CCUS and Hydrogen Contributing to Decarbonization of Energy-intensive Industries

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Key takeaways

- In Germany and Japan, industry is not only relevant in an economic sense, but it also contributes almost 37% and 39% of total GHG emissions (including indirect emissions from public electricity and heat supply), respectively.
- The potential role of **hydrogen** and **carbon capture, utilization and storage** (CCUS) technologies for decarbonization of industry is generally acknowledged in both countries, but several points of differentiation exist.
- In Japan, the development of **direct use of hydrogen** has so far focused on power generation, transport and Enefarms (small scale fuel cell co-generation units for households), while its role for industry has only recently gained more attention; whereas Germany's National Hydrogen Strategy (NHS) was published in 2020 – several years after that of Japan – but industry's role is framed as a key factor for hydrogen demand.
- Germany's NHS focuses on hydrogen from renewable electricity, even though experts expect that blue hydrogen will be necessary to meet demand, while in Japan the debate is more open and accepts any form of clean hydrogen with the relatively lowest cost.
- RD&D for the industrial application of hydrogen appears to be more advanced in Germany.
- Costs will be a key challenge that must continuously be addressed in Germany and Japan; Germany's policy framework for deployment of industrial hydrogen solutions is evolving (e.g. Carbon Contracts for Difference, Carbon Border Adjustment Mechs are considered).
- **Hydrogen blended with natural gas** is more prominently discussed in Germany than in Japan, also due to the comprehensive gas transport infrastructure in Germany and Europe.
- However, mostly energy companies and gas suppliers advocate for blending, while industry rather fears that blending may create scarcity and increasing prices, and science points to the fact that direct use of green electricity would be the much more energy-efficient low-carbon solution than using green hydrogen blended with natural gas.
- The technology pathways of **CCUS** are tightly integrated into Japan's vision of a decarbonized society, and in the field of CCU the Japanese Government focuses on non-hydrogen-based products until 2030. In Germany, there is research on both CCU and CCS, and pilot testing of some CCU paths, but both are not uncontested for various reasons, and several challenges would need to be solved for the breakthrough of CCUS (e.g., CO_2 transport and other infrastructure). Taking a consistent life-cycle approach will be key.
- **Future cooperation** may include joint RD&D in the fields of hydrogen direct use and CCU, drawing lessons from policies and policy mixes being established for facilitating hydrogen direct use and CCU, as well as the development of international sustainability and safety standards regarding hydrogen production and transport.
- While it is worthwhile in any case to monitor technology and policy developments in Germany and Japan, it should be acknowledged that other options including **circularity, resource and energy efficiency** in industry may deserve attention as well.

1 Introduction

Hydrogen and carbon capture technologies have been gaining increasing attention as decarbonization options for different sectors of the basic materials industry. Since the production of basic materials is responsible for substantial greenhouse gas emissions in Germany and Japan, this study looks systematically at the role these technologies could play for industry.

In particular, case studies are developed for both countries focusing individually on hydrogen direct-use, hydrogen blended with natural gas as well as carbon capture and storage (CCS) and utilization (CCU; both together also abbreviated as CCUS). In these three technology-specific sub-chapters, we successively concentrate on country strategies, draw a picture of relevant research, development and demonstration (RD&D) projects and discuss challenges and perspectives. As regards the latter, we seek to provide an understanding of what hinders market penetration of these technologies and how these barriers can be overcome. We, therefore, sketch economic, technological, infrastructural, acceptance and other regulatory issues in different levels of detail. Following the two case studies, we compare the situation in both countries before providing country-wise recommendations for a way forward. While the industry perspective is the priority in both case studies, we try to open up the broader context, if relevant. For instance, in both countries, hydrogen is seen as a solution not only available to the industry sector, but stakeholders from other sectors also have an interest in making use of the technology pathway. Teams of country experts in the field of industry decarbonization carried out the case studies.

Through this study, the authors seek to contribute to the GJETC's objective to deliver strategic and systemic analysis in order to develop policy advice focused on problem solutions respecting the different framework conditions and energy policies in both countries.

2 Germany

2.1 Germany's basic materials industries

The basic materials industry is a relevant pillar of the German economy, with a total turnover of EUR 250 billion in 2017 and 550,000 direct employees. At the same time, industry produces 36.7% of Germany's greenhouse gas emissions (GHG) as of 2019, including both direct and indirect emissions (VCI, 2021). While indirect emissions are accounted to the energy sector in Germany, direct industrial emissions are at around 22% of total GHG emissions, of which 32% are process-related, for instance in steel, basic chemicals and cement production (Agora Energiewende & Wuppertal Institut, 2019). In addition, significant indirect emissions from electricity use suggest that increases in energy efficiency have a positive (climate) effect on the energy sector (BMU, 2018).[1] [2]

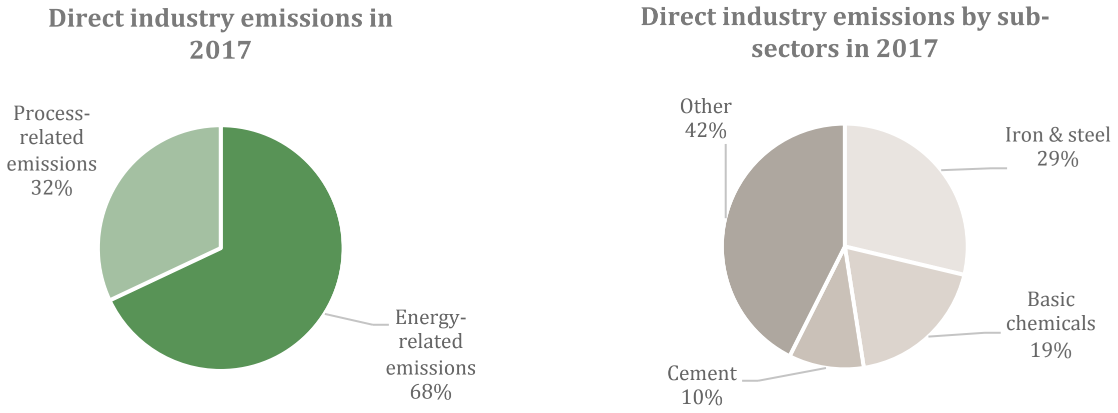

Figure 1: Key data for direct industrial emissions in Germany as of 2017 (based on Agora Energiewende & Wuppertal Institut, 2019).

Due to these process-related emissions, the transformation of these sectors towards climate neutrality is considered to be extraordinarily challenging (Agora Energiewende & Wuppertal Institut, 2019; Federal Government, 2016).

The lifespan of industrial facilities can be up to 70 years, so today's investments have implications for the future. By 2030, German-based production facilities will be facing substantial reinvestment decisions. For example, in steel production around 50% of blast furnaces will reach their end of life by 2030 (Agora Energiewende & Wuppertal Institut, 2019). However, investments in low-

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[1] For instance, as of 2016, industry consumed 246.700 mn. kWh, of which the major share (214.700 mn. kWh) was provided through the grid counted as indirect emissions (BDEW, 2017).

[2] A sub-sectoral differentiation of data on direct and indirect emissions from the industry sector is not available, which is why the figure above focuses on direct emissions.

carbon facilities and/or their operation are often more expensive than conventional technologies, and as most basic materials are globally traded, companies fear competitive disadvantages, if transformative investments increase the sales price of their products.

In the following, policy strategies and research, development and demonstration activities as well as challenges and policy recommendations are highlighted for the three technology pathways, which are analyzed in this study, for German industry. These pathways are

- Hydrogen direct use
- Blending hydrogen with natural gas (HNG) and
- carbon capture utilization and storage (CCUS).

2.2 Hydrogen direct use

2.2.1 Strategy

In Germany, hydrogen and, in particular, green hydrogen is seen as a central technology pathway to decarbonize hard-to-abate sectors including industry. Green hydrogen is produced from water and renewable electricity through electrolysis (Shibata et al., 2020). When industrial application cases are discussed for hydrogen, steel and chemistry production as well as refineries are mentioned frequently, including in Germany's National Hydrogen Strategy (NHS) published in 2020. For instance, in the steel sector, (green) hydrogen can substitute other CO_2-intensive production inputs, underlined by the Government's recently published Action Plan Steel. In the chemical industry and refineries, green hydrogen can substitute grey hydrogen, which is produced from natural gas (BMWi, 2020b; Federal Government, 2020a; Hebling et al., 2019).

In Germany, there are hardly any alternatives to green hydrogen in order to decarbonize industry, which is why a climate-friendly industry production and hydrogen development are closely connected. In contrast to that, if hydrogen is blended with natural gas, it would not be directed towards industrial purposes only but to other sectors, as well. However, the building sector, which relies on gas supply for heating is considered to have better alternatives, in general, such as direct electrification (e.g. through battery electric vehicles or heat pumps). Hence, blending hydrogen with natural gas is seen as wasting the green gas, and green hydrogen should be a priority for industry before 2030 (BDI, 2019; BMWi, 2019a; Federal Network Agency, 2020). The Government acknowledges that industry will be the key player for hydrogen's market ramp-up, but after 2030 other sources of demand "can" be added (BMWi, 2021).

Today, Germany's total hydrogen demand is at around 55 TWh, mostly from the chemicals and petrochemicals sector; the production of green hydrogen is negligible. In 2030, the Government expects a total (cross-sectorial) demand for hydrogen of 90 to 120 TWh (Federal Government, 2020a). For 2050, Germany's industrial demand for hydrogen may range between 94 and 145

TWh by 2050,[3] steel industry alone may require between 38 and 56 TWh by then (Hebling et al., 2019; MWIDE, 2020; Robinius, 2020).

In order to supply industry with hydrogen, the NHS outlines electrolysis development: the Government intends to develop 5 GW of domestic hydrogen generation capacity by 2030 and an additional 5 GW of hydrogen capacity is supposed to be added if possible by 2035 but no later than 2040. A comprehensive sector-wise planning for hydrogen applications does not exist so far with the exception of 2 GW of electrolysis capacity allocated to petrochemicals (Energieinformationsdienst, 2020; Federal Government, 2020b). Germany's hydrogen ambitions are also embedded the EU's plan to set up 40 GW of electrolyzers in the EU and another 40 GW in the EU's neighborhood countries by 2030 ("2x40 GW plan"). As an intermediate step, 6 GW of electrolysis capacity are to be installed by 2024 on EU territory (European Commission, 2020a).

In line with the domestic development of hydrogen production, the German Government plans to add renewable electricity generation underlining the focus on green hydrogen. However, domestic hydrogen production through electrolysis will only serve around 12 to 16% of the total (cross-sectoral) hydrogen demand expected by the NHS in 2030 (Federal Government, 2020a). Also due to the high demand for (green) hydrogen, some industry associations wish for a more ambitious expansion of domestic renewable electricity capacities (VDMA, 2020). Hence, a key question will be, how the rest (> 80%) of the demand will be met, also pointing to the role of imports. The NHS acknowledges that blue and turquoise hydrogen will be traded globally and used domestically until green hydrogen is available at competitive prices (Federal Government, 2020a). Blue hydrogen is produced from natural gas using gas reforming in combination with carbon capture and storage technology in order to store CO_2 underground, while turquoise hydrogen is the result of methane pyrolysis producing solid carbon as a by-product.

While the Government does neither domestically nor internationally facilitate the production of blue hydrogen (Federal Government, 2020b), it has initiated several projects worldwide (from Chile to Morocco to Australia) facilitating green hydrogen production and investigating upon local and international value chains, modes of transportation and logistics (acatech, 2020; Fraunhofer IGB, 2020; Produktion, 2020).

The discussion on how to meet domestic demand for green hydrogen is also accompanied by the Government's relative reliance on natural gas. For the steel sector, the German Ministry for Economic Affairs and Energy acknowledges natural gas to be an essential element to bridge the transition towards a comprehensive hydrogen-based steel sector (BMWi, 2020b). In one of the most promising technologies for the steel sector, which is direct reduction of iron, the application of natural gas and hydrogen is possible with varying concentrations of natural gas and hydrogen (dena, 2019). Hence, if available at lower prices, industrial players will be inclined to make use of cheaper natural gas (instead of expensive green hydrogen). In the end, the application of hydrogen in the industry sector is to some extent also dependent on how natural gas is considered a "bridge technology"in Germany (and Europe) and at what costs it will be available.

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[3] These figures exclude the demand for hydrogen in the chemical industry.

A newly established steering committee will "decide on the further development and implementation of the Strategy" (Federal Government, 2020a). It is comprised of representatives from various ministries and supported by experts from academia, business and civil society. For instance, it publishes statements on policy adjustments such as in the case of discussions revolving around the renewable energy levy, which increases electricity prices and also affected green hydrogen production, until this was recently exempt from the renewable energy levy.

2.2.2 Snapshots on research, development & demonstration

As regards research, development and demonstration (RD&D) activities for the direct use of hydrogen, refineries as well as the chemical and steel industries are central. In the cement industry, another relevant emitter of CO_2 emissions, the application of hydrogen will only reduce energy-related emissions, but hydrogen will not contribute to reducing the sector's large-scale process-related emissions resulting from the deacidification of limestone. Such process-related emissions make up for two thirds of the CO_2 emissions associated with cement production (Verein Deutscher Zementwerke, 2020).

Today, several large-scale RD&D projects have been initiated (or completed), most of which have been focusing on various parts of the hydrogen value chain, as Table 1 displays.

Table 1: Snapshot on RD&D projects on hydrogen in industrial applications in Germany

Sector	Project and description	Value chain
Refinery	The companies BP and Audi Industriegas cooperated in a 30-day test-project to demonstrate the use of green hydrogen in refineries in 2018. Audi Industriegas produced and transported hydrogen to BP's refinery to desulfurize fuels (energate 2018).	• Production • Transport • Application
Refinery	In the project "REFHYNE", the company Shell started to realize a 10 MW electrolyzer, based on which the technology provider ITM Power seeks to draw lessons learned for a 100 MW facility (IN4climate.NRW, 2020a).	• Production • Application

Sector	Project and description	Value chain
Refinery	In the project “Westküste 100” (Engl.: West Coast 100) an electrolyzer of 30 MW will be installed and fed by offshore electricity with high(er) full load hours compared to other renewable energy technologies. Green hydrogen is, then, supposed to be used for aviation fuel production as well as for increasing hydrogen concentrations in the grid. Due to these two utilization options, green hydrogen demand is safeguarded. The project envisions a scaling up of the original electrolyzer by adding around 700 MW (Raffinerie Heide, 2020).	• Green production • Transport • Application • Blending
Chemicals	The project “GreenHydroChem” develops two electrolyzers (100 MW and 40MW), which are connected to the grid and to a regional wind farm. The existing hydrogen pipeline infrastructure will be expanded to connect the new production sites with large-scale consumers from the chemical industry (Fraunhofer IMWS, 2019).	• Green production • Transport • Application
Chemicals	In the “GET H_2 Nukleus”-project, a consortium of energy companies, pipeline operators and chemical companies installs an electrolyzer with a capacity of 100 MW, which is fed by an offshore wind farm and connected to refineries and chemical production facilities via a hydrogen pipeline of 130 km. The pipeline consists of former natural gas pipes, which have been retrofitted, and 50 km of new constructions (GET H2 Nukleaus, 2020).	• Green production • Transport • Application
Chemicals	BASF has tested methane pyrolysis, which allows to produce hydrogen from natural gas; biogas as feedstock is also possible. While the process of methane pyrolysis is electricity intensive, BASF is interested in using renewable electricity. An advantage is that carbon is derived in granular form and not as a gas. The solid material can be used as a fertilizer in agriculture (energate messenger, 2019).	• Turquoise production • Application

Sector	Project and description	Value chain
Steel	ThyssenKrupp Steel tests a new blast furnace process, in which hydrogen will become the reducing agent. In conventional processes, this function is performed by fossil carbon emitting CO_2. This, however, is avoided through applying hydrogen transported via truck to the location. If the test phase is successful, the project will be scaled up by 2022 and the plant will be fully connected to a hydrogen network nearby. The company estimates a theoretic emission reduction potential at around 20%. A milestone will be the transformation to direct reduction. The company declares to become climate-neutral by 2050 (Thyssenkrupp Steel, 2020).	• Transport • Application
Steel	ArcelorMittal plans the large-scale production and use of direct reduced iron (DRI) through a complete switch to hydrogen. For this, grey hydrogen from natural gas will be used initially. Given the demonstration projects location in Northern Germany, it is envisioned to use green hydrogen from offshore wind facilities once it becomes available at competitive costs. The company plans to start operation in 2023 (ArcelorMittal, 2019).	• Production • Application
Steel	The steel company Salzgitter AG, plans to develop a DRI plant operating with 35% green hydrogen produced on-site and 65% will be natural gas. Part of the "WindH_2" project is the development of seven wind power plants, three on-site and four in proximity to the site, which will feed into the electrolyzer. In a complementary project, the company demonstrates high temperature electrolysis, which makes use of waste heat from steel production (Salzgitter AG, 2019).	• Green production • Application

2.2.3 Challenges and perspectives

Economic issues

Most of the economic discussions regarding the hydrogen use in industries are about both CAPEX and OPEX, perhaps with a higher focus on the latter as these are more difficult to address through policy measures.

Relatively high OPEX for the application of (green) hydrogen in industry is also due to all the costs associated with hydrogen production. Literature suggests that costs for green hydrogen are around EUR 5-6 /kgH_2, while blue and grey hydrogen cost only EUR 2.1 /kg H_2 and 1.5 €/kg H_2, respectively.[4] For green hydrogen, investment requirements for electrolyzers as well as the procurement of electricity are central cost factors at the moment, which would have to be passed on to industry. Price drops of electrolyzers through switching from manual to (semi-)automated production as well as price increases of emission certificates (increasing costs of conventional production) may help to make green hydrogen cost more competitive (BDI, 2019; Bukold, 2020; World Energy Council, 2018). The EU's and Germany's hydrogen strategies to facilitate electrolyzer capacity abroad can also be seen as a lever to achieve economies of scale and gain learning curves for reducing costs for developing domestic capacities. Taxes, duties and levies have been applicable in Germany for using electricity, which is elementary for green hydrogen production, increase the costs of power purchase and, thus, the costs of green hydrogen production. Recently, green hydrogen production has been exempted from the renewable energy charge (Appunn, 2020).

However, the discussion on imports of hydrogen and related products from areas not connected via pipelines to Germany and the EU goes hand in hand with costs for shipping and value chains and value creation. Literature suggests that ship imports of hydrogen only pay off for long distance transports (> 4,000 km), mostly because of the necessary liquefaction of hydrogen. This makes the import of hydrogen-based products instead of hydrogen more attractive due to better transport characteristics (Wuppertal Institut & DIW Econ, 2020). In addition, it may make more economic and environmental sense to replace Ammonia production in Germany from grey hydrogen directly by import of green Ammonia, rather than using imported green H_2 for Ammonia production, and similar for other uses of grey hydrogen in chemical industry or refineries. Therefore, if downstream products are imported, such as Ammonia, questions will arise regarding the impacts on domestic value creation in the chemicals and petrochemicals industries, which currently produce Ammonia, methanol and the like in Germany.

Apart from questions on high costs for hydrogen production (or for, generally, safeguarding that sufficient quantities of hydrogen are available in Germany), high capital expenditures for low carbon breakthrough technologies such as DRI plants exacerbate respective investments. For instance, direct reduction through hydrogen is expected to increase costs of iron production by 36 to 61 % (Agora Energiewende & Wuppertal Institut, 2019). Hence, Germany's National

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[4] Costs reflect an EU average (Bukold 2020).

Decarbonization Program in Industry can provide funding for upfront investments. Under this program, the Government plans to spend EUR 2 billion for investments of large-scale industrial facilities also making use of hydrogen to decarbonize manufacturing processes between 2021 and 2024 (BMU, 2021; Federal Government, 2019, 2020a). The program will fund research and demonstration projects and market introduction activities in the industry sector. The Government's Package for the Future that has been designed to mitigate the impacts of the COVID-19 pandemic makes available an additional EUR 7 billion for the hydrogen market ramp-up in Germany (as well as EUR 2 billion for international partnerships).

On the EU level, further funding opportunities exist. The Innovation Fund will assist in bridging the 'valley of death' for innovative industrial projects. The fund's preceding program, the NER 300, was restricted to energy sector projects (e.g. large-scale CCS), while the Innovation Fund also targets industrial activities specifically. The first round of applications shows that energy intensive industries in the EU submitted several hydrogen projects, showcasing their interest in this field. Moreover, Carbon Contracts for Difference (CCfD) will be implemented in Germany targeting the steel and chemical industries, at first (Federal Government, 2020a). CCfD are supposed to cover OPEX resulting from investments in low carbon breakthrough technologies.

Textbox: Brief introduction to carbon contracts for difference

While the concrete design is still discussed, CCfD are a contract between the state and an industry company that plans to realize a climate-friendly project. Both parties agree upon a strike price for avoiding CO_2 emissions, which is project-based (e.g. realization of a DRI-plant), set for around 20 years and above the current price for emission allowances. The cost difference between the strike price and the allowance price is paid from the Government to the company for every avoided ton of CO_2 (probably on an annual basis). In doing so, the contract ensures the company investing in low-carbon technologies against a low allowance price. As the allowance price is generally considered too low and too volatile, it does not create a sufficient incentive for investing in capital intensive projects. This is where CCfD become relevant (Agora Energiewende & Wuppertal Institut, 2019; BMWi, 2020b; Leipprand et al., 2020; Richstein, 2017; Sartor & Bataille, 2019).

Other instruments envisaged seek to create green lead markets for industry. For instance, the Action Plan Steel notes that a sustainable public procurement criterion for energy intensive products, a labelling scheme for climate friendly materials, and / or a quota for processing a certain share of climate friendly basic materials in a final product (e.g. a car) could help to pull capital-intensive climate-friendly technologies into the market. Last but not least, the EU discusses the design of a Carbon Border Adjustment mechanism, which seeks to create a level-playing field between climate-friendly products produced within the EU and materials produced conventionally abroad (Agora Energiewende & Wuppertal Institut, 2019; BMWi, 2020b; Leipprand et al., 2020).

There are several other instruments currently under discussion, but their individual design and their orchestration is still pending.

Technological issues

While a snapshot on RD&D projects has been given above (Table 1), technological challenges must be solved. For instance, in steel production, research must, among other things, focus on dynamic operation of DRI facilities with alternating hydrogen concentrations and potential implications on product quality.[5] Moreover, the new DRI production route might affect cross-industrial networks. For instance, today, cement industry makes use of slag from steel production, which avoids CO_2. However, if the steel industry applies direct reduction technology, the quantity and quality of slag changes and it is unknown whether this new slag quality is fit for purposes in the cement industry. Hence, the transition to a hydrogen-based production route might bring along negative side-effects in other sectors, which deserves attention. Moreover, small-scale demonstration plants must be scaled. Demonstration projects mentioned above (s. Table 1) seek to address this problem by starting demonstration projects small-scale with a gradual expansion (e.g. scale-up of electrolyzers) already intended in project proposals. Industries require a constant supply with hydrogen, drawing attention to the development of hydrogen storage technologies (Hebling et al., 2019; Verein Deutscher Zementwerke, 2020).

As for the international dimension of the NHS, some other technological advancements need to be taken into account. For imports, certain imports via ship remain challenging and need to be addressed. Apart from that, if hydrogen is produced in countries with water scarcity, the production of hydrogen might either require (additional) desalination facilities or the production of hydrogen from salt water (Wietschel et al., 2020).

Different instruments have been or are planned to be implemented aiming at facilitating RD&D for applying hydrogen in industry, even though a differentiation of those policy programs between the direct use of hydrogen and admixtures of hydrogen and natural gas would deserve a deeper analysis. These include:

- The National Innovation Program on Hydrogen and Fuel Cell Technology, which delivered EUR 120 million for industrial purposes between 2006 and 2016; more than 50% went into demonstration projects (BMVI & BMWi 2017); figures include public funding blended with private means. While transport and building technologies were the dominant funding areas in the original funding stream, its follow-up for the period between 2016 to 2026 has doubled the total amount of public funding to EUR 1.4 billion, so that more budget can be assumed to be used also for industry-relevant themes.
- The Government's Energy Research Program, which allocated EUR 100 million to "sector coupling and hydrogen technologies"; due to data constraints, an indication as regards the program's relevance for the industrial use of hydrogen cannot be made.
- The Energy and Climate Fund; for the period between 2020 to 2023, EUR 310 million will be facilitated to practice-oriented basic research on green hydrogen.

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[5] DRI facilities can, in principle, make use of hydrogen and natural gas in alternating ratios.

- Regulatory sandboxes also targeting hydrogen with EUR 600 million (Federal Government, 2020a).

Data covering all RD&D projects realized through Federal Government funding for hydrogen in industrial applications shows a substantial increase in public investment.

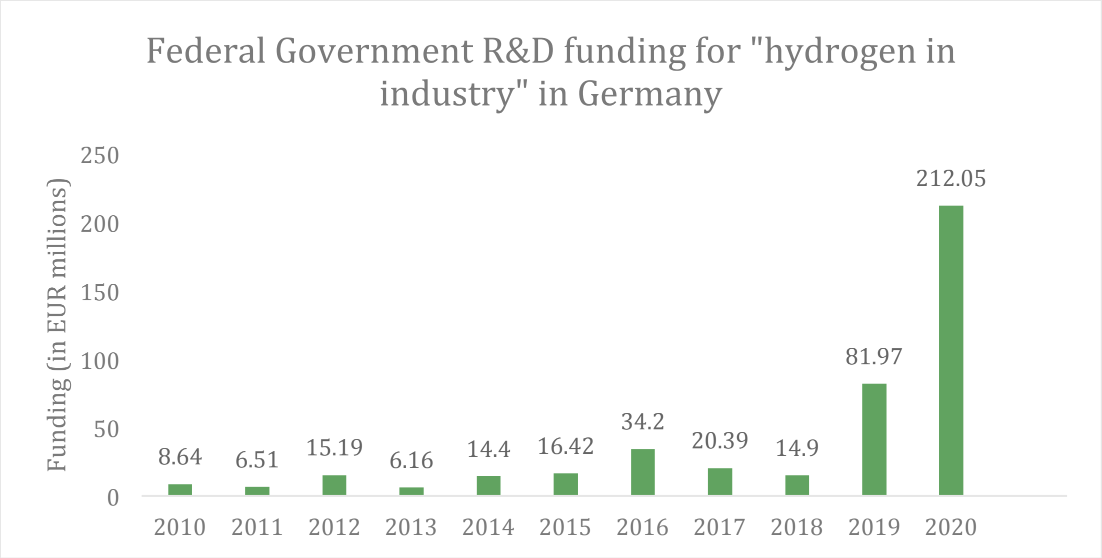

Figure 2. Federal Government funding for RD&D for "hydrogen in industry" in Germany, based on PTJ (2021).

Federal States have their own regional R&D programs, which take into account regional needs of respective companies. For instance, as of 2018, research in hydrogen technologies received another EUR 12 million from the Federal State Governments (Jessen, 2020).[6]

Infrastructural issues[7]

The German hydrogen infrastructure is limited at the moment. At present, there is very little electrolyzer capacity in Germany for green hydrogen production. The current industrial demand for hydrogen dwarfs green hydrogen supply, even though aforementioned research projects such as West Coast 100 and GreenHydroChem add some capacities. It will be crucial to realize RD&D projects seeking to scale-up electrolyzer capacities, if small-scale tests turn out to be promising business cases. While the NHS has set up objectives to install electrolyzer capacities, their locations are unknown so far.

In its stakeholder consultation for hydrogen network regulation, BNetzA (2020a) outlines three scenarios, which are not to be regarded as isolated from each other but are rather sequential (BNetzA 2020b). First, local hydrogen island networks develop around current and future demand centers in the chemical and steel industry (scenario I). Two of such pure but small-scale hydrogen

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[6] Funding provided by regional authorities is published with a delay of around two years.

[7] This chapter focuses on physical infrastructure due to its role in providing large quantities of hydrogen from production sites to demand centers. Trucks and ships also play a role in hydrogen delivery. However, literature suggests that pipelines will play the central role for importing hydrogen, especially if transport costs will not be reduced dramatically (Wuppertal Institut & DIW Econ, 2020)

networks exist already today in Germany (cf. BWMi 2019). These local island networks could then be connected with hydrogen transport pipelines delivering hydrogen from other regions in Germany and beyond (scenario II). Scenario III, in which a hydrogen distribution grid becomes necessary for hydrogen filling stations targeting heavy transport, is less relevant for industry. These three scenarios are considered to be realistic by the majority of stakeholders taking part in the consultation process, but more concrete forecasting is necessary (Federal Network Agency, 2020).

Even though transport network operators of gas grids have published a draft proposal, in which they suggest to make more than 1,100 km of natural gas pipelines ready for pure hydrogen transport and construct 151 km new gas pipelines by 2030, of which 94 km will also be for pure hydrogen transport (FNB Gas, 2020; von Burchard, 2020), the planning processes for power and gas networks are not done in an integrated way. A more coordinated planning between power and gas infrastructure providers may realize optimization potentials for the overall energy system. For instance, hydrogen for industrial purposes could be produced on-site or regionally, for which electricity transmission lines need to be built connecting industrial centers with large-scale offshore wind farms. Another option is to produce hydrogen close to the wind parks and make use of hydrogen/retrofitted gas pipelines to safeguard supply to demand centers. A proposal exists to better coordinate energy infrastructure planning: a System Development Plan precedes both, the Network Development Plan Gas and the Network Development Plan Electricity, in order to elaborate cross-infrastructural questions (dena & BET, 2020). Others propose to establish an independent expert panel, which will assess infrastructural and cross-infrastructural demands and grid expansion (E3G, 2020). Policy-making will have to find a way to identify the ideal infrastructural design option (Hegnsholt et al., 2020) and should also coordinate the increasing policy initiatives by Federal States (MWIDE, 2020; Roland Berger et al., 2020).

For a European hydrogen network, cooperation between governments and pipeline operators will be key. But initiatives have been started already with a proposal to develop a European Hydrogen Network (Wang et al., 2020). While there are projects that deal with hydrogen imports and the construction of electrolyzer capacities abroad, including projects on green ammonia in Morocco or the HySupply project assessing the creation of a value chain for hydrogen imports from Australia to Germany, relevant information such as scenarios on hydrogen import needs and logistics are missing (acatech, 2020; Fraunhofer IGB, 2019; Hebling et al., 2019; Wietschel et al., 2020).

Even though the role of blue hydrogen is less prominently discussed (publicly), it should be acknowledged as an option. However, the annual injection rate of (potential) underground CO_2 storage sites may pose a significant infrastructural challenge to blue hydrogen production (Wuppertal Institut 2012). In this respect, it would be key to check how much CO_2 can be annually injected and to identify (and prioritize) the relevant CO_2 sources (including hydrogen production and other industries) for underground storage.

Further regulatory issues

Several of the above-mentioned topics would also deserve to be mentioned here, as regulators and policy makers can provide relevant support. However, this subchapter focuses on some new aspects as regards hydrogen production, pipeline transport and the creation of lead markets.

Advancing the certification of green hydrogen will safeguard that sustainability criteria for production are applied at a European level and internationally, if the criteria also address imports. It must also be avoided that green hydrogen producers are put in unfair competition with blue or grey hydrogen producers/importers. All types of hydrogen have the same application characteristics, but they differ in costs. Green hydrogen based on renewables is more expensive than, for instance, natural-gas-based (grey) hydrogen or (yellow) hydrogen produced from the current electricity mix still including coal power in Germany. In the end, a certification scheme will have to increase transparency of hydrogen supply to industry (and other users).

Future hydrogen sustainability criteria should not only safeguard that hydrogen is produced from renewable energy sources but go beyond a narrow definition. For instance, these renewable electricity capacities must either be *additionally* implemented or excess electricity must be used which would otherwise have been wasted (cf. Shibata et al., 2020 for a thorough discussion). Only if renewable electricity is not withdrawn from other utilization options, green hydrogen will be in line with climate objectives. In some countries with exceptional potentials for renewables and, thus, for green hydrogen, water scarcity plays an important and restrictive role. Hence, sustainability criteria for hydrogen production must be comprehensively thought through (Shibata et al., 2020). On the EU level, a project consortium seeks to set up a certification scheme for green and low carbon hydrogen called CertifHy. Internationally, the German Energy Agency has been assigned to develop a certification system for green hydrogen and climate-neutral fuels in Australia, which will reflect the CertifHy initiative, showcasing Germany's commitment in this area (Peacock, 2021).

At the moment, *regulation for hydrogen networks* is pending, and there are different aspects to consider. For instance, regulation could guarantee access to the grid for industrial applications and prevent market abuse of hydrogen network operators. On the one hand, this would increase investment security of hydrogen producers and users. On the other hand, a regulatory approach might also result in costs due to operators being responsible for reporting substantial amounts of data to a regulating agency. The latter would also need to enhance its capacities to process and verify respective data. If the Government opts for a regulatory approach, the question is whether original transport network operators (TNOs) of gas networks will be in charge of building up the envisioned hydrogen network or whether this will be carried out by specialized hydrogen network operators (HNOs). TNOs will be able to easily retrofit network structures, which they own anyway. Specialized HNOs would have to engage with TNOs and negotiate the takeover of natural gas network structures for making them hydrogen-ready (EWI, 2020). Also based on the market consultation, the BNetzA will decide whether and how hydrogen networks will be regulated (Federal Network Agency, 2020).

According to the Renewable Energy Directive (2018/2001/EU), revised in 2018, Article 25 requires each Member State to "set an obligation on fuel suppliers to ensure that the share of renewable energy within the final consumption of energy in the transport sector is at least 14 % by 2030 (minimum share)" (European Commission, 2018). The revised Directive allows fuel producers / refineries to count emissions saved by making use of green hydrogen (e.g., in the desulphurization process). The German Government set the minimum share at 28%, which is effectively at 22% without double counting (dena, 2021). This allows for phasing in green hydrogen into petro-chemicals and, thus, the transport sector safeguarding demand for hydrogen producers.

2.3 Hydrogen natural gas blending

2.3.1 Strategy

The blending of natural gas with hydrogen (HNG) for industrial purposes is not prominently discussed in Germany's NHS. Blending hydrogen with natural gas is an opportunity to make use of Germany's existing natural gas network. However, depending on the hydrogen concentrations in a certain admixture, network upgrades (and, thus, investments) have to take place. As mentioned earlier, an HNG admixture is frequently rather seen as an option to decarbonize heating, in general. This, in turn, is seen as unrealistic for the time until 2030 or even beyond, as it would waste the valuable hydrogen gas in sectors, which have better alternatives such as stronger energy efficiency and direct electrification, while industry hardly has any other options (BDI, 2019; BMWi, 2021; DUH, 2020; EEB, 2021; Federal Network Agency, 2020). Some industrial actors are afraid that HNG admixtures create scarcity of green hydrogen, increasing prices. Proponents of blending green hydrogen with natural gas include the natural gas supply industry, and they focus on the central role of the building (and heat) sector for a climate-neutral Germany. One of their key arguments is that although the energy efficiency of buildings needs to be increased, in fact, the building renovation rate has been lower than expected for many years. Hence, the gradual increase of green hydrogen concentrations would allow for decarbonizing Germany's building stock independent from renovation measures (BDEW, 2020). On the other hand, using green hydrogen for heating buildings would need circa five times the amount of electricity compared to direct use of electricity with heat pumps (Gerhardt et al., 2020).

The NHS recognizes the need to check for opportunities to increase the H_2compatibility of the natural gas network, which is, in principle, capable of transporting a gas blend with hydrogen amounting to 10 % by volume (Federal Government, 2020a). A share of 2 % by volume is what Germany's Federation of German Industries considers realistically possible for a nation-wide hydrogen blending. One of the reasons is to protect sensitive users including natural gas motors and turbines, most of which only tolerate very low shares of hydrogen concentrations in an HNG admixture today. Higher hydrogen concentrations are considered an option in areas without sensitive industrial users (BDI, 2019), stressing the role of blending rather for the heat and building sector.

In general, this part of the discussion factors in that hydrogen and natural gas are blended into a *single* HNG admixture provided through an upgraded pipeline network. If hydrogen concentrations increase, two main options for sensitive industrial users are at hand: a) to upgrade or exchange existing systems that allow higher hydrogen concentrations for operation or b) to, ultimately, separate hydrogen from natural gas, e.g. through membrane technology. Alternatively, c) HNG concentrations in transport or distribution pipelines connected to sensitive users remain within the limits of below 2 % by volume.

2.3.2 Snapshots on research, development & demonstration

With regard to infrastructure-related RD&D activities, different projects test increasing concentrations of hydrogen in isolated natural gas grids. Among others, concentrations of 20% and 30% by volume are applied. However, their focus is rather on heat and the building sector (Tenge & Brandes, 2019; Verband Kommunaler Unternehmen, 2020). An EU project with German stakeholder participation investigates upon the impact of high amounts of hydrogen on the gas infrastructure and its components (European Commission, 2020b).

On the application of HNG admixtures in industrial facilities, the HyGlass research project investigates the use of hydrogen in the glass industry and the implications on glass production. HyGlass is funded by the regional government of the state of North-Rhine Westphalia. The glass industry belongs to the group of sensitive users and given that hydrogen has different characteristics compared to natural gas, it becomes crucial to identify the impacts on material quality. In particular, different concentrations of hydrogen mixed with natural gas are taken into account in the analysis, from 10% to 100% by volume (BV Glas, 2020).

Other activities focus on the aforementioned separation of H_2 in a certain admixture with natural gas. Since German research projects found that membrane technologies have several advantages in contrast to chemical conversion processes, a demonstration plant will be set up in order to identify the best membrane technologies for separating different HNG blending ratios (DVGW, 2020; Lubenau & Kussin, 2020).

2.3.3 Challenges and perspectives

Economic and technological issues

The production of (green) hydrogen mixed with natural gas faces similar economic challenges as described in the chapter on the direct use of hydrogen (see 0). Apart from that, concerns are that hydrogen blending may create scarcity for the green gas, which would, then, increase its purchase price for industrial users relying on pure hydrogen.

Admixture poses technological challenges that will require investments. For instance, increasing hydrogen concentrations will affect hydrogen-sensitive industrial applications. The maximum share of hydrogen blended with natural gas is restricted to 2% by volume, if sensitive end-users are connected to the network including industries with gas-fired motors and turbines (Lubenau & Kussin, 2020). Next to projects for enhancing the pipeline infrastructure (European Commission, 2020b), the exact composition of the gas affects the combustion process and, thus, industrial applications: higher shares of hydrogen reduce the calorific value, which would require an adjustment of the gas flow in a furnace. Without an adjustment, the temperature would drop resulting in problems regarding the material quality of glass, for example. The aforementioned

HyGlass project acknowledges this challenge and identifies the impacts of higher and varying hydrogen concentrations on glass quality (BV Glas, 2020). Moreover, another research project works on measurement and control technologies in order to identify fluctuating gas compositions in real time (IWR, 2020).

Apart from capital and time intensive exchange of certain equipment in relevant industrial applications in order to make use of HNG admixtures, other technologies separating hydrogen from natural gas are not considered to be market-ready yet such as membrane technologies. For instance, while membrane technology has a technology readiness level (TRL) of 9 for general industrial use, its readiness for separating H_2 from natural gas is considered much lower (TRL 5) with only some pilot projects being implemented (Lubenau & Kussin, 2020). Testing the latter is considered to be of high significance in future RD&D activities (BDI, 2019; DVGW, 2020; Fraunhofer ISI & DVGW, 2019; Lubenau & Kussin, 2020).

In a market consultation, quite a significant number of participants believed infrastructural planning should avoid an increase of hydrogen concentrations, in particular, in networks which hydrogen sensitive users are connected to. If hydrogen concentrations increase, others call for a funding program assisting industrial companies in financing the large costs associated with retrofitting or exchanging existing equipment or facilities (Federal Network Agency, 2020).

Infrastructural issues

At the moment, the role of hydrogen in Germany's grid infrastructure is largely unclear and includes discussions on the development of new structures for pure hydrogen as well as the rededication or retrofit of the existing networks. If hydrogen concentrations exceeding current restrictions are intended to increase nationwide, a strategy pointing to new framework conditions and necessary technological retrofits will be necessary. Due to European pipeline network, a dialogue at the EU level is key. Large-scale technology upgrades in infrastructure must be in line with long-term objectives of the Government; hence, unnecessary investments recurring every few years for increasing hydrogen concentrations in a step-by-step-approach in pipelines should be avoided (Fraunhofer ISI & DGVW 2019).

Further regulatory issues

The German Technical and Scientific Association for Gas and Water (DVGW) seeks to adjust its documents regulating hydrogen concentrations in natural gas networks in order to increase the H_2 shares in HNG admixtures by up to 20% by volume (Wirth, 2019). Apart from that, for transnational transport of natural gas blended with hydrogen, restrictions in receiving (and transit) countries must be factored in. The maximum shares in EU countries vary from 0.1 to 12% by volume. Hence, European harmonization is key.

2.4 Carbon capture, utilization and storage

2.4.1 Strategy

The technology pathways of carbon capture and storage (CCS) and carbon capture and utilization (CCU) rely both on technologies relevant for capturing and transporting CO_2. As regards CCU, removed CO_2 is directed to other processes, where the CO_2 is absorbed for a certain period of time depending on the lifespan of the product. In the CCS-route, removed CO_2 is stored underground.

In order to understand the situation of CCUS in Germany, the more recent historic context is relevant. In particular, the role of onshore CCS was originally considered important for capturing CO_2 from power plants, but it has long been controversially debated raising massive public protest in respective regions. Most of Germany's onshore storage capacities are located in the North German basin, which is a relatively populated area. Skepticism *vis-à-vis* both the technology and the companies leading the project consortia (e.g. power companies such as Vattenfall and RWE) was huge.

Even though Germany's Federal Environment Agency (UBA) does not consider CCS a sustainable climate protection measure, it recognizes the need to continue RD&D, as other measures may not prove to be sufficient. Moreover, the discussion around CCS has shifted in a double sense. First, policy makers, industry and research investigate offshore storage capacities circumventing concerns by the larger population. Second, unavoidable process-related emissions from energy intensive industries enjoying hardly any alternatives (in contrast to conventional power stations) are in the spotlight now; and the role of CCS for such unavoidable process emissions has been acknowledged by stakeholders from different parties and societal groups as well as the Government (Federal Government, 2018; Fried & Kornelius, 2019; Nijhuis, 2020; Stratmann, 2020; WWF, 2019b). In particular, Germany's Ministry for the Economic Affairs and Energy (BMWi) works on CCS and participates in a European coordination instrument for facilitating CCS (and CCUS) projects. The Industry Strategy 2030 mentions CCUS briefly stressing the role of RD&D (BMWi, 2019b).

In a way, the discussion on capturing CO_2 has also shifted towards its utilization (CCU), which has not raised massive public resistance yet. In contrast to the technology pathway of hydrogen, however, CCUS does not enjoy any technology-focused strategic outline by the government describing, for instance, how much CO_2 will be stored and / or utilized and by when. The NHS acknowledges CCU's relevance and hydrogen-based business models are mentioned to integrate CO_2 as a further resource input. For instance, in the chemicals sector, CO_2 and hydrogen can be combined to produce chemicals. Given that industrial representatives belong to the newly established hydrogen steering committee, it should contribute to bringing the technology pathways of hydrogen and CCU together. The Ministry for Education and Research facilitates CCU (Federal Government, 2018; Mennicken et al., 2016).

In the absence of a Government strategy, the German cement industry published a CO_2 roadmap to decarbonize the sector by 2050. The document differentiates between an "ambitious scenario" and a “climate-neutral scenario”. In the former, important innovations are realized (e.g. application of CEM II/C-cements), but CCUS is *not* considered. In this ambitious scenario, 19% and 36% of CO_2 emissions are avoided by 2030 and 2050, respectively, compared to 2019. In the climate neutral scenario, 27% of CO_2 emissions are avoided by 2030, while in 2050 the sector is climate neutral. The climate-neutral scenario includes highly innovative developments (e.g. CEM IV-cements), of which CCUS is a key element. In this scenario, CCUS is relevant for 50% of CO_2 emissions avoided suggesting that hopes of the cement industry rely to a large extent on this technology pathway for a climate-friendly transition of their sector (Verein Deutscher Zementwerke, 2020).[8]

2.4.2 Snapshots on research, development & demonstration

Current research mostly focuses on carbon capture and utilization. Projects listed in the following table show that research is mostly interested in investigating carbon capture and carbon utilization.

Table 2: Snapshot on RD&D projects on carbon capture, storage and utilization in industrial applications in Germany

Sector	Project and description	Value chain
Cement	An EU project called “Low Emissions Intensity Lime & Cement” (LEILAC), in which the German company Heidelberg Cement participates, investigates upon CO_2 capture technologies for cement production in Belgium. While it is stated that both utilization and storage might follow the initial research activities, the intended publication of a CCS roadmap suggests that CCS is considered the more likely option (Leilac, n.d.). This LEILAC approach is highly electricity-intensive: if 50% of Germany’s cement production switched to this process, an additional 18-25 TWh of electricity would be necessary (Agora Energiewende & Wuppertal Institut, 2019).	• Carbon capture (Leilac approach)

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[8] A differentiation between the roles of CCS and CCU as regards their impact on CO2 avoidance has not been made. Since the study acknowledges that the market for utilizing CO2 is small in size, it can be suggested that the focus of the paper is on CCS (cf. Verein Deutscher Zementwerke, 2020)

Sector	Project and description	Value chain
Cement, petro-chemicals	In the project “catch4climate”, the cement company Schwenk seeks to test oxyfuel technology for capturing CO_2 on a semi-industrial scale. The project consortium applied for funding, permission is pending. Schwenk seeks to forward CO_2 to the production of aviation fuels (Agora Energiewende & Wuppertal Institut, 2019; Schwenk, 2020).	• Carbon capture (oxyfuel) • Utilization
Steel, chemicals	The consortium of the project “Carbon2Chem” consists, amongst others, of the Companies ThyssenKrupp, BASF, Covestro and Linde. It can be considered a cross-industrial consortium between different sectors of the basic materials industry. The project aims at making use of CO_2 and H_2 from metallurgical gases produced in a steel plant for chemical purposes, e.g. methanol and ammonia production. Renewables provide the electricity for this conversion process. The second phase has been granted EUR 75 million. The process will be validated and upscaled by 2025, so that the chemical industry can make use of sequestrated CO_2 in an industrial scale (BMBF, 2020a).	• Carbon capture • Utilization
Energy, chemicals	The energy company RWE operates a post-combustion carbon capture facility in one of its conventional power plants supplying CO_2 for the production of methanol, of which the EU is a net importer. In the “Mef CO_2”-project[9], excess electricity from renewables has been used for green hydrogen production. Researchers working in the project suggest that CO_2 capture is commercially viable and sustainable if used for higher-value chemicals. The technology investigated is considered to be transferable to other industries (European Commission, 2020c).	• (Green hydrogen production) • Carbon capture • Utilization

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[9] MefCO2 stands for “synthesis of methanol from captured carbon dioxide using surplus electricity”.

Sector	Project and description	Value chain
Chemicals	In the project series called “DreamProduction”, the chemical company Covestro and others succeeded in producing polyether-carbonate-polyols with CO_2. These polyols are an input for foam mattresses, for example, whose new material quality is considered outstanding. In the wake of the pilot stage, a commercial plant was realized. The CO_2 footprint was reduced substantially as the CO_2 is provided by a chemical plant close to the production site. Hence, this aligns companies of a single sector within the basic materials industry. In the Rheticus project, the companies Siemens and Evonik develop a technology to produce high-value chemicals (butanol, hexanol) from CO_2, power and water. These chemicals are inputs for special plastics, fuels and cosmetics. Together with the company Beiersdorf, Evonik plans to set a business model (BMBF, 2020b; IN4climate.NRW, 2020b).	- Utilization

Apart from the petrochemical industry, research also focuses on CO_2 as an ingredient for cement production. However, the process is relatively electricity intensive and lacks a business case (Ostovari et al., 2020; WWF, 2019a).

2.4.3 Challenges and perspectives

Economic issues

In the field of CCUS, economic issues revolve around carbon capture technologies and carbon utilization. CO_2-capture and utilization are both electricity-intensive processes resulting in a higher electricity consumption. In order for CCUS to have a positive climate effect, electricity needs to come from renewable sources – at competitive prices (adelphi & IASS, 2016; Verein Deutscher Zementwerke, 2020). For CO_2 storage offshore, costs are higher compared to an onshore option (Federal Government, 2018)

Products resulting from removed CO_2 vary in competitiveness. While the production of polyols is considered to be a business case, the production of synthetic methane and methanol suffers from relatively high prices. In this respect, the availability of green hydrogen is considered a bottleneck for the CCU route also requiring renewable electricity for electrolysis (acatech, 2019). Moreover, the capacity of the chemical industry and refineries to make use of CO_2 from other sectors is only about to take off. Hence, the demand for CO_2 is low, affecting the price of CO_2 as a raw material, and provides few opportunities to develop cross-industrial business models (Verein Deutscher

Zementwerke, 2020). The following figure shows the market-readiness of certain CCU products from the chemical industry.

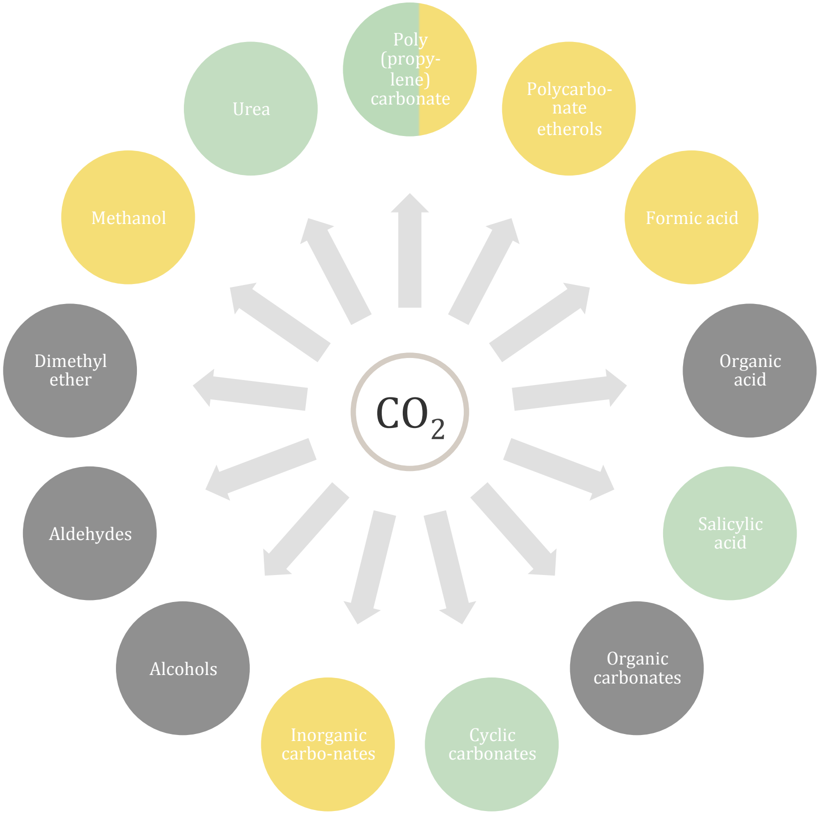

Figure 3: CCU products and their market-readiness based on (acatech, 2019); green: commercial scale, yellow: demonstration scale, dark grey: laboratory scale.

Financial assistance for capture and utilization technologies and / or a higher price tag on CO_2 for conventional production may increase CCUS' market deployment. With regard to CCU, synthetic methane would require a CO_2 price of EUR 90 per ton of CO_2 to become a business case, which is more than three times the current allowance price. In its Climate Action Program 2030, the Government introduces the program for CO_2-Avoidance and Utilization in Basic Materials Industries, which, among other things, seeks to facilitate a carbon circular economy, adjust and scale-up methods to capture CO_2 in industrial uses and develop regional, transregional and European CO_2 networks. Moreover, the National Decarbonization Program provides grants for the uptake of technologies for utilizing CCU (Federal Government, 2019). Upfront investment can also be supported via the EU's Innovation Fund, while the instrument of Carbon Contracts for Difference supporting OPEX will be implemented soon; however, so far, discussions focus on implementing CCfD as a means to facilitate hydrogen in industry and not on CCUS, even though literature suggests that, for instance, CCfD can be a lever for oxyfuel technologies (see chapter 2.4.1 for an overview of CCfD).

Other recommendations for supporting the CCUS uptake revolve around tax allowances for CO_2 utilization (Bazzanella & Krämer, 2017), the design of lead markets, in which consumers are informed and enabled to purchase CO_2-efficient or -free products such as cement or concrete, and life-cycle analysis for the CO_2 performance of products (Verein Deutscher Zementwerke, 2020).

Technological issues

The following figure provides an overview of RD&D funding priorities of the Federal Government in the field of CO_2 technologies. It shows that investment increased from 2016 onwards focusing on basic research and CO_2 utilization and conversion. As the newly established funding schemes mentioned above also facilitate RD&D, it can be assumed that figures will very likely increase.

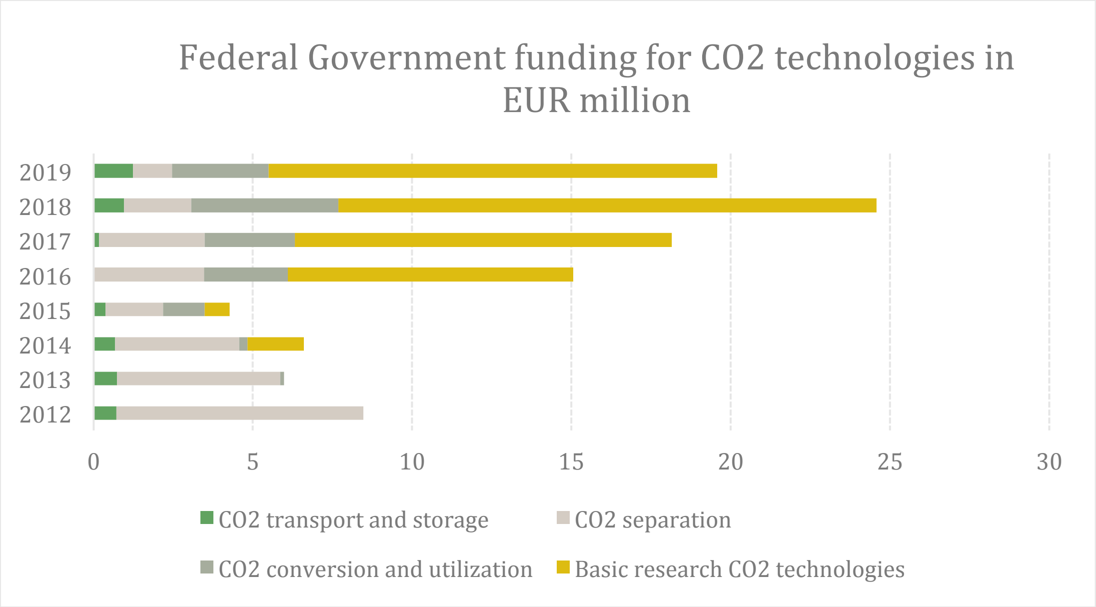

Figure 4: Federal Government funding for CO_2 technologies in EUR million based on (BMWi, 2020a)

Some technological challenges remain in the field of CO_2 capture in industrial plants, where they need further demonstration (acatech, 2019; Markewitz et al., 2017). Due to the high energy demand of CO_2 removal technologies with industrial sites, it is key to facilitate energy efficiency, which will also reduce the need to expand renewable power plants (WWF, 2018). CO_2 transport is a mature technology also reflected by the lack of R&D budget attached to this element of CCUS. For onshore storage, if this unlikely pathway were taken up again, further feasibility studies for saline aquifers would have to be carried out (Markewitz et al., 2017). A key point of critique has been the unknown implications of underground storage on groundwater and soils and risks of CO_2-leaks; challenges would need to be solved for progressing in the field of onshore storage (adelphi & IASS, 2016).

For offshore CO_2 storage in the North Sea region, close cooperation with European partners is envisioned in Germany's Industrial Strategy 2030 (BMWi, 2019b). As offshore storage is more expensive, research may focus on identifying low-cost solutions.

For the utilization of CO_2, literature suggests a RD&D focus on the lime and cement industry and on products and processes resulting in substantial CO_2 savings, particularly on those products with a strong capacity to store CO_2 over a long period of time such as buildings (adelphi & IASS, 2016) as well as on reducing energy demand for chemical conversion processes (Bazzanella & Krämer, 2017).

Textbox: Carbonation

The process of carbonation, also called mineralization, makes use of CO_2 as a feedstock. In this process, CO_2 is reacted with other substances (e.g. ash, sand) to certain carbonates / minerals. These minerals can, in turn, be used for developing cement- or concrete-like building materials. Carbonated cement can be mixed with ordinary Portland cement to realize a blended type of cement. Carbonation can also recycle former building materials, which would contribute to establishing a circular economy in the construction sector. However, research needs to advance this process, and regulations for building materials would have to be updated (Agora Energiewende & Wuppertal Institut, 2019; Ostovari et al., 2020; WWF, 2018).

As areas of research, the following are acknowledged by the Government (BMWi, 2019b):

- capture technologies for industrial plants,
- regional and European CCS/CCU infrastructure of other new CO_2 use options, and
- reducing CO_2 abatement costs.

Germany's research ministry BMBF funds research on CCU and PtX. For instance, several of the above-mentioned research projects have received funding by the ministry, including Carbon2Chem and Rheticus.

Another issue discussed is whether CCU technologies truly reduce environmental impact. Life-cycle assessments can help to figure out the environmental impact of CCU. Today, CCU-focused LCA-studies cannot be compared and are very complex, not least because several CCU-technologies are only in the development stage. Projects have been initiated to figure out what an LCA for CCU can look like (DG ENER, 2020; Müller et al., 2020).

Infrastructural issues

Infrastructural issues revolve around production sites, transport, demand centers for CO_2 use and capacities to store CO_2.

While industrial networks / clusters exist, where one industrial player can provide CO_2 to another one, as demonstrated by the Carbon2Chem project, these clusters are limited in quantity. This, in turn, raises questions regarding the development of a CO_2 infrastructure. If large quantities of CO_2 need to be transported from suppliers to storage or demand centers, a pipeline infrastructure might be a central option. However, fears exist that carbon capture technologies and particularly a pipeline-based infrastructure may result in lock-in effects, which keeps traditional business models alive while, hindering the realization of more climate-friendly solutions. In other words, once infrastructures are set up, their economic operation requires sufficient quantities of CO_2 to be transported. Avoiding such lock-ins must be part of a Government strategy, which must safeguard that the utilization of CO_2 does not go hand in hand with slower GHG reduction (adelphi & IASS, 2016; Ausfelder & Dura, 2019).

The lack of overall planning of a CO_2 infrastructure results in reluctance to invest in individual but interdependent links in CCUS value chains. For instance, companies wishing to capture CO_2 do not know whether infrastructural preconditions will be available once the investment is realized, while investors in transport and storage facilities remain in the dark whether and by when CO_2 delivery may begin. An opportunity can be to develop a so-called market facilitator, whose task is to "plan infrastructure projects, provide funding and assume liability and risks, so creating the necessary certainty and security for each link in the process chain" (acatech, 2019).

In a very rough estimation, CO_2 captured by the German cement and concrete industry would require 500,000 truck rides per year, even though CO_2 transport will need a more differentiated approach also including ships and, above all, a pipeline infrastructure as its backbone. Concepts for (trans-)regional CO_2-infrastructures would have to be developed (Verein Deutscher Zementwerke, 2020), which is also addressed through the program for CO_2 Avoidance and Utilization in Basic Materials Industries and reaffirmed by Germany's Industry Strategy 2030, both of which are, however, relatively little concrete (BMWi, 2019b; Federal Government, 2019).

Facilities to capture, utilize and store CO_2 require electricity based on renewables in order to have a climate effect. To apply CCUS, industry players require renewable energy to be available all over Germany. However, it has been estimated that very high amounts of electricity from renewable energy sources would be needed to achieve this, so that using the green electricity for substituting fossil fuels in other applications would have priority. This, in turn, shows that it is essential to have a CCUS strategy to be coordinated with renewable expansion planning (acatech, 2019). For decarbonizing cement and concrete, the respective association requests a renewable energy expansion to happen country-wide.

As regards CCS, potential onshore storage capacities in Germany exist, but given strong public resistance it is unlikely that these potentials will be realized. As long as these persist, undersea storage might be the better option despite higher costs, even though annual injection rates of different potential sites need to be taken into account (acatech, 2019, Wuppertal Institut 2012). Huge storage capacities in Europe exist beneath the North Sea and the Norwegian Sea.[10] If CO_2 storage is restricted to industrial emissions, these capacities will be sufficient for many decades (acatech, 2019; Federal Government, 2018).

Further regulatory issues

The legal regime for CO_2 pipelines is considered to be "rather rudimentary" reflecting the "lack of maturity and corresponding experience as well as the absence of mind of the legislator in regard to CO_2 transport" (Benrath et al., 2019). However, whether this weak CO_2 transport regime would prevent a valid business case from being realized has not been analyzed. While Germany's Carbon Dioxide Act (KSpG) introduced in 2012 allows the capturing and transportation of CO_2 in unlimited

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[10] For a discussion on blue hydrogen from Norway, see (Shibata et al., 2020).

quantities, the law *de facto* prohibits CO_2-storage onshore (acatech, 2019; Federal Government, 2018). At present, even discussions revolving around the production of blue hydrogen do not appear to open the door for an adjustment of this policy (Federal Government, 2020b). For transporting and particularly for storing large quantities of CO_2, a revision of the legal regime appears to be necessary. Another important legal challenge for the implementation of a European CCS infrastructure has been overcome in late 2019; the London Protocol, which forbade the transport of CO_2 from one country to another for offshore storage, does no longer stand in the way of cross-country CO_2 transport for offshore storage (IEAGHG, 2019).

Acceptance issues

Four projects initiated at the end of the 2000s originally aimed at storing CO_2 in geological formations onshore. Three of the four projects faced public resistance of people and societal groups in the respective region. These three projects sought to store CO_2 on a large scale and were led by industry players viewed critically by the people. In these contexts, communication and information campaigns did not result in higher acceptance. The only project that was largely accepted by the public was of scientific nature and limited in scope; both factors are assumed to have had a positive effect (Federal Government, 2018). It needs also to be acknowledged that CO_2-storage from power plants has alternatives such as increasing energy efficiency and the use of renewable energy. People living close to potential storage facilities located in the East and North of Germany felt to bear all the risks associated with CO_2 emissions mostly produced in Southern and Western Germany.

Moreover, the case in Germany has shown so far, that onshore storage is hardly accepted (Federal Government, 2018). Today, almost two thirds of Germans surveyed are either very concerned or fairly concerned as shown in the following figure.

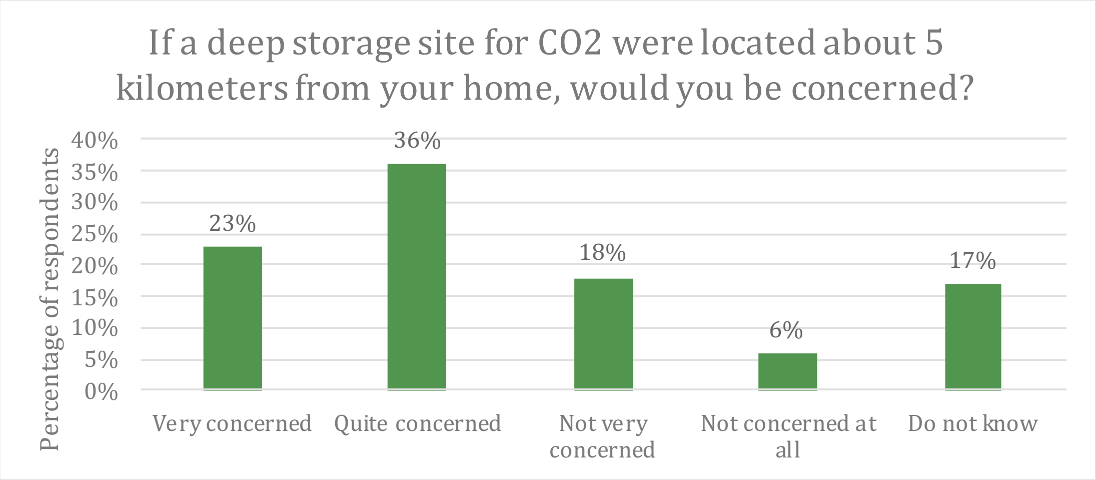

Figure 5: Public acceptance of CCS in Germany (based on Statista, 2021)

Literature indicates that public acceptance in Germany might be higher if industrial emissions are stored underground in comparison to emissions from power stations (Dütschke et al., 2016; Federal Government, 2018). However, in the end, it remains open whether old reservations can be overcome by a new approach to the overall debate on CCS, even though some environmental

NGOs today advocate CCS (WWF, 2019b). Still, it is seen as key to embrace societal actors in any further steps regarding CCS. Given the low acceptance of onshore storage, offshore storage is seen as a better alternative with higher monetary but lower political / acceptance costs.

CCU has, so far, not raised major public reservations (Federal Government, 2018), even though a flagship research project on Power-to-X financed by the Ministry on Education and Research distills two positions on the use of CO_2. While some argue for either using sustainably cultivated biomass and direct air capture as the only ways for the technology to operate in a climate neutral way in the long run, others embrace the role of industrial sources (Ausfelder & Dura, 2019). In how far these positions will feed into public discourse is unclear yet.

For the debate on CCU, it also needs to be acknowledged that CO_2 can be stored for very different time scales—from weeks to multiple decades, depending on the final product (e.g., synthetic fuels vs. materials in buildings). In particular, the role of CCU for synthetic fuels is debated as the fuel is combusted relatively quickly emitting the CO_2, which has captured originally. Apart from that, the expansion of renewables necessary to generate synthetic fuels is problematic (WWF, 2018).

3 Japan

3.1 Japan’s basic materials industries

Moving towards carbon neutrality has been accelerating globally. In October 2020, Japan jumped on the ‘net-zero bandwagon’ as Prime Minister Suga announced that Japan would achieve carbon neutrality by 2050. Hydrogen and carbon capture utilization and storage (CCUS) are critical technologies to reduce CO_2 emitted from the industry sector, for which it is hard to abate CO_2 emissions otherwise.

Similar to Germany, the basic material industries lead the manufacturing sector in Japan[11]. In 2018, the number of persons engaged was about 1.4 million and the value of manufactured goods shipments was JPY 62 trillion (EUR 480 billion) in these industries, equivalent to a share of 18% and 22% of the manufacturing sector, respectively (Ministry of Economy, Trade and Industry (METI), 2020b).

According to the preliminary data published by the Ministry of the Environment (MOE), Japan’s CO_2 emissions in fiscal year (FY) 2019 were 1,106 million tons, of which 93% were energy-related emissions. The industry sector accounted for the largest part of 39%, which consisted of 35% of energy-related emissions and 4% of industry process-related emissions (Figure 6: Key CO_2 emission data for industry in Japan (based on MOE, 2020).) (MOE, 2020). CO_2 emissions of the industry sector had gradually decreased due to improved CO_2 emission intensity per electricity generated and energy consumption decreases as a result of energy efficiency enhancement. Still, further efforts to mitigate CO_2 emissions are expected for the industry sector since they will affect whether or not Japan’s commitment to carbon neutrality would be achieved by 2050. Among others, the iron and steel industry and the chemical and petrochemical industry made up more than half of the CO_2 emissions of the sector. Then, hydrogen and CCUS have come into the picture to enable these industries to become carbon-neutral.

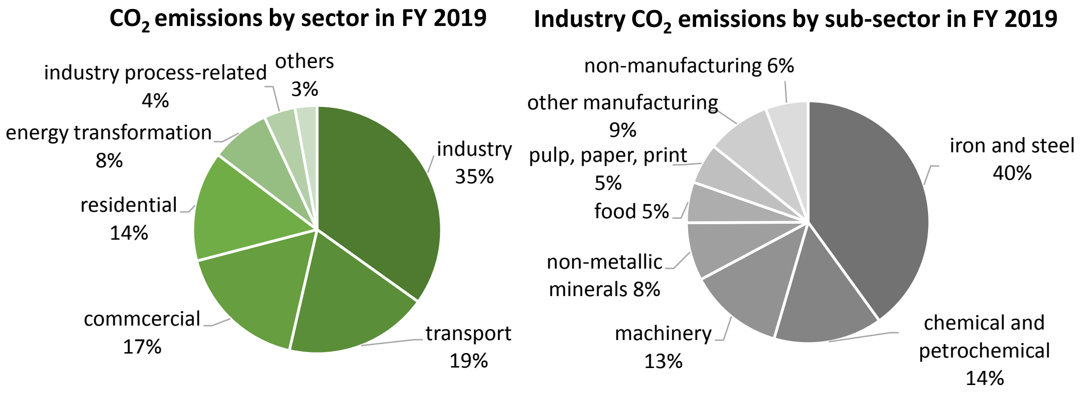

Figure 6: Key CO_2 emission data for industry in Japan (based on MOE, 2020).

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[11] The basic material industries include chemical, pulp/paper, and non-metallic minerals.

3.2 Hydrogen direct use

3.2.1 Strategy

Japan has developed its first Hydrogen and Fuel Cells Strategic Roadmap (mentioned as the "Hydrogen Roadmap" hereafter) in 2014, which has been revised twice in 2016 and 2019. Japan has also published the Hydrogen Basic Strategy (mentioned as the "Hydrogen Strategy" hereafter) at the end of 2017. In both the Hydrogen Roadmap and the Hydrogen Strategy, hydrogen's application in the industry sector was not mentioned much. The main focuses of hydrogen/fuel cell's application in Japan have been hydrogen power generation, fuel cell vehicles, and Enefarms (small scale fuel cell co-generation unit for households).

However, after the announcement of the carbon neutrality target in 2020, Japan's hydrogen strategy is likely to be revised significantly. One of the revisions would be hydrogen's application in the industry sector. In the Green Growth Strategy towards Carbon Neutrality by 2050 (mentioned as the "Green Growth Strategy" hereafter) published in December 2020, the Japanese government envisioned that by 2050 hydrogen's demand from industry sector could be 7 million tons/year (233 TWh/year[12]), combining with hydrogen consumption for power generation (5-10 million tons/year (167-334 TWh/year)) and for transport (6 million tons/year (200 TWh/year), especially trucks and buses), low-carbon hydrogen (including green and blue hydrogen) supply to Japan is expected to be around 18-23 million tons/year (600-767 TWh/year) (METI, 2020f).

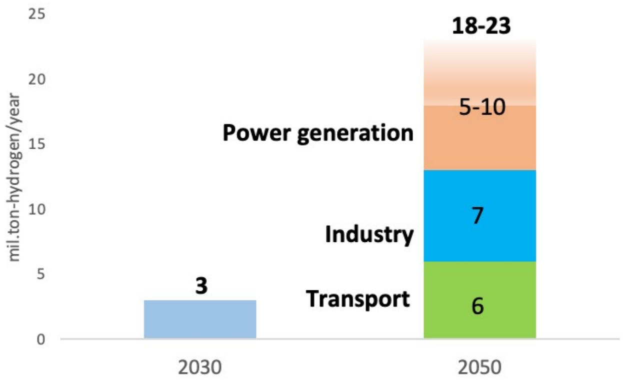

Figure 7: Hydrogen demand in Japan envisioned by the Green Growth Strategy (based on METI, 2020f).

3.2.2 Snapshots on research, development & demonstration

The Fukushima Hydrogen Energy Research Field (FH2R), located in Namie town Fukushima Prefecture, is the largest green hydrogen project operating in Japan. The system supplies electricity from a 20MW solar PV plant to a 10MW-class water electrolysis unit for green hydrogen production. The system has the capacity to produce, store, and supply up to 1,200Nm^3 hydrogen per hour. FH2R aims to maximize the utilization of renewable power despite its intermittency and to establish low-cost green hydrogen production without battery system.

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[12] Energy value of hydrogen (LHV): 120MJ/kg

Green hydrogen produced by the system will be used to power stationary fuel cells as well as to supply to hydrogen refuelling stations, and other applications including industrial sector. The project is supported by the New Energy and Industrial Technology Development Organization (NEDO) and is carried out by Toshiba ESS, Tohoku Electric Power Co., Inc., and Iwatani Corporation.

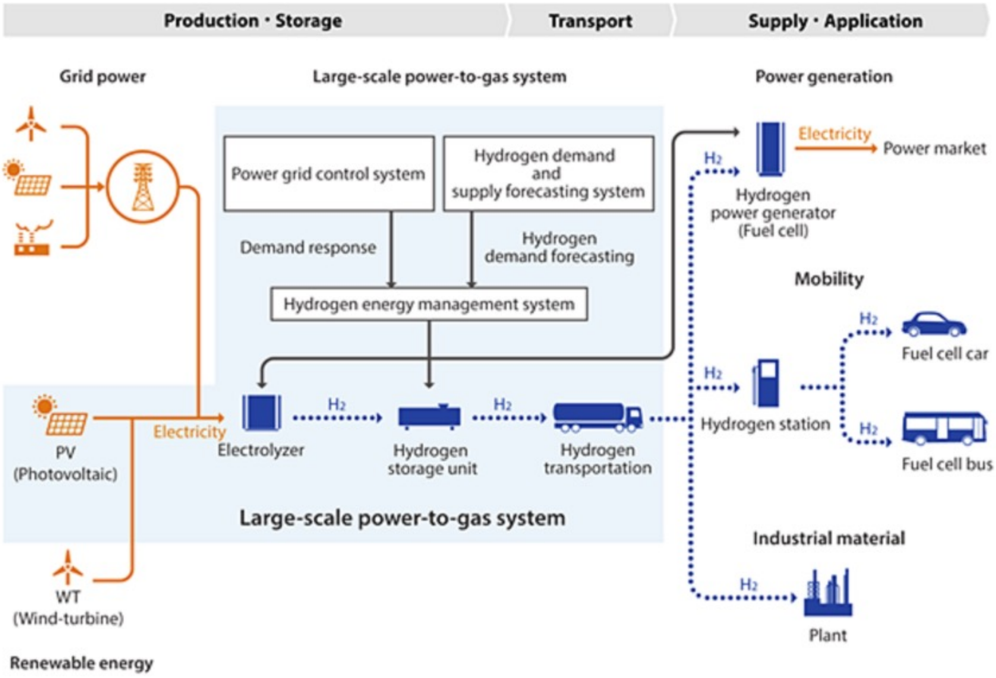

Figure 8: Framework of FH2R (Source: NEDO, 2020a).

One of the noteworthy projects on hydrogen's direct use in the industry sector is the COURSE50 (CO_2 Ultimate Reduction in Steelmaking Process by Innovative Technology for Cool Earth 50) initiative. The initiative started from 2008 and activities under the initiative are managed by the Japan Iron and Steel Federation. NEDO provides funds for the initiative. Hydrogen direct reduction and CO_2 capture are two pillars of COURSE50. The initiative aims to reduce CO_2 emission in steelmaking by 30% till 2030 and fully industrialize and adopt the new technologies by 2050. Japan's major steel makers are participating in the initiative.

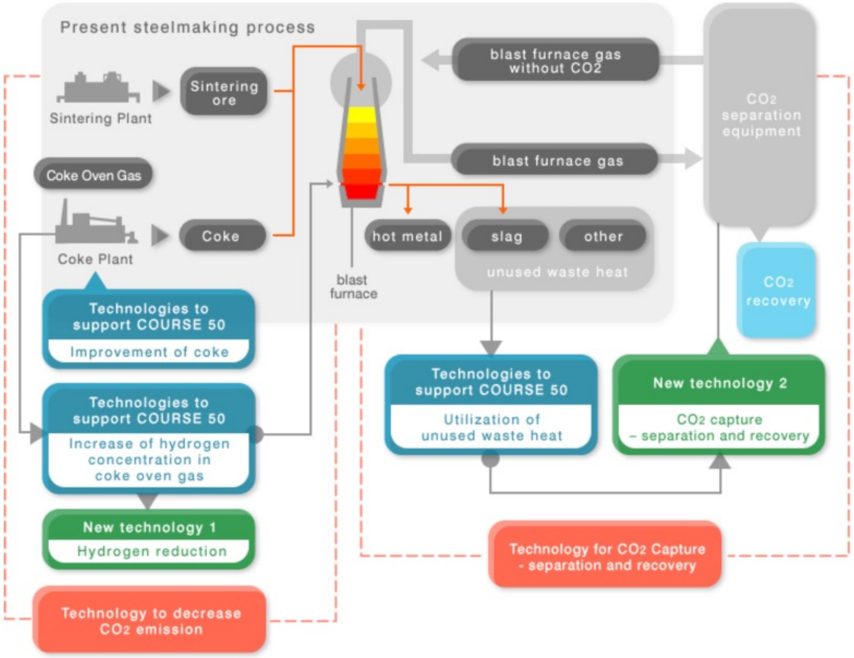

Figure 9: The COURSE50 Initiative (Source: Japan Iron and Steel Federation, n.d.).

The two cases mentioned above are all supported by NEDO, an agency overseen by the METI. Meanwhile, the MOE also implements a hydrogen demonstration program in cooperation with local governments. Main purpose of the MOE's program is to support domestic hydrogen production and hydrogen's application in local communities.

Table 3: Demonstration projects supported by the MOE

	Location	Partners	Source of hydrogen	Application	Scale	Period
1	Yokohama, and Kawasaki city	TOYOTA, etc.	Hydrogen produced by wind power	FC forklift	-Wind: 1980kW -Electrolyzer: 10Nm3/h -Trucks for hydrogen refueling: 270 Nm^3 * 2 units	FY2015~FY 2018
2	Hokkaido	Air Water, Kajima Corporation, Nippon Steel P&E, Air Products	Hydrogen production from biogas	Hydrogen Refuelling Station (FCV, forklift), and stationary hydrogen fuel cell	-Hydrogen storage at HRS: 739 m^3	FY2015~
3	Yamaguchi prefecture	TOKUYAMA, TOSOH, etc.	Byproduct hydrogen (NaOH)	HRS (FCV, forklift), Hydrogen FC , hydrogen pipeline	- Hydrogen FC: 100kW	FY2015~FY 2019

4	Kawasaki city at Kanagawa Prefecture	SHOWA DENKO, TOSHIBA, Daiwa House, MIZUHO	Hydrogen production from wasted plastic	Hydrogen supplied to hydrogen FC by pipeline Hydrogen supplied to HRS by trailer	-Hydrogen FC: supply 30% energy consumption at a hotel; -HRS: can supply hydrogen to 5~6 FCV per day	FY2015~
5	Hokkaido	TOSHIBA, Iwatani	Hydrogen production by micro hydro power	Hydrogen FC FCV	-Hydro power:200kW -Electrolyzer: 35 Nm3/h -Stationary FC: 100kW/7kW/3.5kW	
6	Miyagi	Hitachi, Marubeni	Hydrogen produced from power from rooftop Solar PV on a logistic center	Hydrogen storage and delivery: metal hydride Hydrogen FC installed at households, one super market, and one hospital		August 2017~
7	Akita	NTT data, Mitsubishi Kakoki Kaisha, OHMORI-KENSETSU, Dainichi Machine and Engineering, Aisin,	Hydrogen produced from wind power and battery storage	Hydrogen blended gas (hydrogen blended with domestic produced gas) that meets the city gas standard Testing the compatibility of the blended gas with gas appliances including gas stove, gas co-generation engine, small size gas boiler, and Enefarm	-Wind: 39.1MW -Battery: 24.192MWh	FY 2018~
8	Hokkaido	Taisei Corporation, Kyushu University, The Japan Steel Works, Ltd., Tomoe Shokai Co., Ltd.	Hydrogen produced from wind power	Low pressure hydrogen transport (metal hydride) Hydrogen supplied to stationary hydrogen FC	-Wind: 1,000kW -Hydrogen production: 1Nm3/h -Metal hydride tank: vehicle mounted 45Nm^3, fixed 45 Nm^3 -Hydrogen FC: 700W -Hydrogen transport vehicle: 2t (container attachable/removable)	FY 2018~
9	Fukuoka	Kitakyushu Power, IHI, Fukuoka Oxygen, ENEOS	Wind, solar PV, municipal waste power generation	Domestic low-carbon hydrogen supply chain Kitakyushu hydrogen town, hydrogen refuelling station		December 2020~

Note: HRS=Hydrogen Refueling Station; Hydrogen FC=Fuel Cell using pure hydrogen as input fuel; FCV=Fuel Cell Vehicle

(*Source: MOE, n.d.*)

3.2.3 Challenges and perspectives

Economic issues

Cost reduction of low-carbon hydrogen supply lies in the center of scaling up hydrogen application. Price target for low-carbon hydrogen supply is set at JPY 30/Nm^3-H_2 (around USD 3/kg-H_2) by 2030 and JPY 20/Nm^3-H_2 (around USD 2/kg-H_2) by 2050. However, in some cases the required price is even lower in the industry sector. For example, it is estimated that, for low-carbon hydrogen to be a competitive substitute of natural gas-based hydrogen, its cost needs to be less than JPY 20-25/Nm^3-H_2 (USD 2-2.5/kg-H_2) (METI, 2020c). And for the Iron and Steel sector, in order to make hydrogen direct reduction produced pig iron to be competitive with conventional product, the cost of hydrogen would need to be less than JPY 8/Nm^3-H_2(around USD 0.8/kg-H_2).

In Japan, future hydrogen supply will come from two sources: hydrogen produced by domestic green power, and low-carbon hydrogen imported from overseas. For either case, the cost reduction is challenging. Renewable power generation cost in Japan is among the highest in the world, which means domestic green hydrogen production cost is also high. For example, according to International Energy Agency (IEA), renewable power generation cost needs to be less than 4 cents/kWh[13] (IEA, 2019) to make green hydrogen production cost below USD 3/kg (the government hydrogen supply price target for 2030). However, even the future purchasing price targets for solar PV and wind (onshore) in Japan set by the government are about two times of that level.

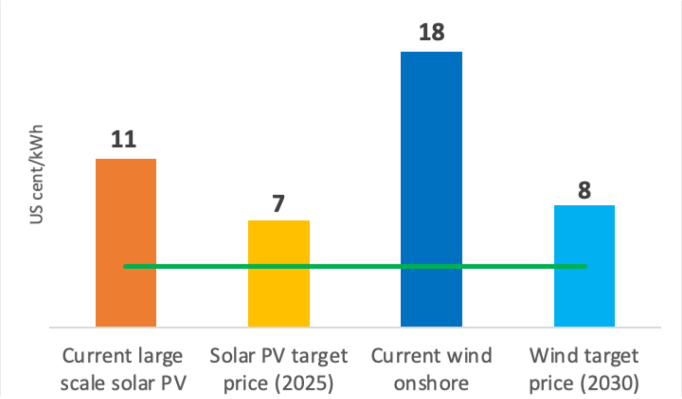

Figure 10: Renewable power price in Japan and the required renewable power price for green hydrogen to be competitive (based on METI, n.d.; METI, 2019a; METI, 2020a).

At the same time, although Japan has carried out several demonstration projects, international hydrogen supply chain has not been developed yet and drastic cost reduction is needed. For

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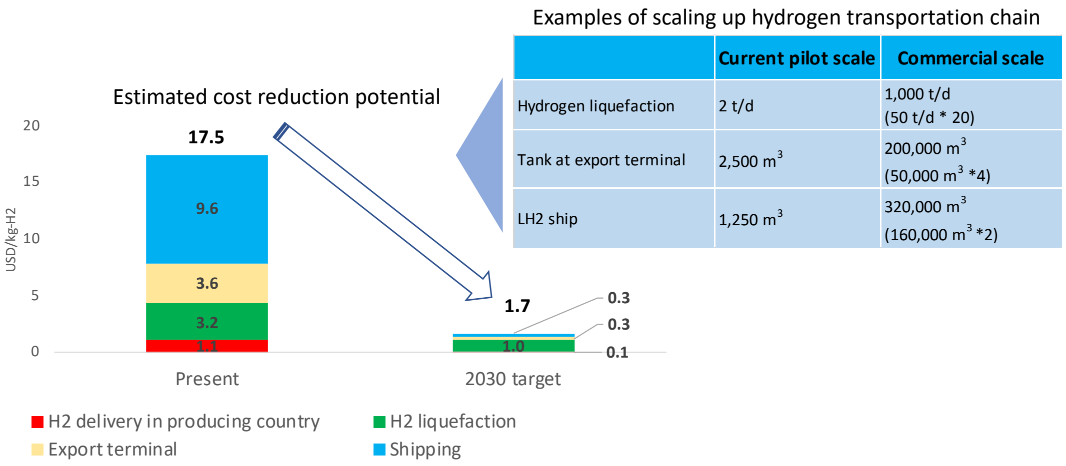
[13] Load hours 2000, CAPEX of electrolyzer USD 450/kW

example, based on the current pilot project scale, cost associated with liquefied hydrogen transportation is estimated at around USD 17.5/kg. To achieve the 2030's hydrogen supply price target the total transportation cost needs to be less than one tenth of the current level within the next decade and the cost reduction requires significant scaling up of the supply chain.



Examples of scaling up hydrogen transportation chain

	Current pilot scale	**Commercial scale**
Hydrogen liquefaction	2 t/d	1,000 t/d (50 t/d * 20)
Tank at export terminal	2,500 m^3	200,000 m^3 (50,000 m^3 *4)
LH2 ship	1,250 m^3	320,000 m^3 (160,000 m^3 *2)

Figure 11: Cost reduction of liquefied hydrogen transportation (based on METI, 2020e).

Technological issues

Hydrogen used in the industry sector (refineries, petrochemical facilities, etc.) today is almost fossil fuel based. Some of the hydrogen is a byproduct from industry processes and the replacement of this hydrogen with low-carbon hydrogen will require changes to the process. However, the non-byproduct fossil fuel-based hydrogen could be substituted by low-carbon hydrogen. For example, hydrogen consumption of Japan's biggest oil company, ENEOS, is around 6.6 billion Nm^3/year (around 0.6 million tons/year) in 2017, within which around 4.2 billion Nm^3/year (around 0.4 million tons/year) is byproduct from the refinery process and the remaining 2.4 billion Nm^3/year (around 0.2 million tons/year) is from outside of the process and can be replaced with low-carbon hydrogen (METI, 2020 c). It is estimated around 7.7 Nm^3/year (around 0.7 million tons/year) hydrogen demand in Japan's overall oil refineries could be replaced with low-carbon one by 2030 (METI, 2020c).

On the other hand, in the future, the Iron and Steel sector is supposed to be the largest industrial user of low-carbon hydrogen. As mentioned before, hydrogen's application in this sector is still at the research stage. Operation of the first prototype of the COURSE50 plant is expected to get started around 2030.

Other issues

Domestic infrastructure of hydrogen transportation and distribution will also be an important issue when the applications of hydrogen get further expanded. However, the natural gas pipeline in Japan is not as developed as that in Europe, and the discussion of converting current natural gas network to hydrogen transportation/distribution is at the very beginning stage (more details in the next chapter).

Furthermore, to facilitate low-carbon hydrogen's usage, clear ownership of its environment attribute will also be needed. This will require certificate of carbon footprint and origin of the low-carbon hydrogen. However, though there are some pilot projects on low-carbon hydrogen's certification system at the local level in Japan, there is still very little discussion at the national level.

3.3 Hydrogen natural gas blending

3.3.1 Strategy

In Japan's Hydrogen Strategy, there was little mention on hydrogen natural gas blend. Meanwhile, hydrogen natural gas blend is within the realm of policy discussions on decarbonization of the natural gas network. However, the discussions are still at the beginning stage. The Japan Gas Association envisioned that towards becoming carbon neutral by 2050, fossil fuel methane (natural gas) will be replaced by low-carbon gases including hydrogen, carbon neutral methane (low-carbon hydrogen methanation), and biogas. There is no pilot or demonstration project on hydrogen natural gas blend being used in the industrial sector in Japan at the moment.

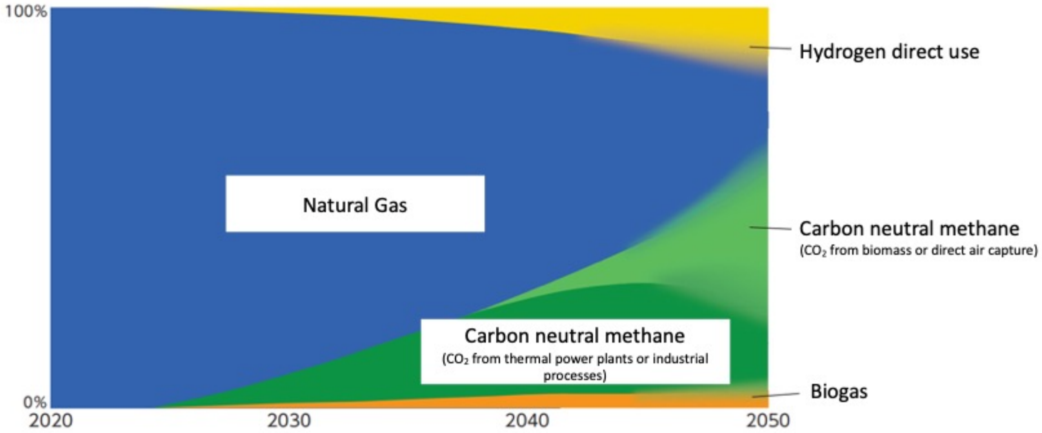


Figure 12: Gas Network's Decarbonization towards 2050 (based on Japan Gas Association, n.d.).

3.3.2 Challenges and perspectives

In Japan, technical readiness of natural gas pipelines for hydrogen blending is still mostly unknown. Hydrogen natural gas blend's impact on gas appliances, especially those which require strict heat control from certain industries, is one of the major concerns. In addition, hydrogen blending into natural gas may also affect some Enefarms' performance.

Meanwhile, discussions on the long-term strategy for decarbonization of the gas network system in Japan has just started. Lacking the clarity of the long-term policy strategy, the industry feels reluctant to make investment commitments. Furthermore, hydrogen is facing competition from other low-carbon gases such as biogas and carbon-neutral methane, which can be used with little technical changes to current infrastructure and gas appliances. The overall cost of hydrogen including fuel cost of hydrogen and the cost associated with infrastructure and appliances adaptation need to be competitive to other competing options. As mentioned before, hydrogen cost reduction for Japan is more challenging than other countries and this gives the gas utilities good reasons to have concerns on stable supply of low-cost hydrogen.

3.4 Carbon capture, utilization and storage

3.4.1 Strategy

While carbon capture and storage (CCS) is recognized to have potential for substantial reductions of CO_2, carbon capture and utilization (CCU) has also gradually received attention as one of effective means to fight against climate change in Japan.

In parallel with commercialized CCU technologies which include enhanced oil recovery (EOR) and direct utilization of CO_2 such as welding and dry ice, Japan specifically focuses on “carbon recycling” which is a concept of using CO_2 as an input (Figure 13: Concept of CCUS (Source: METI, 2019b, p.1).). In the carbon recycling system, CO_2 will be captured and then utilized to produce recycled materials and fuels by mineralization, artificial photosynthesis and methanation. Hence, utilizing recycled materials and fuels produced through the carbon recycling technology is expected to help the industrial process or transport sector to be decarbonized by replacing fossil fuels used conventionally before. Additionally, in case of Japan with heavy dependence on fossil fuel imports, the carbon recycling would enhance energy security since the new supply source for materials and fuels is secured domestically, which would consequently reduce the use of imported fossil fuels.

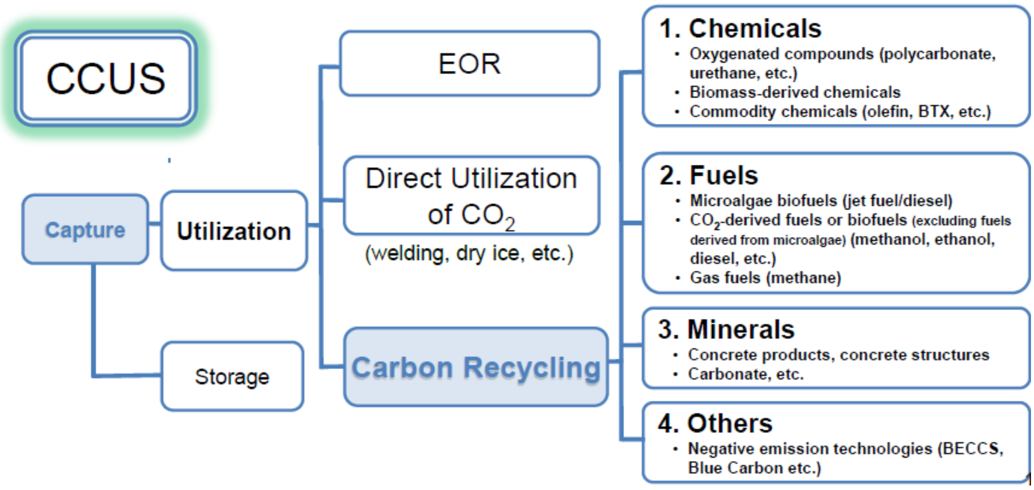


Figure 13: Concept of CCUS (Source: METI, 2019b, p.1).

The government of Japan gives principal support to CCUS technology development as it has been prioritized in the recent public policy domain. The 5th Strategic Energy Plan adopted in July 2018 aims for pursuit of all options regarding decarbonization technologies which cover hydrogen, CCS, and nuclear and renewable power, and collaboration on the development of these technologies through public-private cooperation (METI, 2018). CCS is also recognized as effective technology to reduce greenhouse gas emissions from the coal power plants, which will be included in the medium- and long-term power generation plan. Hence, with prospects for commercialization, the government directed a demonstration project of a whole CCS process from capture, through transportation, to injection and storage as illustrated in the next section.

The Long-term Strategy under the Paris Agreement approved by the cabinet in June 2019 identifies CCUS including carbon recycling as one of the key technologies to achieve the ultimate goal of a "decarbonized society[14]" (the Government of Japan, 2019). CCS and CCU are emphasized in the long-term vision and direction of policies and measures of the energy and industry sectors. For the energy sector, in the context of CO_2 emission reductions from the thermal power plants, the government aims to establish the first commercial-scale CCU technology by 2023 with a vision of deployment after 2030. The industry sector envisages utilization of low-carbon hydrogen and substitution by CCU, particularly carbon recycling, and biomass for fossil resources as feedstock in order to reduce CO_2 emissions from the manufacturing process.

In June 2019, the Roadmap for Carbon Recycling Technologies was published to show the path to commercialization of potential technologies in the three main areas of chemicals, fuels, and minerals (METI, 2019b). The carbon recycling technology is expected to encourage research and development (R&D) and innovation on CO_2 utilization through collaborations among industries, academia, and governments across the world. The roadmap presents technological challenges and the target by 2030 and 2050 onwards by technology. The short-term target covers technologies which will require no hydrogen, produce high-value added materials such as polycarbonate, bio-jet fuel, and road curb blocks, and are expected to be deployed around 2030. The long-term target after 2050 expects commercial deployment of high-demand commodities such as olefins and BTX (benzene, toluene, and xylene) on the condition that the hydrogen supply cost is decreased to JPY 20 (EUR 0.15)/Nm^3.

The roadmap is illustrated in three phases (Figure 14: Carbon Recycling Roadmap (Source: METI, 2019b, p.2).). Phase 1 up to 2030 pursues research, development and demonstration (RD&D) which will advance carbon recycling technologies. Phase 2 (around 2030) aims to reduce costs of technologies targeted in Phase 1 for commercialization and continues technology development and innovation to achieve the long-term target. In Phase 3 (2050 onwards), products and technologies developed through the carbon recycling initiative are to be utilized widely at affordable costs.

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[14] The "decarbonized society" means "achieving a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century." (the Government of Japan, 2019)

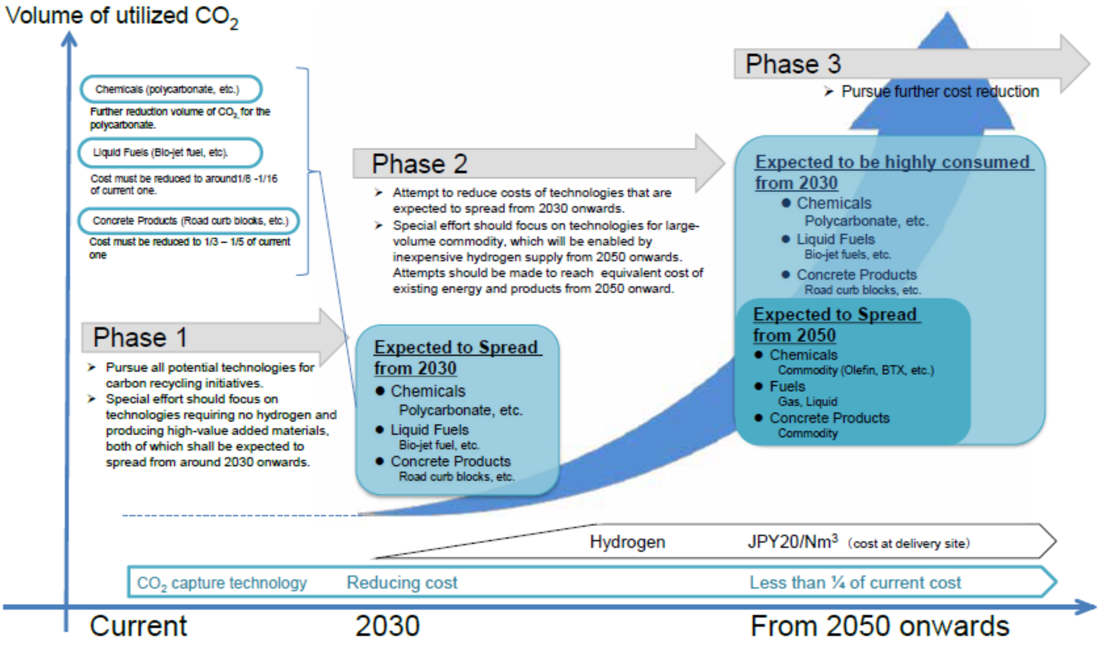

Figure 14: Carbon Recycling Roadmap (Source: METI, 2019b, p.2).

Based on the Long-term Strategy under the Paris Agreement and the Integrated Innovation Strategy 2020[15], the Environment Innovation Strategy was formulated in the fields of energy and environment in January 2020 (Cabinet Office, 2020). This strategy consists of the Innovation Action Plans, the Acceleration Plans, and the Zero-Emission Initiatives. The Innovation Action Plans put priority on the five areas in which the technology related to CCUS is included along with the other focuses (non-fossil fuel energy, energy network, hydrogen, and zero-emission agriculture, forestry and fishery). The second pillar of the strategy are the Acceleration Plans which develop various research frameworks and promote private investment to facilitate the Innovation Action Plans. For instance, the first Green Innovation Strategy Meeting which oversees inter-agency initiatives was held on July 2020 for the effective implementation of the R&D projects. In addition, Hiroshima-Osakikamijima Carbon Recycle Research, Development and Demonstration Base presented in the next section is supported within this framework. Lastly, the Zero-Emission Initiatives are collaborative works and outreach activities to share information and innovative technologies and strengthen international cooperation. Under this initiative, the Government of Japan hosted the International Conference on Carbon Recycling in two consecutive years 2019 and 2020. Carbon Recycling 3C Initiative was announced to accelerate innovation in light of the Roadmap for Carbon Recycling Technologies at the first conference.[16]

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[15] The Integrated Innovation Strategy is devised annually under the Science and Technology Basic Plan.

[16] The 3C of this initiative signifies three actions. First, “Caravan” (promotion of mutual exchange) presents to disseminate the importance of carbon recycling and share the progress of technology development through international conferences. Network development and information sharing are also included. Second, “Center of Research” (establishment of R&D and demonstration base)

The latest policy development is the Green Growth Strategy that Japan revealed in December 2020 (METI, 2020f). This is an industrial policy to lead the challenging goal of achieving carbon neutrality by 2050. This strategy identifies 14 industries including carbon recycling as important areas that have potentials of green growth and are indispensable to reach the carbon neutrality goal by 2050, and specifies an action plan and a target for each area. The carbon recycling area specifically focuses on concrete, microalgae biofuel, plastics produced through artificial photosynthesis, and technology to capture CO_2 from air. The government will leverage various policy tools to promote the green growth, such as funding of JPY 2,000 billion (approximately EUR 15 billion) for technology development for the next decade, tax incentives and regulatory reforms (METI, 2021).

The private sector is also interested in development of carbon recycling technologies. In August 2019, the Carbon Recycling Fund Institute was established to accelerate innovation of carbon recycling technologies (Carbon Recycling Fund Institute, n.d.). As of December 2020, 64 companies or organizations and 12 individuals have a membership of the Institute. Since the carbon recycling technologies can be applied in many sectors, the members participate from a wide range of industries including chemicals, steel, construction materials, fuels, engineering, financial institutions, trading companies, and universities. In FY 2020, 12 research projects were selected for the research grants (METI and NEDO, 2020).

3.4.2 Snapshots on research, development & demonstration

(1) Tomakomai CCS demonstration project

Commissioned by METI and NEDO, Japan CCS Co., Ltd has conducted the first large scale CCS demonstration project in Tomakomai, Hokkaido, from FY 2012 to FY 2020. This demonstration project aimed to establish the first integrated CCS system in Japan from CO_2 capture to storage with commercial-scale facilities. CO_2 generated from a hydrogen production unit in the Idemitsu Kosan Hokkaido Refinery was captured. It also intended to prove safety and security of a whole CCS system and make the public informed and understood about this project through information disclosure and activities to enhance social acceptance, while acquiring skills in operation of the CCS system to prepare for an opportunity when CCS is to be commercialized (METI, NEDO, and Japan CCS, 2020a).

Figure 15: Tomakomai CCS demonstration project (Source: METI, NEDO, and Japan CCS, May 2020b). shows how this CCS project was operated. A portion of PSA (Pressure Swing Absorption) off-gas containing about 52% of CO_2 generated from a hydrogen production unit of the refinery was transported by a 1.4 km pipeline to the facilities where CO_2 was captured. Then CO_2 is compressed, injected and stored 3-4 km offshore in two sub-seabed reservoirs of different depth.

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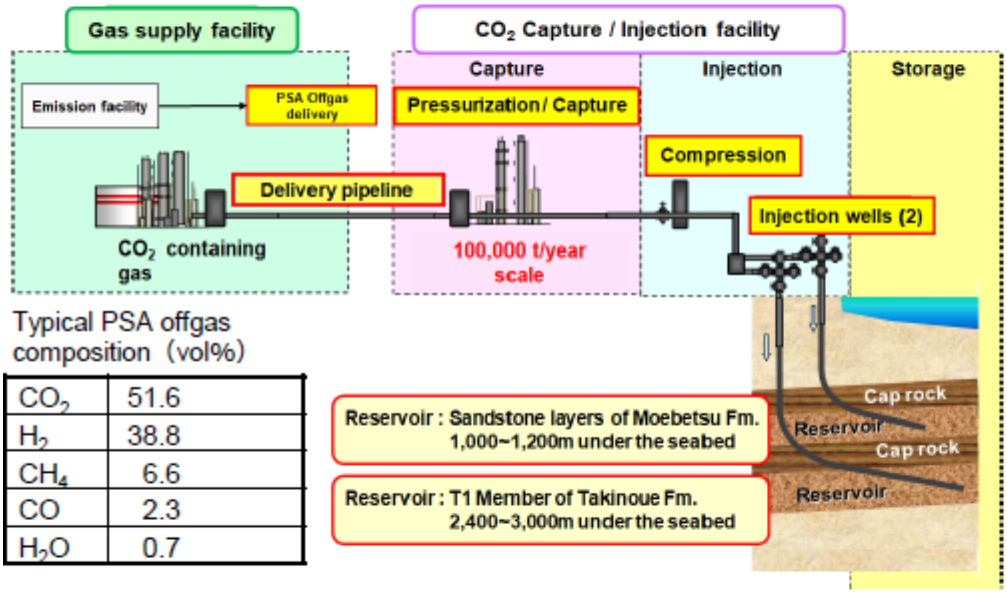
emphasizes on research of carbon recycling technologies and development of an environment for scale-up and commercialization. Third, “Collaboration” (promotion of international joint research) pursues enhanced collaboration among partners including industry, academia, and government and international joint research.



Typical PSA offgas composition (vol%)

CO_2	51.6
H_2	38.8
CH_4	6.6
CO	2.3
H_2O	0.7

Figure 15: Tomakomai CCS demonstration project (Source: METI, NEDO, and Japan CCS, May 2020b).

The first four years were spent to prepare for the demonstration such as construction of facilities and drilling of injection wells. CO_2 injection started with the volume of 100,000 tons per year in April 2016 and reached the targeted amount of 300,000 tons in total in November, 2019 although the CO_2 injection took longer than the initially planned period of three years due to external factors. Data collected from monitoring showed no irregular change in pressure and temperature of the reservoirs, no indication of micro-seismicity or earthquake caused by CO_2 injection, and no CO_2 seepage. The marine environmental surveys did not find any indication of negative impacts like CO_2 leakage, either. Hence, the study result confirmed safety and security of the CO_2 injection and storage in the demonstration project.

While the monitoring of the CCS site will continuously be conducted, the study on CCS is also planned to overcome the obstacles and to enable the CCS system to be commercialized and scaled up. The subjects of the study include identification of suitable sites for CO_2 storage, technology development of long-distance CO_2 transportation, appropriate monitoring technologies and methods, and cost reductions. Furthermore, the CCS facilities in Tomakomai will be utilized to study the effective use of the CO_2 captured such as the synthesis of basic substances (e.g. production of methanol).[17]

(2) Hiroshima-Osakikamijima Carbon Recycle Research, Development and Demonstration Base

Osakikamijima town, Hiroshima Prefecture, is designated to establish a carbon recycling RD&D hub. In this area, a demonstration project of an oxy-fuel integrated coal gasification combined cycle (IGCC) and an integrated coal gasification fuel cell combined cycle (IGFC), which is called the

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[17] To support the next phase of the facilities, the Tomakomai CCS Promotion Council was reorganized to the Tomakomai CCUS/Carbon Recycling Promotion Council in September 2020.

Osaki CoolGen project, has been carried out since FY 2012. After performance of oxy-fuel IGCC was tested in the first phase, the Osaki CoolGen project has moved to the second and third phases which handle the demonstration of oxy-fuel IGCC with CO_2 capture and IGFC with CO_2 capture, respectively (Osaki CoolGen Corporation, n.d.). Meanwhile, the carbon recycling RD&D hub intends to effectively utilize the CO_2 captured in the Osaki CoolGen project (Figure 16: Schematic of Hiroshima-Osakikamijima Carbon Recycling RD&D Base (Source: Cabinet Office, 2020, p.69).).

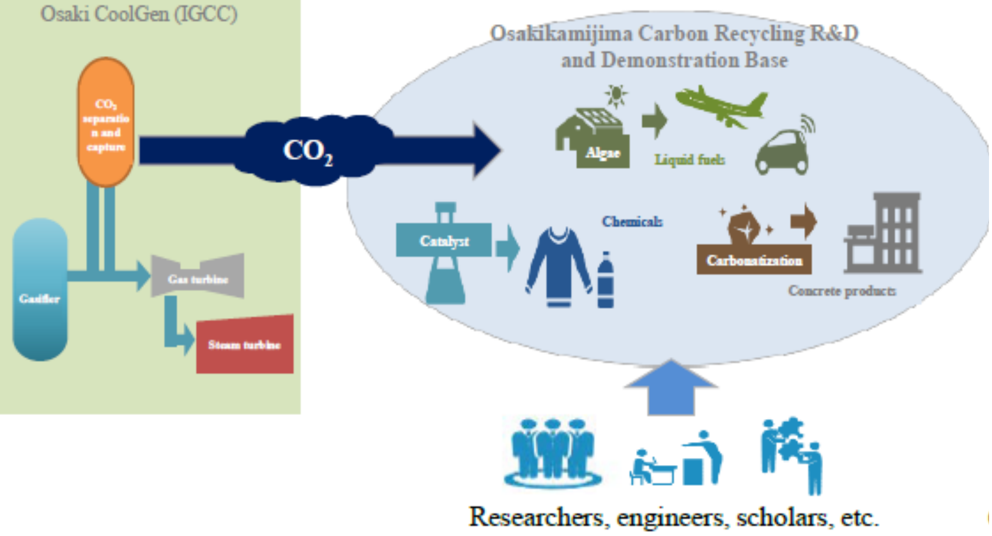

Figure 16: Schematic of Hiroshima-Osakikamijima Carbon Recycling RD&D Base (Source: Cabinet Office, 2020, p.69).

This carbon recycling RD&D hub is planned to have three areas. The 'basic research area' and 'demonstration research area' cover a wide range of R&D such as chemicals and minerals (concrete) whereas the 'algae research area' lays the foundation for research on microalgae (METI and NEDO, 2020). In August 2020, NEDO announced the funding of approximately JPY 6 billion (about EUR 46 million) for FY 2020-2024 to help the Osakikamijima carbon recycling RD&D base to be established for cross-cutting research and technology development in order to utilize CO_2 (NEDO, 2020b). Five projects are selected under the two themes. One subject is to develop facilities and infrastructure and assist management and research activities of the research center. The other focuses on technology development on CO_2 utilization and assessment of commercial feasibility and effectiveness of carbon recycling technologies.

(3) CO2-SUICOM

A concrete product that utilizes CO_2 in the production process has already been commercialized in Japan. The product name is CO2-SUICOM, an acronym of CO_2-Storage Under Infrastructure by Concrete Materials (Yoshioka et. al., 2013).[18] Two distinctive measures in manufacturing this concrete enable CO_2 emission reductions (Figure 17: Schematic of CO2-SUICOM (based on Kajima

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[18] The Chugoku Electric Power Co. Inc, Kajima Corporation and Denka Co., Ltd. jointly developed this technology.

Corporation, n.d.).). First, instead of cement, a special admixture (the γ phase of dicalcium silicate (γ-2CaO.SiO2), described as ‘γ-C2S’ hereafter) which has a lower level of CO_2emissions than cement is used for CO2-SUICOM. This special admixture γ-C2S helps concrete to be solidified by reacting to CO_2 and is made from a by-product such as slaked lime at chemical plants. In addition, coal ash can be a substitute for cement to produce this new concrete. Therefore, the process in which much of cement can be replaced by γ-C2S and coal ash contributes substantial reductions of CO_2 emitted from cement production. Second, CO_2 captured from exhaust gases of coal-fired power plants is utilized for carbonation curing of the concrete by making use of a feature of γ-C2S. As a result, not only coal ash but also CO_2 from the coal-fired power plants is utilized efficiently.

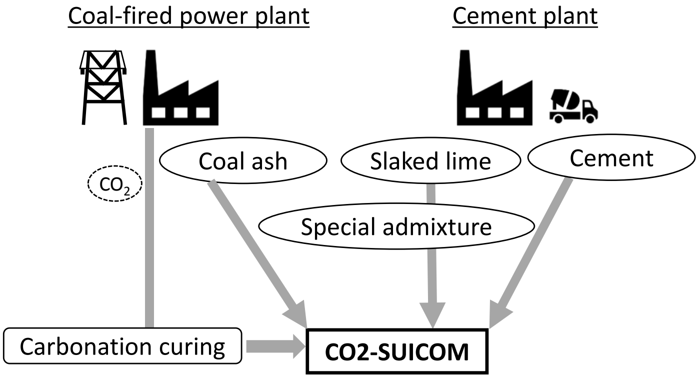

Figure 17: Schematic of CO2-SUICOM (based on Kajima Corporation, n.d.).

The estimation shows that these two processes result in substantial CO_2 emission reductions compared with that of ordinary concrete (Figure 18: CO_2 emissions in concrete production (based on Kajima Corporation, n.d.).). Moreover, this concrete is able to resist efflorescence and abrasion as much as the ordinary one.

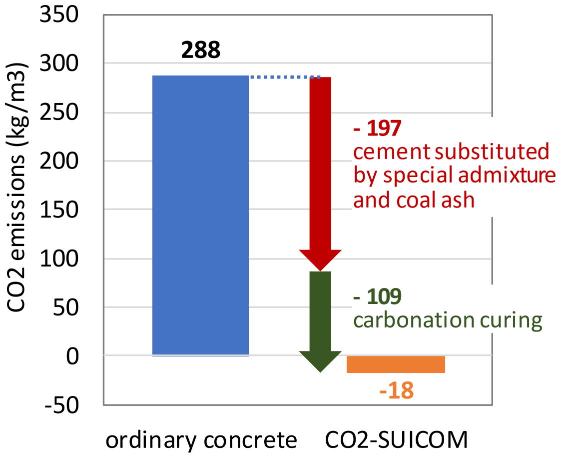

Figure 18: CO_2 emissions in concrete production (based on Kajima Corporation, n.d.).

Although this is available technology to reduce CO_2 emissions in the cement production, the special admixture and process make the production cost high. While CO2-SUICOM has been used in construction work as boundary blocks, foundation blocks, and paving blocks, it is difficult to apply to reinforced concrete and cast-in-place concrete (Challenge Zero, n.d.). Therefore, further technology development is necessary for cost reductions and wider applications.

(4) Technology Development for Para-xylene Production from CO_2

Assisted by NEDO, a group of a university and private companies launched a project named Technology Development for Para-xylene Production from CO_2 in July 2020 (HighChem et.al., 2020).[19] This project aims to improve the innovative catalyst for the production of para-xylene from CO_2, develop a method to mass-produce the catalyst and the process and design, and conduct a feasibility study to prepare for the demonstration stage. Para-xylene is a basic compound in the production of PTA (pure terephthalic acid), which is a feedstock material for polyesters. This carbon recycling technology is expected to have economic and environmental advantages in that it can be produced with a relatively small amount of hydrogen while fixing a large amount of CO_2. This project will be conducted by FY 2023.

3.4.3 Challenges and perspectives

Economic issues

Commercial feasibility is one of the major difficulties that stand in the way of CCS deployment. While Japan has provided assistance towards RD&D on CCS technology, financial measures such as tax credits and subsidies are not put in place yet. For CO_2 storage, in general, if EOR is adopted, economics of CCS projects is likely to improve because it could generate revenues from oil production. As of 2019, CO_2 is injected and stored through EOR in 15 facilities out of 19 CCS large scale facilities (more than 400,000 tons of CO_2 captured per annum) in operation worldwide (Global CCS Institute, 2019). However, appropriate sites for CCS with EOR are likely to be limited. To relieve the economic constraints, financial measures are helpful to encourage CCS development. For instance, the United States, a pioneer of CCS, has provided not only financial supports for construction or operational costs of facilities but also tax credits.[20] These kinds of incentives will be required to make a CCS project feasible in Japan.

The CCUS technologies are not exceptional in that cost reductions are the hurdle to overcome just like other new technologies in the early stage of development. While chemicals and fuels produced from CO_2 through specific treatments are expected to be put in the market and yield revenues, they are not cost competitive due to the production process which keeps the products expensive. To make CCUS technologies competitive and affordable, it is critical to secure

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[19] University of Toyama, Chiyoda Corporation, Nippon Steel Engineering Co., Ltd., Nippon Steel Corporation, HighChem Company Limited, and Mitsubishi Corporation participate in the project.

[20] In the United States, Section 45Q of Internal Revenue Code provides a tax credit on a per-ton basis for CO_2 sequestered. The tax credit is USD 35 per metric ton of CO_2 stored for EOR and USD 50 per metric ton for geologic storage by 2026 (US Department of Energy, 2019).

hydrogen at reasonable cost, ensure deeply decarbonized hydrogen, and reduce costs of the CO_2 sequestration and capture process.

Technological issues

As most CCUS technologies have not reached to the maturity levels, technology development and innovation need to be pursued to reduce costs and to make the technologies more applicable and available. As for CCS, technology development of capturing CO_2 will hold the key to lower costs since the cost of carbon capture process makes up the major part of overall CCS costs. The pre-combustion capture technology was adopted in the Tomakomai CCS demonstration project. The next challenge is to apply this technology to facilities where concentrations of CO_2 are lower at reasonable cost, which will pave the way for further deployment of the technology. For this application, hydrogen or ammonia production facilities and power plants with integrated coal gasification combined cycle are considered to have potentials.

To foster deployment of CCS, scaling up of a CO_2 storage capacity is necessary in Japan and technology enabling efficient operation of CO_2 injection and storage is vital for cost reductions. Japan also needs to establish safety and reliability of CO_2 storage technology in order to conduct a commercial CCS project and enhance public acceptance. There are risks of CO_2 leakage from the stored site underground and, in case of Japan, possible impacts to the CO_2 storage caused by earthquake have to be taken into consideration. To ensure safety of CO2 storage starts with appropriate storage site selection, which necessitates thorough geological assessment. In addition, monitoring technology improvement is critical to detect CO_2 seepage in the subsurface and to collect data as accurate as possible for further study.

Although CCU technologies are expected to reduce CO_2 emissions, it is important to evaluate CO_2 emissions in the whole supply chain. It does not make sense if the amount of CO_2 emitted from the conversion process to chemicals and fuels is larger than the reduced volume of CO_2 through the CCU technologies. Since CO_2 is a stable molecule, substantial energy is required to split CO_2 and synthesize products from CO_2. Therefore, life cycle assessment (LCA) of the CCU technology is necessary to prove effectiveness of the technology. It is difficult to compare CO_2 emissions of chemicals and fuels produced by means of the carbon recycling technology since there are no consistent rules to evaluate CO_2 emissions based on LCA. Therefore, the carbon recycling technology necessitates development and establishment of rules which are approved internationally to measure CO_2 emissions based on LCA, since this is important to prove how much CO_2 emissions would be reduced in society overall. In addition, hydrogen used for this process should be carbon-free, that is, grey hydrogen derived from coal and natural gas are definitely not preferable.

RD&D on carbon recycling technologies are making progress and the following two cases present the recent development in Japan.

In October 2020, the first case of bio-energy with carbon capture has started operation in Fukuoka Prefecture (Toshiba Energy Systems & Solutions, 2020a). A large-scale carbon capture facility sequestrates more than 500 tons of CO_2 per day, which is more than 50% of daily emissions from the power plant with a capacity of 50MW. Fueled with palm kernel shells as the primary fuel source, this power plant is considered carbon-neutral.

Another new development is that six private companies reached an agreement to jointly develop fuel derived from CO_2 in December 2020 (Toshiba Energy Systems & Solutions, 2020b). These companies will review supply chains of sustainable aviation fuel (SAF) which is produced from CO_2 separated and captured from sources such as exhaust gases of industrial emitters, using technologies developed by Toshiba Corporate Research & Development Center which convert CO_2 to CO through electrolysis. This SAF will be supplied for flights in aviation, which will help decarbonize the aviation industry.

Infrastructural issues

Transport infrastructure is fundamental to deliver CO_2 that is captured at an industrial factory or a power plant to a permanent storage site or to a facility which produces chemicals or fuels. For CCU, hydrogen transport also needs dedicated infrastructure to a manufacturing place. Nevertheless, it is unlikely that the transport infrastructure of CO_2 and hydrogen would be developed when commercialization of CCUS is uncertain yet. Rather CO_2 infrastructure would work in the form of a natural monopoly where a single operator could bring benefits and efficiency to the market than multiple competitors due to high initial costs and economy of scale (IEA, 2020). In addition, there are risks of CO_2 leakage that will put an extra burden on the private sector. To assist the private sector who is interested in CCUS, the government could provide supports such as planning, financing and risk management related to CO_2. One possibility is that the government could plan to set up an industrial CCUS hub so that the private companies would benefit from economies of scale in capturing CO_2 with shared transport and storage infrastructure.

Japan needs more information and evaluation about different cases of CO_2 transport. The assessments conducted in the Tomakomai CCS demonstration project did not include the pipeline transport process. Large volumes of CO_2 could be transported either by pipeline or ship. If offshore CO_2 storage is planned in the future in Japan, both onshore transport and offshore infrastructures with regards to CO_2 transport and storage need to be considered. It is necessary to conduct more demonstration projects that deal with CO_2 transport by pipeline and ship under various conditions to collect data and information for evaluation.

Regulatory issues

Although CCS has been focused by the government of Japan, there are no specific rules applicable to a CCS project. The Tomakomai CCS demonstration project was conducted in compliance with the existing laws/regulations. In specific, the CO_2 capture facilities followed the High Pressure Gas Safety Act, the Industrial Safety and Health Act and the Gas Business Act while the Mining Act and the Mining Safety Act were applied to CO_2 injection and storage facilities and safety standards of the injection operation. The Act on Prevention of Marine Pollution and Maritime Disaster was applied to CO_2 storage in the subsurface and the marine environmental surveys.

However, these regulations do not cover all issues about the demonstration project extensively. For instance, the Act on Prevention of Marine Pollution and Maritime Disaster allows the chemical absorption using amine-based solvents only as the carbon capture technology in the subsurface (Research Institute of Innovative Technology for the Earth, 2020). Other CO_2 capture technologies which can be applied in the sub-seabed are not approved within the current legal system in Japan as they are still in the early adoption stage and there are not enough scientific data and information for validation. This implies that law amendment or new regulation will be necessary if CO_2 is captured by other technologies such as physical separation and membrane separation for injection and storage in the sub-seabed. Also, the demonstration project found that some indicators based on the Act were not effective to detect CO_2 leakage in the marine environmental surveys.

Furthermore, one of the important legal aspects with regards to the CCS project is absent in the existing legal context. In other words, long-term liability for a storage site and stored CO_2 and transfers of liability are not specified in the current regulatory framework in Japan. In general, long-term liability refers to “any liabilities arising after the permanent cessation of CO_2 injection and active monitoring of the site” and an issue in question is centered on “whether responsibility for liabilities associated with a storage site should be transferred to government or retained by operators indefinitely” (IEA, 2011). It is difficult to prove that CO_2 stored underground will not be leaked in the very long-term even though it is possible to contain CO_2 in the subsurface completely for a foreseeable future. Therefore, it is vital to clarify who will be held liable and to clearly stipulate certain requirements or conditions if responsibility for liabilities are transferred to the government at some point. There is one more issue identified in CO_2 storage of the demonstration project, which is lack of rules about subsurface access rights. To define where subsurface access rights belong will be necessary for drilling of injection wells and CO_2 storage.

Acceptance issues

Public acceptance is a necessary condition to implement a CCS project. In spite of the CCS demonstration project backed by the government and its high potential to reduce CO_2 emissions, it seems that the level of awareness and knowledge about CCS has been low in Japan. The questionnaire surveys which were conducted in 2010, 2013 and 2015 found that public acknowledgement about CCS had remained low (Kubota, 2016). In a question about the CCS technology in the 2016 survey, the share of the respondents who answered “know about CCS” or “know about it well enough to explain to the others” was merely 8.1%, whereas those who had never been aware or heard of it accounted for 55.1%, and those who had heard of the word “CCS” made up 36.8%[21]. The study also revealed that even those who thought that they knew about CCS did not understand correctly what the CCS technology was. The Tomakomai CCS demonstration project had attempted various activities to improve public awareness such as site tours, publications, lectures at school or forum, and events for children throughout the project period. So far, it was not enough for CCS to be properly understood nationwide. Lack of information is an obstacle to transparency and accountability of the CCS project, making it more difficult for the

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[21] The number of respondents were 3,912.

public to make a decision whether or not to accept the CCS project. Therefore, public awareness about CCS needs to be enhanced by providing correct information through various tools.

4 Comparison of strategies, activities, and perspectives

In Germany and Japan, the basic materials industries are relevant economic sectors resulting in significant shares of greenhouse gas emissions. Almost 37% and 39% of total emissions in the country come from the German and Japanese industry, respectively, to which basic materials industry contributes relatively large shares. In Germany, industry emissions split into direct emissions (around 22%) and indirect emissions from energy supply (below 15%). Industrial direct emissions are mostly energy-related (68%) with process-related emissions being at around 32%. In Japan, 90% of industry emissions are energy-related. Hence, decarbonising these sectors is particularly relevant to achieve carbon neutrality by 2050. However, neither Japan nor Germany have favorable conditions to generate renewable energy on a large scale domestically. This exacerbates the decarbonization of the industry sector as relevant options discussed in this study would require green electricity as energy input, either for direct use, for producing hydrogen or for removing CO2 from industrial plants. Clean hydrogen is the other form of energy or raw material needed in large quantities for decarbonizing industry, as discussed in this study.

Regarding **direct use of hydrogen**, Japan's hydrogen strategy, published a few years ago, has so far focused on power generation, transport/FCV and Enefarms, its role for decarbonizing industry recently receives more and more attention, e.g. as part of Japan's Green Growth Strategy. Policy focuses on facilitating RD&D and improving investment environment through various policy tools such as funding, tax incentives, and regulatory reforms.

Germany has only recently published a relatively comprehensive strategy on hydrogen (NHS), which prioritizes the role of industry for creating demand for the hydrogen. Hydrogen should be green with priority, but blue hydrogen is acknowledged as a transitory solution too. While the NHS includes expansion targets for installing electrolyzers in Germany, natural gas is seen as a bridge for the transition by some. The NHS has installed a steering committee, which supports hydrogen developments in Germany, and sketches policy instruments that facilitate the application of hydrogen in the industrial sector. Policy discussions also revolve around the support needed by the industry for achieving carbon neutrality in the next decades and around hydrogen transport as well as ideal production locations. Germany is more advanced in large-scale RD&D projects for the direct use of hydrogen in the refinery, chemical and steel industries. In contrast, demonstration projects on large-scale direct use of hydrogen are limited in the industry sector in Japan, and small-scale projects of hydrogen applications focus more on the transport and residential/commercial sectors in local communities.

For both countries, scenarios suggest an enormous demand for hydrogen in industry. However, costs for domestic production and for (ship) imports will remain a key challenge. From a technological perspective, the two countries are also likely to face the problem that hydrogen direct-use will require adjustments in manufacturing processes.

The **blending of hydrogen with natural gas** is approached differently by each country. It is less discussed in Japan, also due to the lack of a comprehensive gas network like in Germany. While sensitive users in both countries fear blending (due to its negative impacts on industrial applications and product quality), Japan seeks to decarbonize the natural gas network by phasing in other low carbon gases like carbon neutral methane. Moreover, Japan needs further discussion to clarify the long-term strategy on how decarbonization of the gas infrastructure will be pursued in accordance with future gas demand structure and anticipated commercial benefits or costs.

In contrast to that, blending hydrogen with natural gas is somewhat more prominently discussed in Germany, particularly by the natural gas supply industry, and research takes up technological challenges. However, the phasing in of (green) hydrogen into the German gas network is not uncontested. Industry argues that pure hydrogen is more or less their only option to become carbon neutral, whereas other sectors (which would benefit from blended gas admixtures, like heat and buildings) have better options, such as direct electrification. To date, RD&D projects on blending hydrogen with natural gas are limited by number and scale even in Germany, and a transnational transport infrastructure for either pure hydrogen or natural gas blended with hydrogen will necessitate harmonized rules in relevant European countries.

CCUS also shows a contrast between Germany and Japan in terms of the focus by government. In Japan, CCUS is highlighted as one of the technologies to promote decarbonization in several policies such as the Environment Innovation Strategy and the Green Growth Strategy. It is also part of Japan’s long-term vision of a decarbonized society and, thus, considered a central part in achieving climate neutrality by 2050. As regards CCS, the technology was demonstrated with offshore storage capacity of the targeted amount of 300,000 tons in total and will be continuously monitored and studied for future policy direction. Public awareness of CCS needs to be raised although hardly any public skepticism has emerged so far. The country’s CCU strategy focuses until 2030 on products and materials that do not require hydrogen as an input, due to the limited availability and high costs of the gas. In order to turn CCU into a commercial business case, the Japanese Government has set up the Carbon Recycling R&D Hub and facilitated RD&D projects mainly through financial support.

In Germany, CCUS does not currently enjoy a technology-focused strategy as much as hydrogen does. CCS technology is seen as an important option to decarbonize industry, particularly in the cement industry. However, onshore storage will not be realized in the near future due to unknown impacts (e.g. on groundwater) and public concerns, which is why debates focus on offshore storage with partners such as Norway. As regards carbon utilization, several large-scale demonstration activities are successfully carried out. Still, there are several issues to reflect upon including the product type, in which the removed CO_2 is fed in, and the durability of storing carbon away from the atmosphere in it.

Since CCU technologies are at the early stage of development, there are some issues that both countries would need to cope with in common. For instance, life cycle assessment will be critical to reveal the environmental impact of CCU, because substantial energy is required in the CCU process, and because the durability of removing carbon from the atmosphere may need assessment. Development of a CO_2 transport infrastructure will also be difficult due to uncertain business perspectives without a clear long-term planning of the government. Furthermore, an adequate regulatory framework will be necessary to ensure safety for CO_2 transport and storage.

5 Recommendations for a way forward

5.1 Recommendations for Germany

5.1.1 Hydrogen direct use

The NHS and RD&D activities show the Government's will to facilitate hydrogen production and application in the industry sector, even though some would have wished for a more ambitious electrolyzer expansion (VDMA, 2020). Refineries appear to be the industrial first-movers for taking up hydrogen, which is also acknowledged by the fact that 40% of Germany's new electrolyzer capacity are planned as part of refineries. Several new projects in the chemical and steel industry will be realized in the years to come. For steel, DRI-technology is demonstrated with Germany's main steel producers. Most demonstration cases go hand in hand with rather small-scale electrolyzers being developed, at first, and results feed into the scaling up of larger electrolyzer designs. This can be seen as a step-wise approach to derive learning effects.

The Government expects newly developed domestic electrolyzer capacity to meet only 12 to 16% of hydrogen demand in 2030. Due to the overall focus on green hydrogen, it becomes crucial to increase the pace for finding additional green solutions. The newly established hydrogen steering committee will have to take on this task balancing supply and demand from various sectors, especially for green hydrogen. In order to safeguard imports, which can be considered an important tool to meet hydrogen demand, the thinking together of the international dimensions of the EU's and Germany's strategy might be mutually beneficial.

In Germany, new hydrogen production goes hand in hand with additional renewable electricity. Most industrial demonstration projects include renewable electricity capacities, but natural gas seems to be part of the solution, at least, to bridge the transition period in the steel sector. Hence, the future role of gas deserves substantial attention, particularly its phase out. Apart from that, infrastructural elements are an integral part of such projects, not least because the transport infrastructure for pure hydrogen in Germany is very limited so far. Rough scenarios to concretize infrastructure planning exist (Federal Network Agency, 2020; FNB Gas, 2020) but efforts must be stepped up and become politically legitimated in order to safeguard investment security for hydrogen producers, users and transport operators.

Some policy support exists for industrial hydrogen users. However, given the global market in which most companies of basic materials industry operate, it requires the orchestration of policy revisions and new instruments to be designed so that, ultimately, climate friendly products become competitive. This includes instruments such as CCfD and a Carbon Border Adjustment Mechanism, amongst others (Agora Energiewende & Wuppertal Institut, 2019; Leipprand et al., 2020). Germany's NHS and the Government's Recovery Package give an opportunity to ramp up hydrogen production and use and to facilitate RD&D. Bringing down costs of electrolyzers and energy inputs needed for hydrogen production, transport technology and industrial upgrades will have to be on the Government's agenda.

5.1.2 Hydrogen natural gas blending

The Government and, most likely, the hydrogen steering committee established through the NHS will have to balance the existing positions on HNG admixtures. If hydrogen concentrations in HNG increase, several questions will arise for both infrastructure operators and sensitive industrial applications, amongst others. In the end, higher concentrations come at a cost and it is open who will bear them to finance technology upgrades. European cooperation and coordination are as important here as for the development of a pure hydrogen pipeline infrastructure. Despite controversies on blending hydrogen with natural gas, there are projects which investigate upon the implications of HNG admixtures and offer solutions for increased hydrogen concentrations.

5.1.3 Carbon capture, utilization and storage

While it would go beyond the scope of this paper to neatly discuss alternative pathways in certain industries, some deserve to be mentioned in order to balance decision making in a broader context. For instance, in the construction sector, alternatives to steel and cement can be wood (also storing CO_2 naturally) or lay. Apart from that, (re-)circulation of materials such as steel, aluminum and plastics can bring enormous emissions savings. Literature suggests that 75%, 50% and 56% of demand in steel, aluminum and plastics could be met by recirculated materials (Agora Energiewende & Wuppertal Institut, 2019; Churkina et al., 2020; Material Economics, 2019; Robbins, 2019).

If focusing on CCUS for industry, the discussion can be divided into a few supplementary elements. Due to low acceptance among the German population resulting from onshore demonstration projects for power plants, CCS faces a contested socio-political environment. However, the move to turn to offshore storage as well as using CCS for process-related industrial emissions has apparently reduced public headwinds and increased stakeholder support even from some environmental groups. Relevant legal issues hindering the cross-border transport of CO_2 for offshore storage have been overcome. Given that countries such as Norway seek to store CO_2 underneath the sea shows that the technology is available in principle, even though at higher prices in comparison to onshore storage. Questions for policy makers will also focus on CO_2 transport and (offshore storage) costs, for which solutions are about to be sought with European partners.

Public debates on CCU are less emotional. Some oppose the idea of utilizing industrial emissions and favor technology options such as direct air capture, but, in fact, the amount of heavily funded demonstration projects (e.g. Carbon2Chem, Rheticus) shows that Government sees industry as both a raw material provider and user of CO_2. In the German CCU discussion and RD&D projects, the chemical industry, refineries and cement producers become CO_2 sinks, even though the role of CCU for synthetic fuels (and also for fertilizer production) is not undisputed due to its low / short storage capacity/ service life. In this respect, the process of carbonation, in which CO_2 can be made use of in building materials, is seen as a promising option to store CO_2 permanently, but RD&D needs to push for a valid business case. The limited amount of industry clusters with capacities for cross-industrial business models will have to be explored with priority.

In parallel to that, infrastructural questions will become more and more relevant for CCU connecting supply and demand. However, a physical infrastructure raises fears of lock-in effects keeping CO_2-based business models alive, which must be addressed by long-term policy roadmaps, if large-scale quantities of CO_2 are supposed to be captured. Competitive renewable electricity must accompany a sustainable CCU pathway, along with cross-infrastructural planning connecting power, hydrogen and CO_2 production with (geographically rather diverse) demand centers.

An overall strategy on CCUS may provide a better picture of the role of CCS and CCU in the future and may provide planning security. This would also acknowledge the long lead-times the technology needs to be set up. The national hydrogen committee will play a role for integrating CCU-related developments into hydrogen deployment policy. The institutional development of a market facilitator may overcome some investment restraints. However, the open questions regarding the real contribution of CCU to reducing GHG emissions (especially in comparison with alternatives) and its durability need to first be solved with priority, before embarking on a strong CCUS strategy.

5.2 Recommendations for Japan

5.2.1 Hydrogen direct use

The 6th Strategic Energy Plan is expected to be published in the summer of 2021. After the publication of the Strategic Energy Plan, Japan's hydrogen strategy will also be revised. As mentioned before, in the previous Hydrogen Strategy, hydrogen's application in the industry sector was not mentioned much. More government support and public private partnership on industry's hydrogen use can be expected in the future.

Cost of hydrogen supply is the most important issue. To bring down domestic green hydrogen cost, further efforts on cost reduction of solar PV and onshore wind, as well as accelerating the development of offshore wind will be needed. Furthermore, given the mismatch of the location of hydrogen demand and renewable resources, and for the purpose to improve the capacity factor of water electrolysis units, using grid electricity combined with renewable energy credits could also be an option worthy of more attention and discussion.

To facilitate the development of an international hydrogen supply chain, in addition to accelerating the efforts on scaling-up and cost reduction of the equipment, an internationally agreed low-carbon hydrogen standard and certification will also be needed. It is also necessary to reinforce international coordination and collaboration on low-carbon hydrogen certification for more study and discussion on this issue.

To realize hydrogen use in the industrial sector, a domestic hydrogen-dedicated transport and distribution infrastructure is required, as hydrogen blending into the existing natural gas network is considered as an option that raises a number of challenges (See below). Further studies to figure out the industrial areas which are suitable for developing new hydrogen-dedicated infrastructure rather than hydrogen blending are needed.

5.2.2 Hydrogen natural gas blending

To facilitate hydrogen natural gas blend in Japan, commitment from the government, gas utility companies, as well as cooperation from gas appliances manufactures and gas consumers are necessary. As a first step, the government and gas utilities together with other stakeholders need to work together to draw a clear picture and strategy on how to decarbonize Japan's natural gas network and bring clarity to hydrogen's role in it. Meanwhile, to help policy makers and the industry make their decision, further study on natural gas pipeline's readiness for hydrogen blending is needed. In the short term, the role of government is important. This includes development of a long-term national strategy and support of technical and feasibility studies and pilot projects. In the medium- to long-term, though the industry will be the main player, the government's support on safety standard regulation and price mechanism will still be critical.

5.2.3 Carbon capture, utilization and storage

The CCUS technologies involve potentials of CO_2 reductions and may help the economy in terms of competitiveness and growth in the future if technology development is successfully conducted. The government plays a critical role to cope with challenging issues related to the CCUS technologies which are at the early stage of development. Especially, the public support is essential in the areas where the private sector would not see a rationale for investment due to high upfront costs and uncertain commercial feasibility given unclear foreseeability. It is ideal that synergies would be created from collaboration among the government, industry, and academia.

First of all, continuous financial support for RD&D will buttress the foundation for the technology application and commercialization. Innovative ability and perspectives of the private sector and academia need to be utilized with the public funding. Secondly, the public support will help the shared infrastructure of CO_2 transport and storage to be realized in case investment in the infrastructure is not pursued by the private sector alone. Thirdly, since the CCUS technologies are long-term projects, practical planning and strategies presented by the government will be a good guidance for the private sector where they should be headed for. Following changes or development of the market, however, the government may be required for flexible adjustment in management.

Carbon pricing systems are regarded as one of effective market-based tools to encourage the industry sector to work on CO_2 reduction efforts. As suggested in the Green Growth Strategy, discussion on carbon pricing mechanisms has just started in the committee established by the government of Japan. Revision of the current regulatory framework or introduction of a new measure regarding carbon pricing arrangements will be deliberated to make it more effective to contribute to economic growth. Policy design needs to be carefully balanced between keeping competitiveness of the industry sector and accelerating deployment of the CCUS technologies.

Lastly, Japan proposed the establishment of an Asia CCUS Network at the East Asia Summit Energy Ministers Meeting in November 2020 (METI, 2020 d)[22]. This platform aims to share information on the development of the business and regulatory environment and the best use of CCUS among the participating countries. Such international cooperation will facilitate clean transition beyond national borders and a fair and transparent market for CCUS in the future.

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[22] Energy ministers from Japan, China, South Korea, 10 ASEAN member states, Australia, India, New Zealand, Russia, and the United States participated in the online meeting.

6 Recommendations for cooperation

Chapter 3 has discussed both existing RD&D projects and challenges and perspectives for the three ways that have potential for contributing to the decarbonization of energy-intensive industries. Particularly direct hydrogen use and CCU may hold large potential for further joint RD&D between both countries. For example, at a recent event, Chiyoda corporation expressed its interest to cooperate with European companies in the further development and testing of its technology to catalyze para-xylene, a basis for polyester production, from hydrogen and CO_2. At the same time, the challenges discussed in chapter 3 need to be addressed by RD&D, for example on costs, technologies, regulation, and what is actually the potential for reducing GHG emissions, particularly for some CCU options.

As regards policy instruments and policy mixes, several aspects are to be acknowledged on the German and European side. For instance, CCfD are developed in Germany, in order to financially support higher OPEX resulting from the application of breakthrough technologies and green hydrogen. Moreover, a Carbon Border Adjustment Mechanism might be implemented at the EU level in order to create a level playing field between domestic and non-EU industries and to accelerate a transition of basic material industries beyond EU territory. These and other policy discussions in the EU and Germany can systematically be processed to draw lessons learned for Japan. Likewise, lessons from the orchestration of policy instruments in Japan might provide interesting insights for German and European stakeholders. As basic material industry, in general, faces global competition, higher costs for decarbonizing intermediate products like steel, cement and chemicals should also be reflected upon how to create green lead markets, which might include instruments such as green public procurement of respective products. Therefore, a societal lens is necessary in order to not overburden low-income households.

In this respect, other pathways (complementary to those focused on in this study) may also deserve mutual attention such as increasing circularity, mitigating resource demands and strengthening energy efficiency. For instance, as regards societal acceptance, results from Japan's CCS projects and environmental impacts appear to be relevant for Germany and internationally.

Another possible area for cooperation is to facilitate development of the international sustainability and safety standards regarding hydrogen production and transport (cf. Shibata et al 2020). Such international standards will be essential for hydrogen to level the playing field as well as to ensure safety which is critical to improve public acceptance. Germany is expected to play an important role and make the best use of knowledge and experiences gained through the CertifHy initiative, but certification of clean hydrogen should build on more comprehensive criteria than CertifHy (Shibata et al 2020). For Japan, where a hydrogen certification scheme is not on the table at the national level, it will be a good opportunity to establish national rules consistent with the international standards. Collaboration between the two countries could lead to create a fair and environment-friendly framework for decarbonized materials.

7 Concluding remarks

This report explored policy directions and possible technologies to decarbonize the industry sector in Germany and Japan, because it would be difficult for both countries to achieve the carbon neutrality by 2050 without the sector's efforts of reducing CO_2. In particular, hydrogen direct use, blending hydrogen with natural gas, and CCUS were raised as the subjects to be studied.

Both Germany and Japan have set the policy framework to encourage hydrogen utilization in the industry sector and provided assistance to expedite the RD&D projects covering the hydrogen supply chain. Given the current technology available and technology development perspectives, some energy-intensive industry sectors do not have many choices but hydrogen which is considered an enabler for decarbonization. Still, production costs need to be reduced for hydrogen to be applied in the industry sector. Hence, further RD&D is necessary to advance technology. For instance, the capacity of electrolyzers will be scaled up to the extent that economies of scale work through technological innovation, consequently leading to cost reductions. For both countries, green hydrogen is certainly desirable but blue hydrogen is also in consideration until green hydrogen becomes available at affordable costs.

On the other hand, it seems that Germany and Japan have slightly different stances on blending hydrogen with natural gas and on CCUS. With the extensive natural gas pipeline network, blending hydrogen with natural gas is an opportunity for Germany to make use of the existing infrastructure, although there are alternative options to replace natural gas, which may be more energy-efficient and cost-effective, and various issues need to be overcome before blending is actually put in place. However, Japan may stand back from this area due to a lack of adequate natural gas infrastructure and proper technology, and uncertain commercial feasibility unless the government or the industry is engaged with discussion on the long-term planning. Rather, Japan currently seems to be more interested in deployment of CCUS technologies compared with Germany, where there are a number of pilot projects too, but no strategy as for hydrogen yet. While different circumstances result in diversification of policy directions that the two countries would choose, a fundamental idea is to seek best options which will be technologically available and affordable to keep the competitiveness of the industry sector. Since these technologies are still in the experimental or demonstration phase, it is interesting to see how these technologies will be developed and applied in each country.

Although many obstacles are observed in the above-mentioned technologies, i.e. hydrogen direct use, blending hydrogen with natural gas and CCUS, they will certainly present potentials to abate CO_2 emissions, if a consistent life-cycle approach is taken. Not only Germany and Japan but also the world unexceptionally needs technologies to decarbonize the industry sector to deal with the climate change issues. Hopefully, further collaboration between Germany and Japan will lead and accelerate technology development at global level.

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