hafen Rostock	no data		
Elektrolysekorridor Ostdeutschland	135,000 tons/year	96,560 tons/year-424,320 tons/year	yes
H_2P	1,000,000 tons/year	147,680 tons/year-648,960 tons/year	higher
Hamburg Green Hydrogen Hub	1,000,000 tons/year	56,800 tons/year-249,600 tons/year	higher
Lingen Green Hydrogen	80,000 tons/year	62,480 tons/year-274,560 tons/year	yes
Green Motion Steel	249,000 tons/year	104,512 tons/year-459,264 tons/year	yes
Get H2 Nukleus	210,000 tons/year	119,280 tons/year-524,160 tons/year	yes
Hydro Hub Fenne	no data		

5.2 Electrolysis type

Of the green hydrogen projects shown above, three use AWE technology, four use PEM electrolysis and two are testing both types to see which gives better results for their project. The advantages and disadvantages, as well as the key specifications, of the electrolysis type could explain this.

AWE is the oldest and most well-established form of electrolysis. PEM electrolysis is less developed. There are other types of electrolysis. Recent studies have focused on anion-exchange membrane (AEM) electrolysis. Its structure is similar to that of PEM electrolysis, but the membrane is designed to transport anions rather than protons. The electrode reactions are the same as for AWE. Another electrolysis technology that is not yet ready for commercialisation is the SOEC (solid oxide electrolysis cell). This technique requires much higher temperatures than other electrolyser types. However, as the SOEC technique operates at higher temperatures, it is more efficient. This is an advantage of the technology. (Santos, Cebola, & Santos, 2021)

So, the two types of electrolysers that have been developed enough to produce green hydrogen on a large scale for industrial use are AWE and PEM electrolysis. PEM electrolysis produces hydrogen of a higher purity and can reach a higher current density. PEM electrolysis is slightly more efficient, with an LHV (Lower Heating Value) of 57-64% $_{LHV}$, compared to 52-62% $_{LHV}$ for AWE. However, PEM electrolysis exhibits higher efficiency degradation. Additionally, the cost-efficiency of PEM electrolysis increases with an increase in system capacity. This is why AWE is sold in higher quantities and is currently the most developed and cost-efficient technology. The lower costs of AWE compensate for the slightly higher efficiency of PEM electrolysis. The table below shows the main specifications of the different electrolyser types: AWE, PEM and SOEC. (Santos et al., 2021)

Table 31: Specifications of different electrolysis types (Santos et al. 2021)

Specifications	AWE	PEM	SOEC
Operating temperature (°C)	60–80	50–84	650–1000
Operating pressure (MPa)	<3	<3	<3
Current density (A cm^{-2})	0.2–0.5	0.6–2.2	0.3–2.0
Cell voltage (V)	1.8–2.4	1.8–2.2	0.7–1.5
Voltage efficiency (%)	62–82	67–82	81–86
Production rate ($m^3{}_{H2}$ h^{-1})	<760	<40	<40
Specific system energy consumption (kWh Nm^{-3})	4.3–4.8	4.4–5	2.5–3.5
Hydrogen purity (%)	99.7–99.9	99.999	99.9
Cell area (m^2)	3–3.6	<0.13	<0.06
Minimum partial load (%)	10–40	0–10	-
Stack lifetime (kh)	55–120	60–100	8–20
System lifetime (years)	20–30	10–20	-
System response	s	ms	s
Cold-start time (min)	<60	<15	<60
Capital cost * (€ kW^{-1})	620–1170	1090–1650	>1560

* Prices for 2020 [14].

5.3 Hydrogen costs

The cost data from the projects that can be compared are the investment costs. However, the projects data only provide the total investment figure they currently anticipate. A large proportion of the projects are in the planning and construction phase. The paper "Hydrogen Generation in Europe" from the European Union describes investment costs for hydrogen production technologies, investment costs for the additional needed amount of renewable energy, investment costs for electrolysis manufacturing capacity and investment costs for hydrogen transmission, storage, distribution and dispensing. With the data found from the green hydrogen projects above, it is not possible to compare investment costs with those because the breakdown of investment costs is not available. (European Commission, 2021)

The Research Institute for Energy Economics in Munich (FfE), an independent consultation on energy issues has published a discussion paper in 2025 on the question of hydrogen production costs. It claims that both investment costs and electricity costs are being underestimated. In contrast to the Europeans Hydrogen Observatory forecast investment costs of €2310/kW for AWE and €2503/kW for PEM (chapter 2.4.3 in this thesis), FfE estimates a more realistic number of €3120/kW as total investment for an electrolysis system. It is claimed that significant system costs incurred for detailed plant planning, approvals, project management, procurement not only for the physical production elements and quality assurance were not considered in full. Electricity costs play a significant role in production costs. The FfE questions whether renewable electricity for the production of green hydrogen will be available at the expected price. The figure below illustrates the difference between idealised assumptions and realistic production costs. To improve understanding, it has been translated from German to English. (Research Institute for Energy Economics (FfE), 2025)

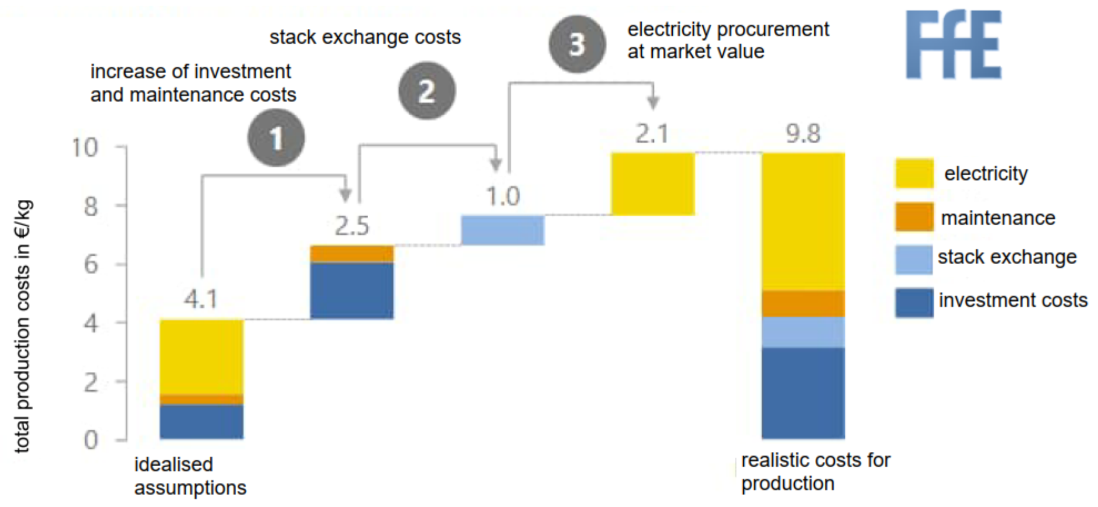

Figure 6: Realistic production costs for green hydrogen (Research Institute for Energy Economics (FfE) 2025)

6 Reflection of green hydrogen projects and recommendations for action

The aim of this thesis is to support Karelia University of Applied Science's "Green Skills for Hydrogen Economy and Renewable Energies" project in Finland by benchmarking with German green hydrogen projects. Another objective is to explain why green hydrogen projects are important and provide an overview of the most relevant ones. In this thesis, practical projects should be compared with theoretical scientific literature.

Outcome of this thesis is that hydrogen is a very fascinating and special chemical element which can significantly contribute to green hydrogen projects in order to support a climate-neutral economy. Production of green hydrogen, together with connected infrastructure projects, might make Germany climate neutral and accomplish the goals of the National Hydrogen Strategy. Among other things, the strategy states that Germany intends to establish an 1,800 km hydrogen grid by 2027/2028 and achieve a green hydrogen production capacity of 10 gigawatts by 2030. This should increase the use of green hydrogen in industry and transport, enabling Germany to become a leading provider in the entire green hydrogen value chain and reach climate neutrality by 2045. Germany has many ongoing hydrogen projects. The IPCEI green hydrogen projects are large projects in various sectors, such as the production, transport and storage of green hydrogen. They are funded by the government and federal states with a significant amount of investment. The projects are among the most significant green hydrogen projects in Germany. A total of nine projects producing green hydrogen are covered in this thesis, as well as three large-scale connected projects combining hydrogen production and infrastructure. The thesis covers two pipeline projects linked to the production projects, as well as one cavern project that is part of a large-scale project. The leader's project from Germany is to be focused on the topic of green hydrogen research on different kinds of solutions. These solutions contribute to the creation of a hydrogen economy. A variety of eight leader projects from different types are showcased in this thesis to provide an overview of the diversity of the research projects.

Most of the projects only have general information available on the internet. The three key figure that can be used to compare the projects with scientific literature is the amount of CO_2 reduction and the electrolyser type. The calculated values from both comparisons are consistent. Therefore, in terms of CO_2 reduction, it can be said that the green hydrogen projects align with the goals of the National Hydrogen Strategy and contribute to create a hydrogen economy in Germany. The different goals of the projects lead to the fact that either AWE or PEM electrolysis are used. These two types of electrolysis are currently the most well-established. At the moment more research is being carried out. This is to make this electrolysis more efficient. It is also being used to develop other types of electrolysis.

In order to implement hydrogen projects, framework conditions must be established to ensure that renewable energies are available in sufficient quantities and at competitive prices. Market conditions must be developed in such a way that companies are willing to invest in hydrogen plants and that there are both industrial and private customers on the market who are willing to accept the prices for hydrogen products.

Regarding the recommendations for action, it can be said that the approval process for an IPCEI project, which is funded, is very long and complicated. In order to encourage more green hydrogen projects and smaller companies to apply, it would be beneficial to clarify and simplify the approval process. There is more research needed of electrolyser types. To make the developed electrolysis more efficient or to develop new types of electrolysis, as it is currently done with AEM electrolysis and the technology of SOEC. In general, too little information about green hydrogen or Power-to-X is provided in general scientific puplications. Those who are interested in hydrogen or are experts know more about green hydrogen, ongoing projects, and Germany's goal of becoming a leading provider in the green hydrogen value chain. Information in the media is scarce, making it difficult for people who want to know more about this topic to find specific information. One recommendation here would be to publish more general information about Germany's hydrogen targets alongside the National Hydrogen Strategy in the media, and to provide more specific information about green hydrogen projects online for interested parties.

Overall, this thesis provides an extensive overview of background information on hydrogen and green hydrogen projects in Germany. With this information, it can support Karelia University of Applied Sciences' project in Finland. The thesis demonstrates the importance of green hydrogen and the reasons why Germany needs a hydrogen economy. Due to the limited number of key figures that can be compared, the comparison with theoretical scientific literature is not detailed. Nonetheless, the IPCEI projects demonstrate the importance of large-scale green hydrogen projects and how a future hydrogen economy could look like.

In my opinion, the background knowledge section provides a comprehensive overview of the essential information on hydrogen, facilitating a better understanding of the main section on the various types of green hydrogen projects. The section of the dissertation that outlines the current hydrogen initiatives in Germany and attempts to provide a summary of the most relevant green hydrogen projects is, in my estimation, quite successful in terms of presenting the essential information regarding the projects and offering a general picture. Some more detailed information would be useful. It would be possible to contact the projects to find out more specific information, for example regarding the efficiency of electrolysis. In this thesis, I focused on providing an overview for benchmarking purposes for the Finnish project. Due to this focus, the section comparing ongoing projects with scientific literature could not be completed.

From this thesis, I have learned that green hydrogen could be very useful in the future. I hope that the mentioned hydrogen projects, along with all the other green hydrogen projects currently underway, are successful, so that the goals set out in the national hydrogen strategy can be achieved. The existence of this strategy and the large number of green hydrogen projects in Germany came as a fresh discovery to me. I became more aware, that the future success of hydrogen depends on good cooperation between all parties involved: suppliers, consumers and government agencies. At least I was able to improve my English language skills by writing this thesis.

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