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Current Situation and Ongoing Projects on Carbon Capture and Storage and Carbon Capture and Utilization in Germany and Japan

Factsheet

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Contribution to the research project *Scientific orientation of the German-Japanese cooperation on selected climate protection technologies within the framework of the German-Japanese climate protection declaration and the German-Japanese environment and energy dialogue forum*

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Table of Contents

List of Figures

List of Tables

List of Abbreviations

BECCS	Bioenergy with Carbon Capture and Storage
BImschG	German Federal Immission Control Law
BMU	Federal Ministry for the Environment (Germany)
BMWi	Federal Ministry for Economic Affairs (Germany)
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilization
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide Equivalents
DAC	Direct Air Capture
DACCS	Direct Air Carbon Capture and Storage
EIA	Environmental Impact Assessment
ETS	Emissions Trading System
EU	European Union
FT(S)	Fischer Tropsch (Synthesis)
GHG	Greenhouse Gas
IGCC	Integrated Gasification Combined Cycle
HT	High Temperature
JPY	Japanese Yen
KSpG	German Federal Law for Carbon Dioxide Storage
LCOE	Levelized Cost of Electricity

LT	Low Temperature
METI	Ministry of Economy, Trade & Industry (Japan)
MoEJ	Ministry of Environment (Japanese)
Mt	Mega tonnes, one million tonnes
NET	Negative Emission Technologies
NGCC	natural gas combined-cycle
PtX	Power-to-X
RWGS	Reverse Water Gas Shift (Reaction)
SC	Supercritical (CO_2 extraction)
UBA	Umweltbundesamt (Germany)
USC	Ultra-supercritical (CO_2 extraction)
USD	United States Dollar

1 Introduction

With Carbon Capture and Storage (CCS), carbon dioxide (CO_2) is captured from either point or dispersed sources and then stored underground for long-term disposal. Accordingly, the CO_2 is no longer emitted into or captured from the atmosphere and is thus not effective as a greenhouse gas. With Carbon Capture and Utilization (CCU), the captured CO_2 is not stored underground but used as input for chemical processes. It will finally be embedded in products and thus not be effective as a greenhouse gas throughout the lifetime of the products. While CCS can contribute to negative emissions, CCU can provide a contribution to climate neutrality through climate neutral products, which would otherwise contribute to global warming. However, both effects only occur when atmospheric CO_2 is used, either directly captured from the air or indirectly via biomass.

It is disputed whether CCS is needed to achieve climate neutrality or not. While the IPCC (2018) in its 1.5° report assumes that CCS and other Negative Emission Technologies (NET) will have to be used to a greater or lesser extent, especially in the second half of this century, Germany’s Federal Environmental Protection Agency (UBA 2019a) shows in its Rescue Study that climate neutrality in Germany can also be achieved with natural sinks alone (forests, moors, etc.). For Germany and all other countries, this presupposes that drastic mitigation policies are implemented. However, the instruments to mitigate climate change that have been adopted so far are not sufficient to achieve this goal by 2050. Current studies on achieving climate neutrality in Germany by 2045 therefore conclude that NET will also be necessary to achieve this goal (Prognos; Oeko-Institut; Wuppertal-Institut 2021; ISI 2021; PIK 2021; dena 2021a). But both IPCC (2018, p 14) and UBA (2019b, p 9) state: The later and the weaker mitigation measures are introduced, the greater the likelihood that, and the extent to which, NET will have to be deployed to achieve climate neutrality.

Against this background, BMUV aims as part of the project *Scientific orientation of German-Japanese cooperation on selected climate protection technologies within the framework of the German-Japanese Climate Protection Declaration and the German-Japanese Environment and Energy Dialogue Forum* (FKZ UM18 18 40 40) to compile relevant data and information on CCS and CCU in Germany and Japan with the view to enhancing understanding of the situation in the other country and thus facilitate mutual learning and also to support and stimulate the political discussion on these topics in both countries.

This factsheet begins with an overview of GHG emission trends, reduction target and key elements of the climate and energy strategies in both countries to facilitate the understanding how CCS and CCU are embedded in these strategies (chapter 2). CCS and CCU overlap to some extent with regard to capturing CO_2 but differ as to how the CO_2 is treated after capturing. Before we scrutinize this background, recent initiatives and projects, potentials, etc. for CCS and CCU in both countries in chapters 4 and 5, we discuss the potential sources of CO_2 (fossil, biogenic, ambient air) and the challenges involved with the different sources in chapter 3. The regulatory frameworks for CCS and CCU in Germany and Japan are compared in chapter 6. Finally, in chapter 7 we compare the situation in both countries and draw conclusions for the political discussion.

2 Background: general climate and energy policy strategies

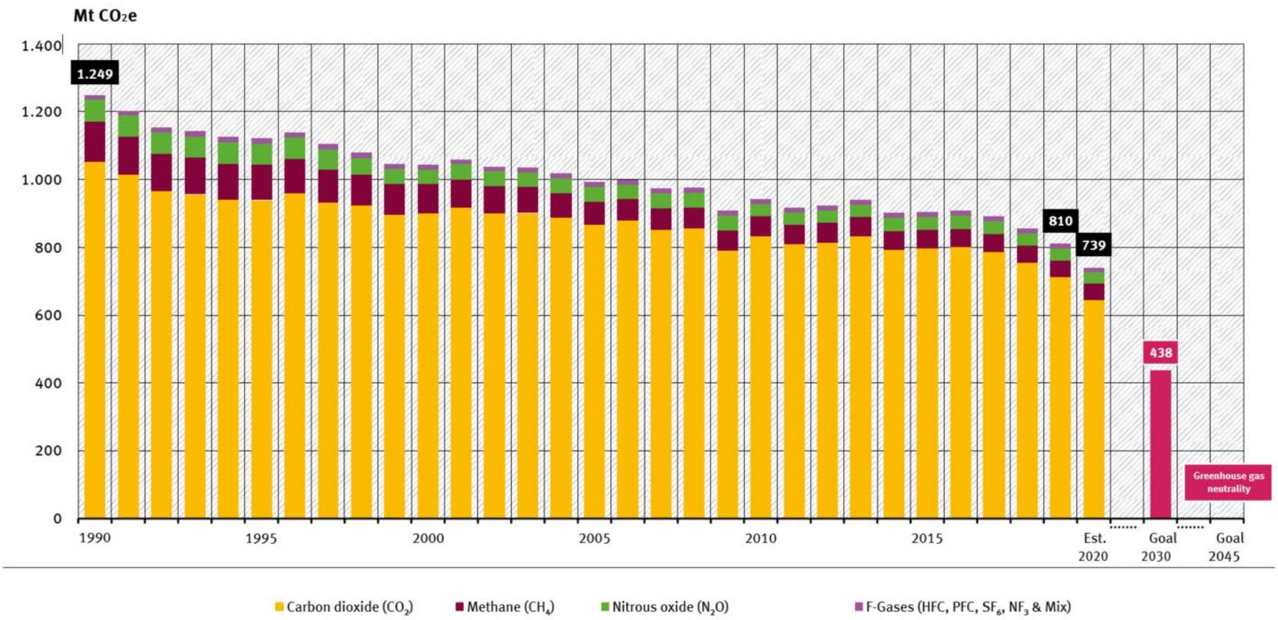
CCS and CCU are elements of the overarching energy and climate policy in both countries. Therefore, it is worthwhile to briefly summarize key elements of the energy and climate policies in which the technologies are embedded before we provide overviews of both technologies and their developments in Germany and Japan.

2.1 Germany

In April 2021, Germany's climate policy was challenged by a decision of the Constitutional Court. This concluded that the Federal Climate Change Act adopted in 2019 was incompatible with the fundamental rights and with the freedom of future generations because it did not provide reduction targets and sufficient details on GHG reduction beyond 2030.[1] Following this decision, the German Parliament revised the Climate Change Act in June 2021, which now aims to become GHG-neutral by 2045.[2]

From 1990 to 2020, GHG emissions decreased by 40.8% (Figure 1). CO_2 emissions, 87% of total GHG emissions, decreased by 38.8%. To achieve GHG neutrality by 2045 according to the revised Climate Act, in 2030/2040 GHG emissions need to be 65%/88% lower than in 1990. In absolute terms, GHG emissions must be reduced by 300 Mt CO_2e within 10 years (-40.8% compared to 2020); these were reduced by 510 Mt CO_2e in the 30-year period between 1990 and 2020.

Figure 1: Greenhouse gas emissions by gas



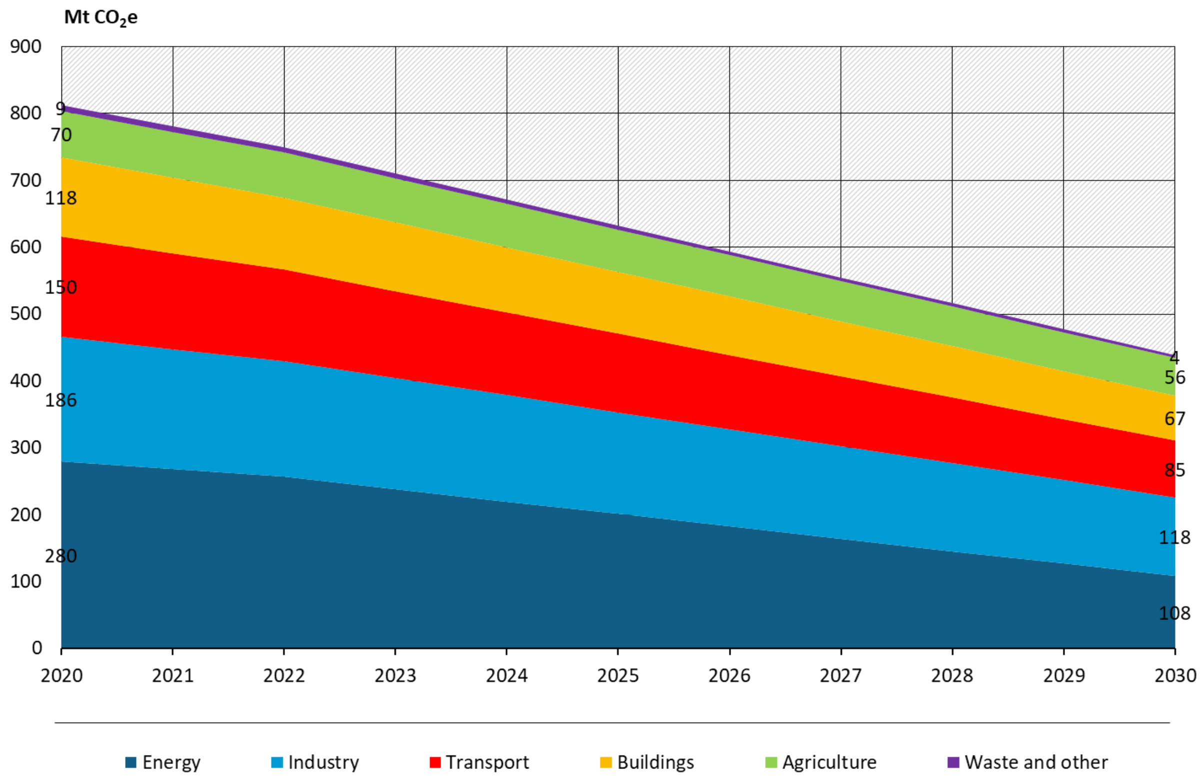
Source: UBA (2021b)

Germany's Climate Change Act sets targets for each sector of the economy (Figure 2). Achievement of the targets will be monitored every year. If the targets are not met, the respective ministries need to develop appropriate policies which enhance the sector's mitigation contribution and ensure that the targets are met in the future. Emissions in the energy sector must be reduced from 280 to 108 Mt CO_2e (-61%) while industry emissions need to decrease from 186 to 118 Mt CO_2e (-37%).

1 Constitutional complaints against the Federal Climate Change Act partially successful, https://www.bundesverfassungsgericht.de/SharedDocs/Pressemitteilungen/EN/2021/bvg21-031.html;jsessionid=6853AA3B37857B5387D2BD57E0334A01.2_cid354.

2 Bundestag verschärft das Klimaschutzgesetz, https://www.bundestag.de/dokumente/textarchiv/2021/kw25-de-klimaschutzgesetz-846922.

Figure 2: Annual emissions by sector



Source: BMU (2021)

Together with the Federal Climate Change Act, the Climate Action Programme 2030 was adopted in 2019. Key elements of the programme are (BMU 2019):

- Renewable energies should contribute 65% to gross electricity generation in 2030.
- Power generation from coal should be phased out by 2038.
- Unavoidable GHG emissions such as from cement production or agriculture CCU and CCS will be required. According to recent studies, 40-100 Mt CO_2 negative emissions will also be necessary to achieve climate neutrality (Prognos; Oeko-Institut; Wuppertal-Institut 2021; ISI 2021; PIK 2021; dena 2021a). Since particularly CCS is contentious in Germany, the programme announces both a dialogue process with relevant stakeholders to clarify the acceptance of these technologies and the promotion of research and development in this area (105 mil. EUR in 2021, 120 mil. EUR/a in 2022-25[3]).

Consideration of storing of CO_2 in domestic sites stalled more than 10 years ago due to both safety concerns and the reluctancy to prolong the lifetime of fossil power generation. Recently, CCS has been reconsidered in the context of negative emissions for heavy-to-abate sectors based on a clear priority (dena 2021b):

1) reducing GHG emissions,
2) CCS for heavy-to-abate point sources such as cement of lime and

[3] Argus (2021): Germany launches CCUS support, https://www.argusmedia.com/en/news/2184819-germany-launches-ccus-support.

3) compensating heavy to abate diffuse GHG emissions such as from agriculture through negative emissions technologies.

After the federal elections in 2021, the new German government aims at enhancing the ambition of several climate policy elements (SPD; B90/G; FDP 2021):

- To accommodate the expected increase of the electricity demand due to electrolysers, battery electric vehicles, heat pumps, etc., the gross electricity projection was increased to 680-750 TWh in 2030. At the same time, 80% of this demand should be provided by renewable energies. For fulfilling this target, the expansion of onshore wind power capacity would need to be tripled from 2021 levels.
- The phase-out of coal power generation will be accelerated and should ideally be accomplished by 2030.
- With regard to CCS and CCU, the agreements states: *"We also acknowledge the need for technical negative emissions and will develop a long-term strategy for dealing with the approximately 5% of unavoidable residual emissions."*

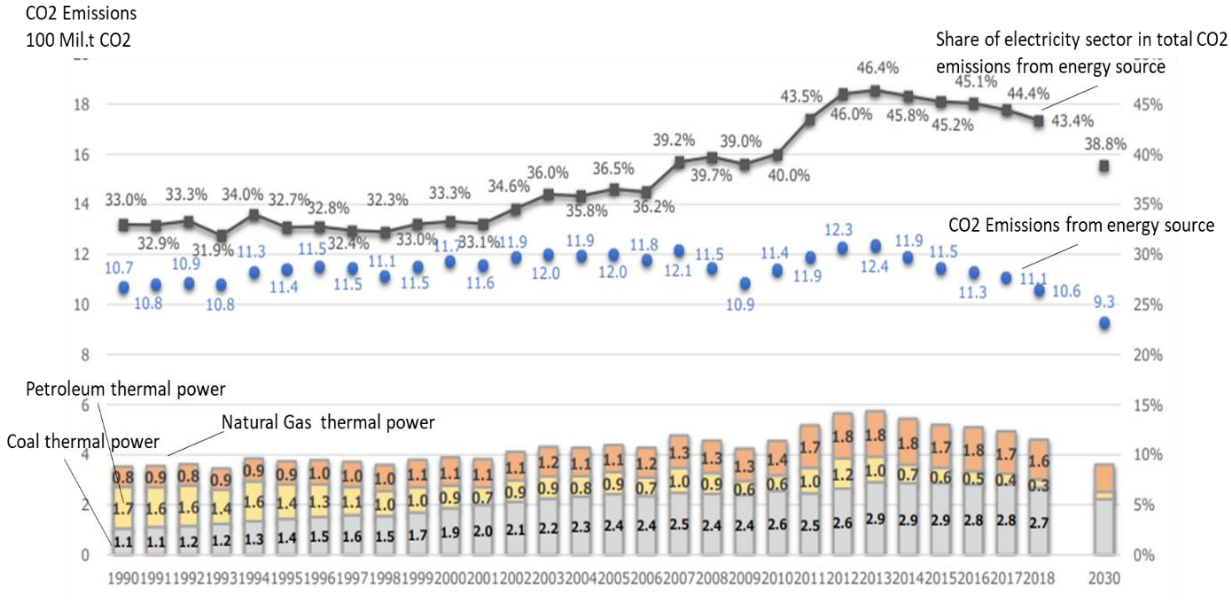
Bellona, a Norwegian environmental NGO active in Germany, welcomes the acknowledgement as an important first step in the right direction but argues that the importance of the capture, transport, use and permanent geological storage of storage of CO_2 as well as the urgent need to develop a legal framework for CCS and CCU is underestimated in the agreement (Bellona 2021).

Industry stakeholders demand that the new government should develop a German strategy and regulatory framework for CO_2 capture, transport and storage, to remove regulatory barriers for industrial CCU and CCS projects aiming at climate neutrality and introducing carbon contracts for difference (CCfD) as a key funding instrument for industrial CCU and CCS projects aiming at climate neutrality (Stiftung 2° et al. 2021).

2.2 Japan

In October 2020, Japan committed to becoming climate-neutral by 2050. The energy sector, which is currently responsible for more than 80% of greenhouse gas emissions, plays an essential role in this. The share of the energy-related CO_2e emissions amounts to over 40%.

Figure 3: CO_2 emissions from thermal power generation in Japan



Source: MoEJ (2020a)

After a one-year discussion process, the Japanese Ministry of Economy, Trade & Industry (METI), which is responsible for energy policy, published the **6th Basic Energy Plan** (METI 2021a). According to this plan, the share of renewable energies in the electricity supply shall reach 36-38% in 2030 (Table 1), which corresponds to double the 18% share recorded in fiscal year 2020. The government's previous target was only to increase the share of renewable energies in the grid to 22-24% by 2030. In, addition, the share of coal in the electricity supply shall be reduced from 26% to 19% by 2030. At the same time, Japan aims to reduce the LNG imports. Japan's target for the share of nuclear energy remains unchanged at 20-22%, while new fuels such as hydrogen and ammonia are to account for about 1% of the electricity mix (METI 2021a).

Table 1: Outline of the 6th Basic Energy Plan

		(2019 ⇒ previous energy mix)		Energy mix in FY2030 (ambitious outlook)	
Energy efficiency improvement		(16.55 million kl ⇒ 50.30 million kl)		**62 million kl**	
Final energy consumption (without energy conservation)		(350 million kl ⇒ 377 million kl)		350 million kl	
Power generation mix	**Renewable energy**	(18% ⇒ 22-24%)	solar 6.7% ⇒ 7.0% wind 0.7% ⇒ 1.7%	**36-38%** ※If progress is made in utilization and implementat of R&D of renewable energy currently underway, 38% or higher will be aimed at.	
Electricity generated: 1,065 TWh ⇒ Approx. 934 TWh	**Hydrogen/Ammonia**	(0% ⇒ 0%)	geothermal 0.3% ⇒ 1.0~1.1%	**1%**	
	Nuclear	(6% ⇒ 20-22%)	hydropower 7.8% ⇒ 8.8~9.2%	**20-22%**	(details of renewable)
	LNG	(37% ⇒ 27%)	biomass 2.6% ⇒ 3.7~4.6%	**20%**	solar 14~16% wind 5%
	Coal	(32% ⇒ 26%)		**19%**	geothermal 1% hydropower 11%
	Oil, etc.	(7% ⇒ 3%)		**2%**	biomass 5%
(+ non-energy related gases/sinks)					
GHG reduction rate		(14% ⇒ 26%)		**46%** Continuing strenuous efforts in its challenge to meet the lofty goal of cutting its emission by 50%	

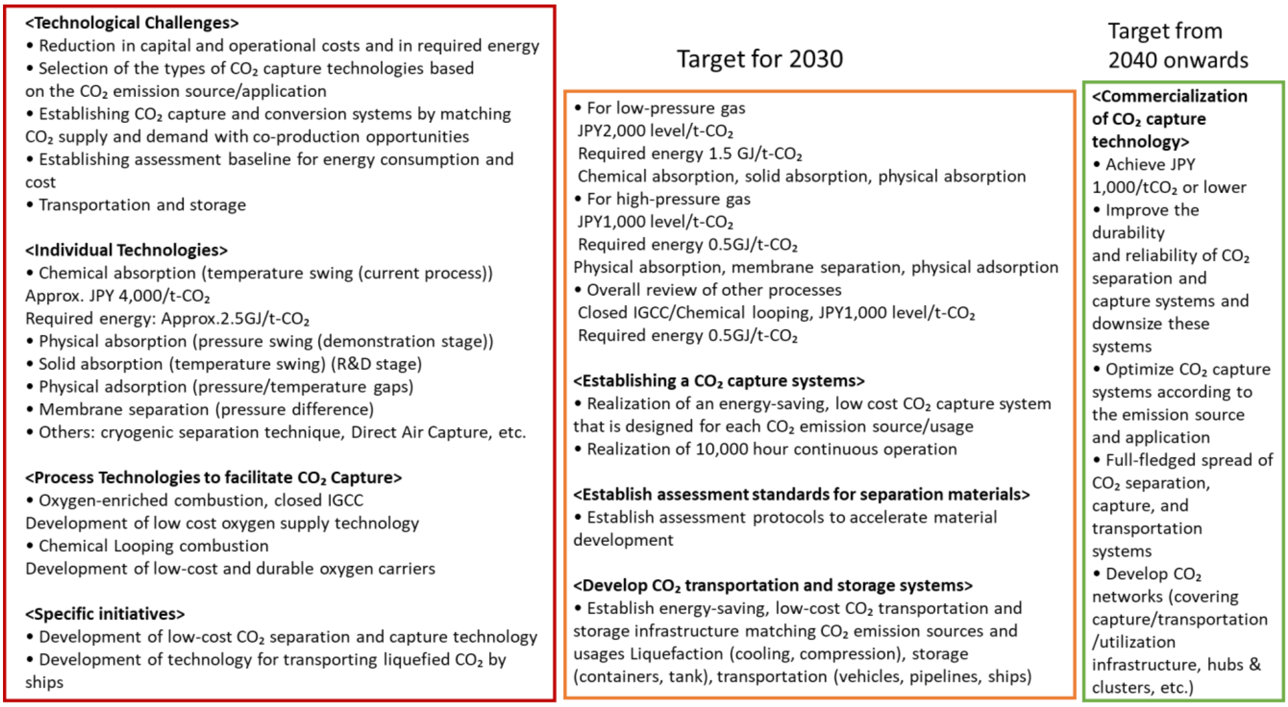
Source: METI (2021a)

The new **Basic Energy Plan** thus explicitly provides for the promotion of decarbonised electricity sources. However, in order to become climate-neutral by 2050, the continuation of thermal power generation using coal and gas, combined with the application of Carbon Capture and Utilization or Storage (CCUS) is also envisaged in order to reduce the GHG emissions of remaining fossil power sources.

Against this background, METI views carbon recycling[4] as a promising way of reducing national emissions and combating climate change. Therefore, the Ministry is actively promoting the development of relevant technologies. The **Roadmap for Carbon Recycling Technologies** (METI 2021c) identifies technological challenges and sets targets and time frames for carbon recycling technologies (capture, transport, storage, reuse) to accelerate innovation in this field. According to the roadmap, the options and requirements for introducing CCUS technologies in existing coal-fired power plants by 2030 will be examined at first. The next step is to gather practical experience for the application of CCUS from 2040 onwards. At the same time, the costs for the processes are to be drastically reduced to a range of about 200-1,000 JPY/t CO_2 (2-9 USD/t CO_2).

[4] Carbon Recycling refers to technologies that suppress CO_2 emissions into the atmosphere by regarding CO_2 as a resource, separating and collecting it, and reusing it for making various products such as concrete, chemicals and fuels, https://www.meti.go.jp/english/press/2021/0726_003.html.

Figure 4: Japan´s Roadmap for Carbon Recycling Technologies



Source: Based on METI (2021c)

3 CO_2 origin

As the terminology illustrates, CCS and CCU overlap to some extent: Both technological strategies rely on CO_2 which is somehow captured but differ in respect of what will be done with the CO_2 once it is captured. Under the CCS route, it will be stored long term while under the CCU route it will be used in materials and products and thus also stored in a way that it does not contribute to global warming. Therefore, CCS can contribute to negative emissions while CCS provides a contribution to climate neutrality. Before looking at both routes in greater depth, we discuss where the CO_2 may come from and which challenges are involved the potential origins of CO_2.

In principle, CO_2 can originate from the following three sources (Minx et al. 2018):

- Captured from waste gas streams of bio-based processes, e.g. biogas plants;
- Captured from waste gas streams of industrial processes that are currently still based on fossil or geogenic carbon sources, e.g. primary steel plants, cement plants, etc.;
- Separated from the ambient air by Direct Air Capture (DAC).

In the case of **biogenic carbon sources**, the carbon comes from atmospheric CO_2 that has been bound into biomass by photosynthesis processes. Bio-based sources are limited in quantity and distributed on a small scale in terms of their occurrence. For this reason, bio-based CO_2 sources are hardly suitable for CCS or CCU on a large scale as the carbon dioxide would have to be transported to the corresponding CCU plants or CCS storage facilities and the costs for this would be relatively high. One possibility would be to use CO_2 from large-scale fermentation processes (e.g. for the production of alcoholic beverages: beer breweries, etc.) but nowadays the CO_2 is often already captured and used further. For the long-term, (IRENA 2021) foresees that global consumption of bioenergy will increase to 100-150 EJ in 2050.

Industrial point sources are large industrial facilities, such as steel mills or cement plants where CO_2 can be extracted from waste gas streams. They are usually preferred because the CO_2 concentration here is more than 100 times greater than in atmospheric air. If the targets of the Paris Climate Agreement are to be met, fossil carbon sources may no longer be used in the long term. As a result, industrial point sources are also limited in the long term as large emitters such as primary steel production will no longer release CO_2 by converting their processes. Certain industrial processes where the CO_2 is process-related, e.g. ethylene oxide production, will themselves be based on renewable[5] CO_2 sources in the long term, so it is rather unlikely that the CO_2 released during synthesis will then be available to the market. It is much more likely that it will be re-used as an input for the company's own process. In a transitional phase, however, there will still be relevant industrial point sources of CO_2, e.g. primary steel production, chemical production or cement plants, where the capture of CO_2 is attractive from an economic point of view, mainly because of the high availability of CO_2 at one location and the low energy demand for CO_2 capture, especially in plants where CO_2 is already captured today, e.g. in ethylene oxide production.

Another industrial point source is the unavoidable CO_2 emissions from geogenic carbon sources, e.g. from lime burning in cement production. While there are some alternatives on the demand side for cement (wood construction, reusage of cement, etc.), there are no alternative processes foreseeable with which CO_2 emissions can in principle be avoided.

There are several types of processes for capturing CO_2 from the air by means of **direct air capture (DAC)**, two of which have become established (Goeppert et al. 2012): A limited number of pilot projects are being carried out, but on a global scale there are also large-scale industrial plants already being planned or under construction.

- The High Temperature (HT) DAC process is based on aqueous solutions of strong bases as sorbents and has a high heat requirement (~ 900 °C). The CO_2 reacts with the bases to form the corresponding carbonate (K_2CO_3, Na_2CO_3, $CaCO_3$) with high selectivity and high yield (>99 %). In the first process step, absorption, the aspirated air is brought into contact with sprayed solvent in the reaction chamber, and the CO_2 from the air reacts with the sorbent (e.g. sodium hydroxide, NaOH, calcium hydroxide, $Ca(OH)_2$ or potassium hydroxide, KOH). In the second step, regeneration, the reaction product is converted, and the sorbent is recovered to be fed back into the absorption process. The CO_2 bound at this stage in another chemical intermediate is separated in a very energy-intensive process at up to 900 °C and is present at the end of the process at a pressure of usually 100-150 bar. In the process, purity levels of up to 97 % can be achieved so far (Fasihi et al. 2019).
- The Low Temperature (LT)-DAC process is based on an adsorption process with a solid sorbent, e.g. supported organo-amines (polyethyleneimine [PEI], amino-trimethoxy silanes [TRI], branched amino silicates [HAS]), and requires significantly lower temperatures (~ 100 °C) for regeneration (Fasihi et al. 2019). Here, the CO_2 is reversibly bound to amine functional groups (-NH2). The most common LT-DAC technology is temperature swing adsorption (TSA) and, like other DAC methods, starts by drawing in atmospheric air through fans in the first step. The air is passed through a solid filter material (cellulose fibres, amino polymers, etc.), which accumulates (adsorbs) the CO_2 from the air on its surface. When the filter material is fully loaded, it is heated up to 100 °C

[5] Renewable CO_2 means CO_2 that does not originate from fossil or geogenic sources but from biomass or directly from the air.

in a second step to dissolve the CO_2 from it. In this process, a purity level of up to 99.9% is achieved (Fasihi et al. 2019).

The second technology requires significantly less energy to release the adsorbed CO_2 and is the basis for Climeworks' plants. But here, too, the energy input and current costs are significantly higher than for CO_2 capture from industrial point sources.

For (HT/LT) DAC systems, a reduction in electricity demand of 5/10 % and a reduced low-temperature heat demand of ~ 14 % every 10 years can be expected for the coming decades, based on the values of currently existing systems (Fasihi et al. 2019). Currently, the largest energy demand is for the electric-powered fans to draw in the air as well as the heat for heating in the regeneration phase. The LT-DAC processes all require a regeneration temperature of 70 - 100 °C, which makes the options of using waste heat from other industrial plants as a source of thermal energy attractive (Fasihi, Efimova, & Breyer, 2019).

The exact demand for thermal and electrical energy varies depending on the plant design and sorbent. According to various scientific publications (Fasihi et al. 2019), the energy demand in 2020 falls within the following range:

Electrical energy:	HT: 1.535 $kWh_{el}/t\ CO_2$ (= 5.633 kWh_{el}/t_C) LT: 250 $kWh_{el}/t\ CO_2$ (= 918 kWh/t_C)
Thermal energy:	HT: 0* $kWh_{th}/t\ CO_2$ LT: 1.750 $kWh_{th}/t\ CO_2$ (= 6.422 kWh/t_C)

Compared to biomass-based negative emissions technologies (NETs) such as the Bioenergy with Carbon Capture and Storage (BECCS) process, DAC plants use much less **land** (> 100 times) , largely due to the land required for biomass cultivation (Sutherland 2019). The land use of DAC plants is currently calculated to be around 0.4 - 1.5 km^2/ Mt CO_2/a, which is mainly the open space between CO_2 collectors (Fasihi et al. 2019). Similar to the expansion of renewable energy, it must be assumed that if DAC technology becomes widespread, it will require a not inconsiderable amount of land (Cames et al. 2021), which may lead to land use conflicts and emissions from LULUCF.

Regarding **water consumption**, the DAC technology types differ, as the HT process is assumed to consume up to 50 $m^3/t\ CO_2$, whereas the LT processes generate water as a by-product (~ 1 - 2 t of water per tonne of CO_2 captured, Fasihi et al. 2019). The latter is a decisive argument in favour of LT-DAC technology, as water will be an even scarcer resource in the future and thus conflicts of use can be avoided. For biomass production in the case of use of biogenic carbon, water consumption would be many times higher.

Currently, the **costs** for DAC are still comparatively high, which is a barrier to investment. In order to increase the effectiveness of the technology for achieving the German climate targets, the costs must still fall significantly. Important factors that influence the economic efficiency include the CO_2 market price, the cycle time of the sorbent, the loading capacity and others (Sutherland 2019). Overall, however, DAC is still a relatively new technology, which is why price reductions for operation by a factor of around three are expected based on future technical improvements, falling energy requirements (including coupling effects due to the possible use of low-temperature steam) and scaling, on which the learning rate and the implementation rate also have a decisive influence.

A significant reduction in capital expenditures (capex) can be assumed simply due to upcoming improvements in the sorbents with an expected tenfold increase in the reaction surface and thus a ten-fold reduction in volume requirements (Fasihi et al. 2019). The assumed lifetime of DAC plants is currently around 20 - 25 years (Cames et al. 2021). The capacity of captured CO_2 per year is seen to be about a factor of three greater for HT DAC systems. In comparison, the capital expenditure for HT and LT-DAC plants is currently still almost the same. However, the option of waste heat utilization in LT-DAC plants is very promising as this reduces operational expenditures (OPEX), making LT technology the more sustainable of the two options (Fasihi et al. 2019). According to (Fasihi et al. 2019), the costs for the plants, for which the energy requirements were also previously listed, are:

CAPEX:	HT: 815 EUR/t CO_2/a (= 2.991 EUR/t_C)	LT: 730 EUR/t CO_2/a (= 2.679 EUR/t_C)
OPEX:	HT: 3,7%	LT: 4,0 %

4 Carbon Capture and Storage

With Carbon Dioxide Capture and Storage, CO_2 is captured (as pointed out in chapter 3) and subsequently stored underground for long-term disposal. Hence CO_2, e.g. from industrial processes, is no longer released into the atmosphere and thus cannot be effective as a greenhouse gas. Via DAC CO_2 is even captured from ambient air; together with subsequent underground storage Direct Air Carbon Capture and Storage (DACCS) leads to negative emissions. The storage of CO_2 captured from processes of bio-energy production is referred to as BECCS.

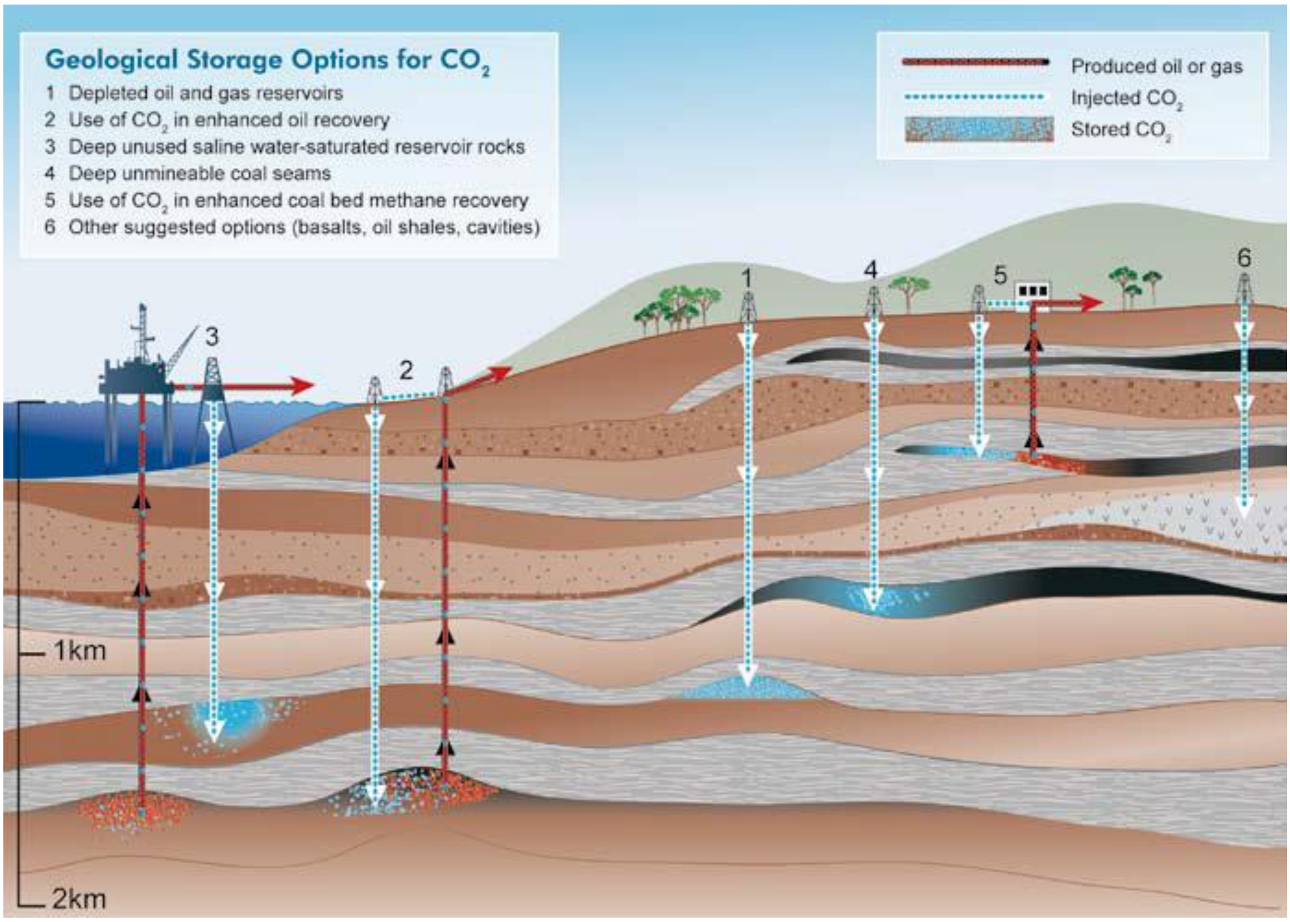
Capturing CO_2 from industrial processes usually leads to a reduced degree of effectiveness of these processes mainly due to energy consumption of the capturing process. Basically, the overall efficiency decreases with both a lower CO_2 concentration in the exhaust stream and with higher capturing rates (dena 2021b). The CO_2 concentration ranges from 30% for certain industrial processes to 5% for gas power plants. The energy demand for capturing increases disproportionally when increasing the capturing rate from 90 to 99%. This loss in overall effectiveness is reflected in the capture costs: The higher the amount of CO_2 concentration rate of an industrial process, the cheaper it is to capture the CO_2. As dena (2021b) points out, a high rate of capture increases the costs, too (section 4.1.3, Table 2).

Methods of CO_2 storage

Storage of CO_2 commonly is conducted in rocks in the underground. There are different technical processes already being used or under investigation for CO_2 storage:

- Storage inside depleted hydrocarbon reservoirs (Figure 5, number 1)
- Storage in saline aquifers, i.e. deep, saline groundwater levels (Figure 5, number 3)
- Storage in un-mineable coal beds (Figure 5, number 4)
- Storage in the form of solid carbonate minerals within the pore volume of suitable rocks (Figure 5, number 6)

Figure 5: Options for CO_2 storage



Source: IPCC (2005)

For storage inside depleted hydrocarbon reservoirs and saline aquifers, CO_2 is injected into the pore volume of rocks. For that purpose, boreholes are drilled inside the reservoir rock formations or pre-existing boreholes from hydrocarbon production are reused. In hydrocarbon reservoirs this process is often combined with enhanced oil recovery (EOR). The pressurised injection of CO_2 facilitates the recovery of oil that cannot be extracted using conventional production technology. A geologic trap, i.e. an upheaval of the reservoir rock and overlying sealing cap rock, the gas is kept underground.

Saline aquifers are deep reservoirs of groundwater that have no exchange with higher, used levels of groundwater. According to (dena 2021b) storage in saline aquifers can usually be done in depths between 800 and 2.500 m below ground level. Due to the environmental conditions in that depth, CO_2 exists in a fluid or hypercritical state. Water in these depths is often enriched with dissolved Ions and therefore is of a higher density than meteoric water of near-surface groundwater levels. In combination with overlying sealing caprocks the high saturation and density prevent the release of CO_2 from the aquifer.

CO_2 may be stored in coal beds that are likely to be un-mineable in the foreseeable future. The gas could be injected into a coal bed via boreholes and be absorbed on the coal surface. This concept is subject to scientific research.

In Iceland, the company Carbfix has been working on the storage of CO_2 in basaltic rocks since 2007. During the process water with dissolved CO_2 is injected into basaltic rocks of the Atlantic mid-ocean ridge. Due to the low pH, the water reacts with the silicate minerals of the basalt, forming carbonates that mineralise within fractures inside the rock.

Besides storage in crustal rocks ocean storage and the forming of artificial carbonate minerals or rocks are discussed.

Risks of CO_2 Storage

The storage of CO_2 underground is not without risk. In principle, there is always the possibility of leakage from storage rocks. This risk is to be assessed differently, depending on the respective process.

In the course of the Earth's history, oil or gas has naturally collected in hydrocarbon reservoir rocks, mostly in the pore cavities of sedimentary rocks and has remained there for long periods of millions of years. It can therefore be assumed that other gases that are stored there after the end of hydrocarbon production will also remain in place after the wells have been sealed. To ensure this, the tightness of the sealed wells is monitored by pressure measurements, gas sensors and temperature measurements at the wellheads. It is important that the rocks of the reservoir, especially the sealing cap rocks, are not damaged during oil or gas production. In principle, structures that have several sealing geological barriers should always be envisaged for the storage of CO_2. According to IPCC (2018), it can be assumed that after 10,000 years, 70% of the stored CO_2 will still be retained in the subsurface; this corresponds to an average leakage rate of 0.003 % or 30 ppm (Cames et al. 2021). A similar assumption can be made for storage in saline aquifers, as pore storage is also used under similar geological conditions.

The company Carbfix states that within 2 years 95% of the injected CO_2 mineralises; leakage is excluded after the formation of stable carbonate minerals. To what extent and over what periods of time the carbonate minerals can re-enter the carbon cycle by dissolution after the end of storage and equilibration of the chemical milieu in the pore spaces of the basalt with the surrounding seawater is not yet known.

To store CO_2 underground, the CO_2 must first be transported to the location of an injection well. Transport can be by pipeline, but also by ship or by rail or road. There is also the possibility of leakage during transport, for example during pipeline transport over long distances or to offshore injection facilities. Leakages can be identified by the difference in the amount of gas between the injection point and the withdrawal point. The risk of such leakages can be reduced by regular and careful maintenance and constant monitoring of the pipelines.

Further risks exist during the injection process itself. For example, overpressure during storage can lead to contamination of groundwater or seismic activity (Fuss et al. 2018).

Monitoring of the reservoirs must be ensured during storage and in the long term. In this way, leakages can be detected at an early stage and counter-measures can be initiated.

Potentials and limits of CO_2 Storage

CCS is a technological way of reducing CO_2 emissions or even of generating negative emissions. The storage of CO_2 in depleted hydrocarbon reservoirs is the most accessible option. Reservoirs are available and easy to develop for the storage of CO_2. Due to the previous extraction of oil or gas, the reservoir rocks and their geological situation are well known and characterised. The storage of CO_2 in depleted hydrocarbon reservoirs or in underground pore reservoirs is already practised on a small scale, e.g. in the USA in connection with EOR and in Norway in underground reservoirs in the North Sea. However, the volume of these reservoirs is limited. (Kearns et al. 2017) estimate the global capacity for practically accessible geologic storage to be between 8,000 and 55,000 Gt CO_2. (dena 2021b) calculate the storage capacity for Europe to be at least 300 Gt.

Suitable storage rocks are usually not located directly near large industrial CO_2 producers. The captured gas has to be transported to storage sides. From a global perspective, large hydrocarbon reservoirs exist, for example, in the Middle East, North Africa, Siberia or the Gulf of Mexico. Large producers of CO_2 through industrial processes or energy generation, on the other hand, are located in the USA and the European and Asian industrial nations. This leads to long transport routes for CO_2 captured from processes.

Storage in deep saline aquifers is also linked to suitable site conditions. Suitable geological structures, dense barrier rocks and sufficient saturation of the groundwater must be present. In addition, these reservoirs must first be developed, i.e. extensive exploration of the subsurface is necessary in order to locate and use suitable aquifers. The technology is still being researched. In Brandenburg (Germany), for example, storage in saline aquifers was carried out as part of a research project.[6] With the invention of the Northern Lights[7] project in Norway, commercial storage of CO_2 in deep saline aquifers will be implemented on a larger scale in Europe.

Storage through mineralisation in basaltic rocks is currently being tested in Iceland (by Carbfix, see above). Since September 2021, a commercial plant has been in operation there that realises direct air capture in connection with the mineralisation of the extracted CO_2 underground, i.e. it enables negative emissions.

Renewable energy and land required

Resources are also needed to implement CCS. Depending on the process, energy and land consumption as well as underground reservoirs are the main factors to be considered. For storage in pore reservoirs, CO_2 must be dried and compressed. In the Carbfix process for storage in basalts, the gas is dissolved in water. In all cases, pumps have to be operated to generate and maintain the necessary pressure for injection.

Energy is also needed before the actual storage. DAC in particular is an energy-intensive process. The ambient air contains only about 0.04% CO_2. Therefore, a correspondingly large amount of air must be converted in order to extract CO_2. Due to this low efficiency, a large technical effort is required in relation to the amount of gas produced. In order to achieve negative emissions, the energy used must also be generated in a climate-neutral way.

The above mentioned company Climeworks in Iceland uses energy from a geothermal power plant for this purpose. At the sites of suitable pore storage facilities in depleted hydrocarbon deposits, solar plants or wind turbines might have to be erected for this purpose. This leads to a high consumption of land. Solar plants in desert regions would potentially be dependent on regular cleaning of the surfaces with water, which leads to further consumption of resources.

6 Pilot project Ketzin, https://www.co2ketzin.de.
7 https://northernlightsccs.com/.

For the storage of CO_2 produced by bioenergy generation, the need for biomass in particular leads to land consumption. In the case of large-scale industrial application, further problems can be expected, such as a reduction in biodiversity due to the large-scale cultivation of plants for BECCS.

The use of CCS to store CO_2 from industrial processes also consumes energy. The capture of the gas reduces the efficiency of industrial plants. This means that additional energy is required for the same production. Furthermore, transport of CO_2 also requires energy; the construction of a pipeline network is also associated with resource consumption. Since such a CO_2 pipeline network does not yet exist in Europe, transport will first have to be carried out by ship. This results in further CO_2 emissions.

4.1 Situation in Germany

4.1.1 Overview

In Germany, the Federal Act Concerning the Demonstration of the Permanent Storage of Carbon Dioxide regulates the research, testing and demonstration of technology for the permanent storage of carbon dioxide in sub-surface rocks (Kohlendioxid-Speicherungsgesetz - KSpG 2021). To date, there is no regulation for the commercial or industrial use of carbon dioxide storage in Germany.

A number of research projects dealt with the subject of CO_2 storage. Between 2008 and 2011 the project *Information System on reservoir rocks in Germany – a base for the climate-friendly geotechnical and energetical use of the deep basement* developed a nationwide coordinated overview of areas with reservoir and caprocks worthy of study, with a focus on the permanent geological storage of CO_2.

In Ketzin in the federal state of Brandenburg, a research team headed by the German Research Center for Geosciences injected 67.271 tons of CO_2 in porous rocks and investigated underground processes during injection and the subsequent propagation of CO_2 inside the reservoir[8]. From 2016 to 2020, scientists from the German Helmholtz Centre for Ocean Research in Kiel joined in the European research project STEMM-CCS[9] on the monitoring of CO_2 stored in sub-seabed reservoirs.

4.1.2 Recent initiatives

To date, the pilot reservoir of Ketzin is the only storage facility for CO_2 in Germany. It is also the first storage site for CO_2 in the world that has been shut down permanently. The KSpG has been evaluated by the German federal government in 2018 (BMWi 2018). On CCS the evaluation report concludes that there is little acceptance within German society on the industrial use of CCS, mainly because most of the storage capacity, i.e. suitable reservoir rocks, in Germany is situated onshore and CCS, especially the danger of leakage, is seen as a threat to public health and safety.

With a view to European and international CCS initiatives, German companies are engaged in a number of projects. Wintershall/DEA[10] is cooperating with the Danish Ministry of Climate, Energy and Utilities and the Danish companies Maersk Drilling and INEOS Oil & Gas Denmark to develop the offshore CO_2 storage site Greensand[11] in the North Sea. The project aims at storing CO_2 in depleted oil and gas reservoirs. During a pilot phase, injection in the oil field Nine West is being used

8 https://www.co2ketzin.de/en/pilot-site-ketzin/summary.
9 https://www.stemm-ccs.eu/.
10 https://wintershalldea.com/en/newsroom/offshore-ccs-planned-2025-project-greensand.
11 https://projectgreensand.com/.

to demonstrate the feasibility of sub-seabed storage. Finally, up to eight million tons of CO_2 per year shall be stored. This corresponds to 25-40% of the Danish target on carbon reduction.

One of the largest producers of CO_2 in Germany, RWE, and the Royal Dutch Shell company signed a memorandum of understanding to cooperate in the field of green hydrogen production. Furthermore, the companies aim at decarbonising RWE's gas- and biomass-power stations by capturing and storing CO_2 arising during energy production.[12] Both companies already collaborate in the project NortH2 on the development of a green hydrogen supply chain.[13]

Another main German industrial producer of CO_2, Heidelberg Cement, is currently engaged in building the first industrial-size CCS facility at a cement production facility in the world. In Brevik, Norway, Heidelberg Cement plans to capture 400.000 t CO_2 annually, which will subsequently be transported to a storage site and permanently stored.[14] For that purpose, the company cooperates with the state-owned Norwegian oil- and gas-company Equinor.

Equinor is currently developing the CCS project Northern Lights.[15] With Northern Lights, Equinor will offer the permanent burial of CO_2 in reservoir rocks of the Norwegian continental shelf to industrial producers in Europe, including the transport of captured CO_2 by ship to an injection plant on the island of Ljøsøyna west of Bergen. Northern Lights is part of the Norwegian CCS initiative Longship.[16]

After successfully storing more than 19 Mt CO_2 inside the reservoir rocks of the Sleipner gas field, CCS in rocks of the Norwegian North Sea is being upscaled by Longship. Starting with Northern lights, which shall be capable of storing 1.5 Mt CO_2 a year from 2024 onwards, Norway wants to offer a way of decarbonising industrial processes to emitters from all over Europe. Depending on market demand, Northern Lights shall be developed to a capacity of up to 5 Mt a year. Quality specifications for liquified CO_2 and CO_2 Cargo Quality Specifications are readily available for interested industrial emitters through the project's website as well as a mutual confidentiality and non-disclosure agreement to be signed by the Northern Lights and potential industrial partners.

4.1.3 Abatement costs: capture, transport, storage

In Germany, CCS was intensively discussed in the early years of this century, particularly as an option for extending the lifetime of coal power plants (clean coal). However, the acceptance of the technology was limited because large majorities of the population have preferred decarbonisation strategies to be based on renewable energies rather than fossil technologies. In 2019, the government and the coal industry agreed to phase-out electricity generation form coal by 2038 the latest, although the end date was advanced to "ideally" 2030 in the coalition agreement of new government. However, with a clear end date for coal and the view that negative emission technologies may be required in the future to counterbalance GHG emissions, which are heavy to abate, the interest in CCS has increased again.

12 https://www.rwe.com/en/press/rwe-generation/2021-11-10-shell-and-rwe-want-to-drive-energy-transition-forward/.
13 https://www.north2.eu/en/
14 https://www.heidelbergcement.com/en/pr-15-12-2020.
15 https://northernlightsccs.com/.
16 https://northernlightsccs.com/about-the-longship-project/.

Table 2: Cost ranges for capture, transport and storage

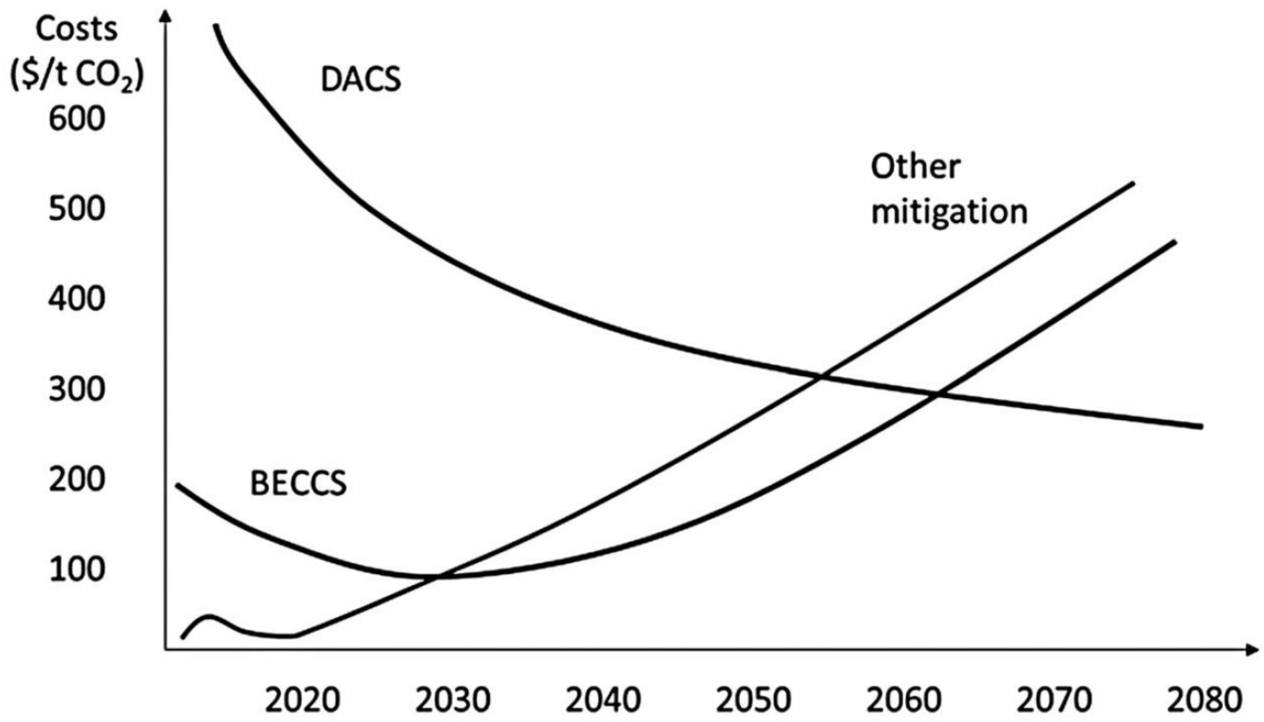
	USD/t CO_2	
Capture		
Price range	Low	High
Post-combustion capture		
Power plants	53	106
Iron & steel	59	106
Cement	59	175
Basic chemistry	26	38
Steam reforming	15	64
Oxyfuel combustion Capture		
Power plants	38	71
Cement	57	57
IGCC: Per-combustion capture	41	48
DAC low temperature (2030)	118	118
DAC high temperature	101	550
Transport		
Distance	180 km	1,500 km
Truck	27	231
Train	2	21
Ship		
Low capcity (2.5 Mt CO_2/a)	17	24
High capacity (20 Mt CO_2/a)	13	20
Onshore pipeline		
Low capcity (2.5 Mt CO_2/a)	6	6
High capacity (20 Mt CO_2/a)	1	6
Offshore pipeline		
Low capcity (2.5 Mt CO_2/a)	11	60
High capacity (20 Mt CO_2/a)	4	20
Storage		
Price range	Low	High
Onshore		
Exploited oil and gas fields	5	12
Saline aquifere	7	14
Offshore		
Exploited oil and gas fields	9	17
Saline aquifere	13	24
Total		
Price range	Low	High
Power plants	54	142
Iron & steel	76	142
Cement	73	211
Basic chemistry	43	73
Steam reforming	32	99
DAC low temperature (2030)	123	248
DAC high temperature	117	585

Source: dena (2021b), authors' own calculation

Against this background, dena (2021b) has analysed the most recent cost estimates for the individual process steps involved in CCS (Table 2). These cost ranges included both capital and operational expenditure.

Capture costs mainly depend on the concentration of the source and thus on the technology of the source and whether it is a point or a dispersed source. Point sources range from 15 to 175 USD/t CO_2 with a realistic order of magnitude of 70 USD/t CO_2 for point source. DAC is significantly more expensive but expected to become significantly cheaper in the future (Figure 6).

Figure 6: Indicative cost development curves for DACCS and BECCS



Source: Honegger und Reiner (2018)

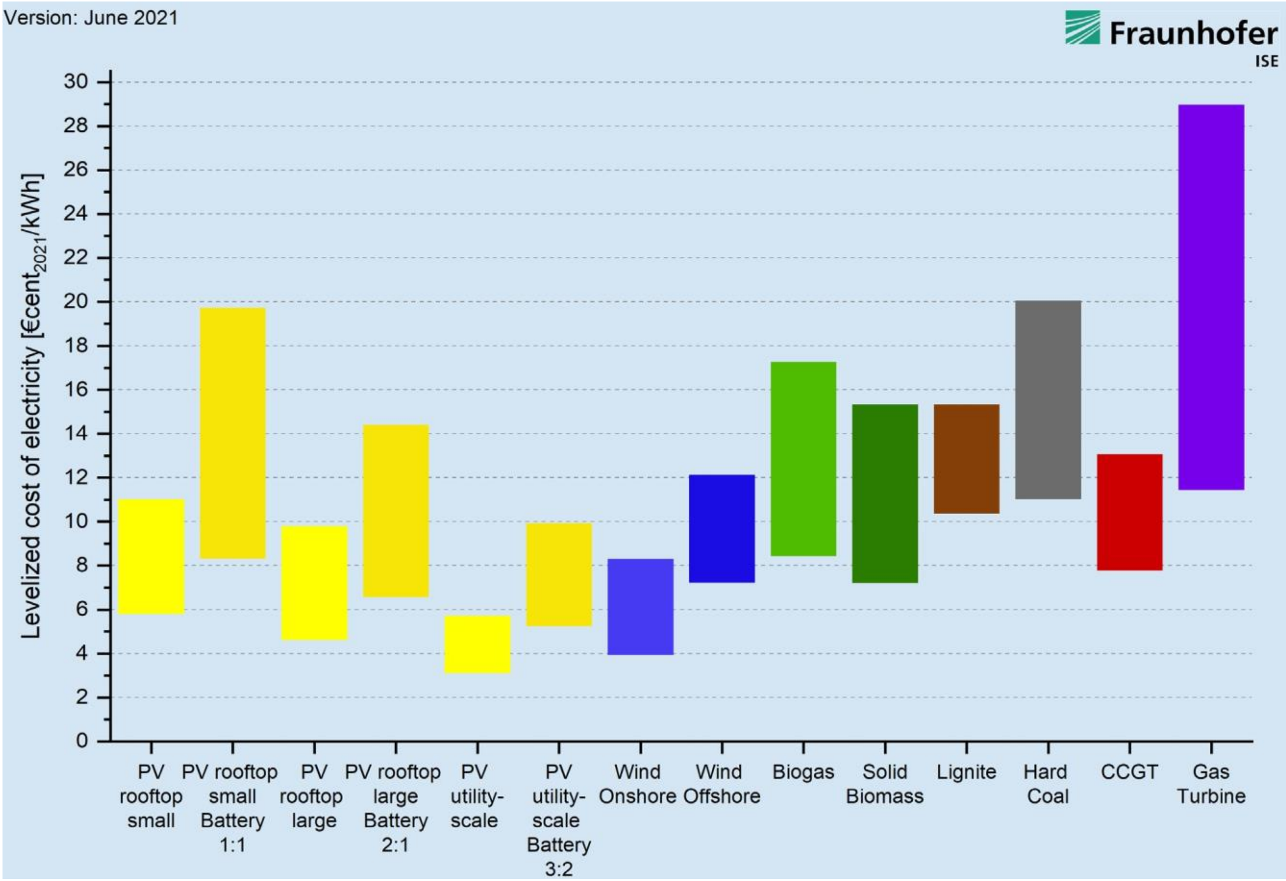
Transport costs depend on the mode of transport, the distance and the transport capacity, which involve strong economies of scale with increasing transport capacities. On distances of 180 km, they can be as low as 1 USD/t CO_2 in pipelines but can also amount to 27 USD/t CO_2 if the CO_2 is transported with trucks.

The storage costs depend on both whether the sites are onshore or offshore and whether exploited oil or gas fields or saline aquifers are used. However, the cost range is smaller than for the other process steps involved. In addition, storage is likely to be the smallest cost component of the overall CO_2 avoidance costs through CCS.

For comparing the total avoidance costs for the different source, we have assumed the CO_2 is transported over 800 km. The total avoidance costs vary significantly between point and dispersed sources. For point sources, they range from 32 USD/t CO_2 to more than 200 USD/t CO_2. For dispersed sources, they range from more than 100 USD/t CO_2 to more almost 600 USD/t CO_2.

Dispersed sources are likely to be applied both as negative emissions technologies towards the mid of this century and for generating climate neutral synthetic e-fuels for sectors which are heavy to abate, e.g. aviation and shipping. For point sources, the avoidance costs have to be added to the production costs. For electricity generation this is unlikely to be more cost-efficient than electricity generation from renewable energy since the Levelized Cost of Electricity (LCOE) for many renewable technologies are currently already lower than those of fossil technologies (Figure 7).

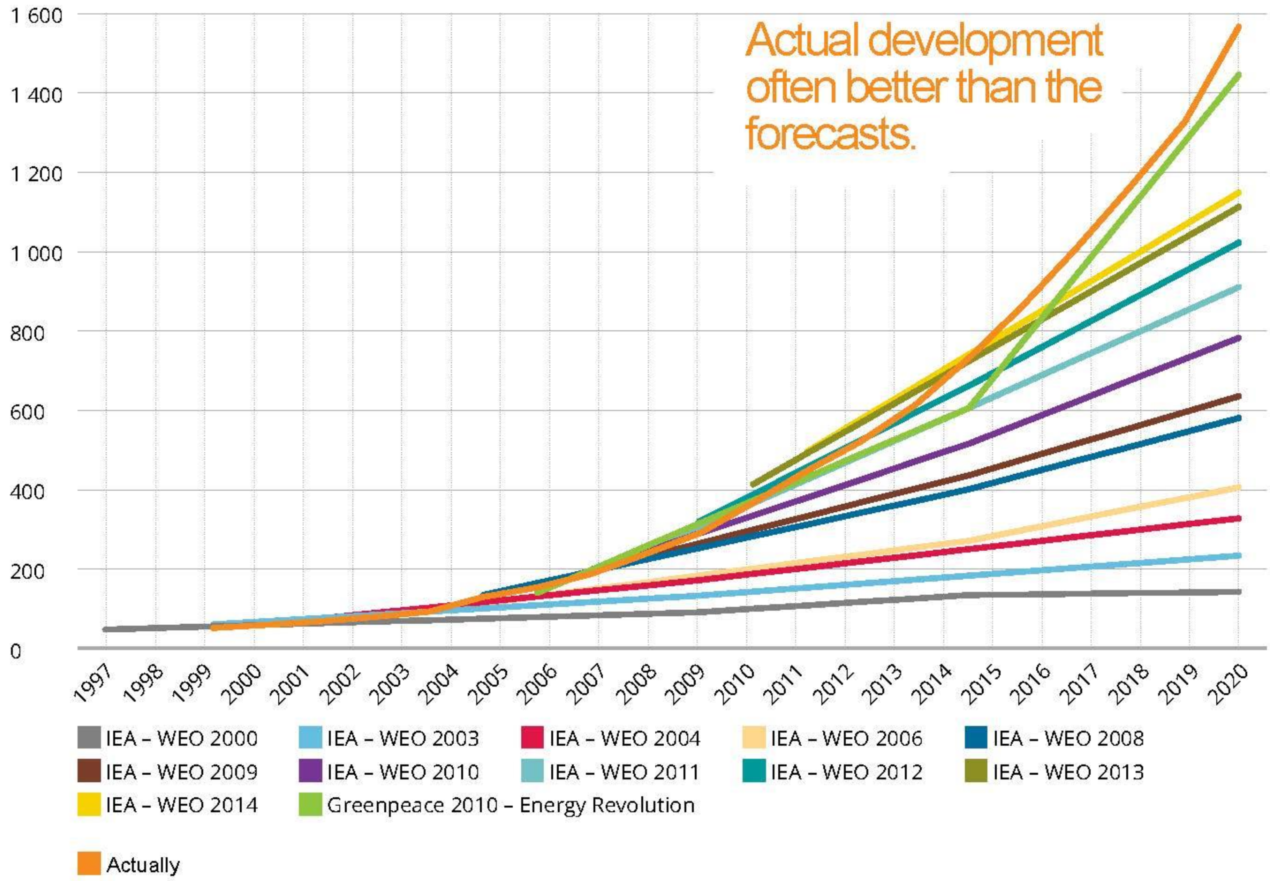
Figure 7: Levelized cost of electricity generation



Source: ISE (2021)

The figures include CO_2 prices of about 40 USD/t CO_2. CO_2 prices are projected to grow further, with the result that CCS may seem economically feasible in certain constellations. However, despite the price growth this is unlikely to be the case in Germany since the LCOE of renewables are expected to decline further; as a consequence their capacity is likely to expand globally and in Germany faster than projected (Figure 8).

Figure 8: Global expansion of renewable energies in GW



Source: WWF (2022)

4.2 Situation in Japan

4.2.1 Overview

CCS plays a key role in Japan's energy strategy for which METI is responsible. In its long-term growth strategy based on the Paris Agreement, which was decided by the Cabinet in June 2019, Japan positioned CCS as a technology that "should be developed toward the introduction of CCS by 2030 on the premise of its commercialization, in particular for coal-fired power generation".[17] The **6th Basic Energy Plan** states that CO_2 from thermal power generation must be recovered and stored to achieve carbon neutrality by 2050. For CCS, the roadmap for technical development, cost reduction as well as development of suitable sites shall be designed. The government is also working on demonstration tests for liquid CO_2 transportation by ships and optimizing networks among CO_2 emissions source, recovering and storage sites (METI 2021b).

[17] METI (2020): Report on Large-scale CCS Demonstration Project Compiled, https://www.meti.go.jp/english/press/2020/0515_004.html.

Japan's coastal areas are estimated to hold a geographical CO_2 storage potential of about 150-240 billion tonnes[18] (ANRE 2020). Waters less than 200 m deep are of particular interest with an estimated capacity of about 146 billion tonnes and a further storage potential of about 90 billion tonnes lies in waters with a depth of 200-1,000 m (MoEJ 2019). Overall, ongoing research estimates that there are several sites across the country where hundreds of millions to billions of tonnes of CO_2 could be stored. However, further research and assessment is needed to give an accurate indication of the amount of storage. As of March 2020, the following data was available (JCCS 2021):

- Evaluation based on 3D survey data from 7sites: total approx. 9 billion tonnes;
- Evaluation based on 2D survey data from 5 sites: total approx. 3 billion tonnes;
- Evaluation based on rough estimate of 14sites: total approx. 43 billion tonnes.

While industrial areas with high CO_2 emissions are mainly located in coastal areas on the Pacific side, areas suitable CO_2 storage are mainly located on the Sea of Japan side. Due to the resulting long distance between emitters and the planned storage site, the stored CO_2 cannot be transported via pipelines, but must be transported by ship (ANRE 2020).

Because of this problem, a demonstration project for the long-distance transport of CO_2 is currently planned which will transport captured, recovered, and then liquefied CO_2 from a coal-fired power plant in the city of Maizuru (Kyoto Prefecture) by ship over about 1,500 km to the storage site near Tomakomai (Hokkaido). Transport of liquefied CO_2 by ship at low temperature and low pressure has not yet been realised in any country. Japan plans to pioneer the demonstration of CO_2 shipments in 2024 (ANRE 2020).

4.2.2 Recent initiatives

4.2.2.1 CCS demonstration plant in Tomakomai, Hokkaido

Since 2012, Japan's first large-scale CCS demonstration project for CO_2 capture (injection, storage and monitoring) has been running in Tomakomai (Hokkaido). In the project by METI, NEDO and Japan CCS Co. Ltd, part of the waste gas extracted by Pressure Swing Adsorption (PSA) from a hydrogen production plant of Idemitsu Kosan Co., is transported via pipeline to the neighbouring capture plants. PSA waste gas has a CO_2 content of 52%. The captured CO_2 is then compressed and pumped via pipelines to two underground reservoirs located 3 to 4 km offshore under the seabed at different depths. The project uses BASF's licensed technology - OASE®. By using the amine absorbent with excellent recovery efficiency and applying the energy saving two-stage absorption process, the heat input to the amine reboiler was reduced to 0.907 GJ/t-CO2, which is less than one third compared to the conventional process.[19]

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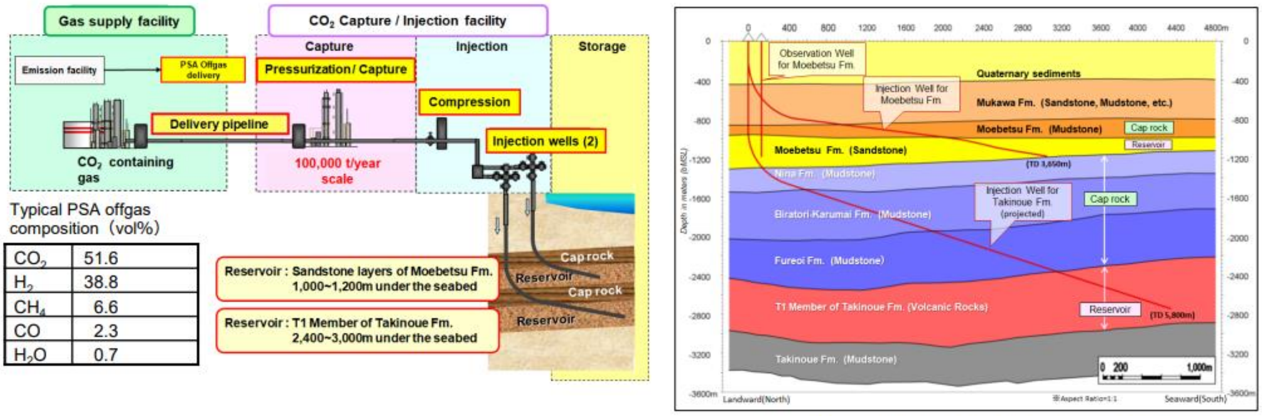
[18] Japan's annual CO_2 emissions are 1.19 billion tonnes, of which about 300 million tonnes are from coal-fired power stations, http://www.env.go.jp/earth/ccs/ccus-kaigi/2-1_CCUS_storage.pdf.

[19] BASF. OASE®: 日本初CCS大規模実証試験の成功に貢献 - 苫小牧CCSプロジェクト. OASE® contributes to the success of Japan's first large-scale demonstration of CCS - Tomakomai CCS Project, https://www.basf.com/jp/ja/media/Story/ccs-project.html.

Figure 9: Overall scheme of Tomakomai CCS Demonstration Project

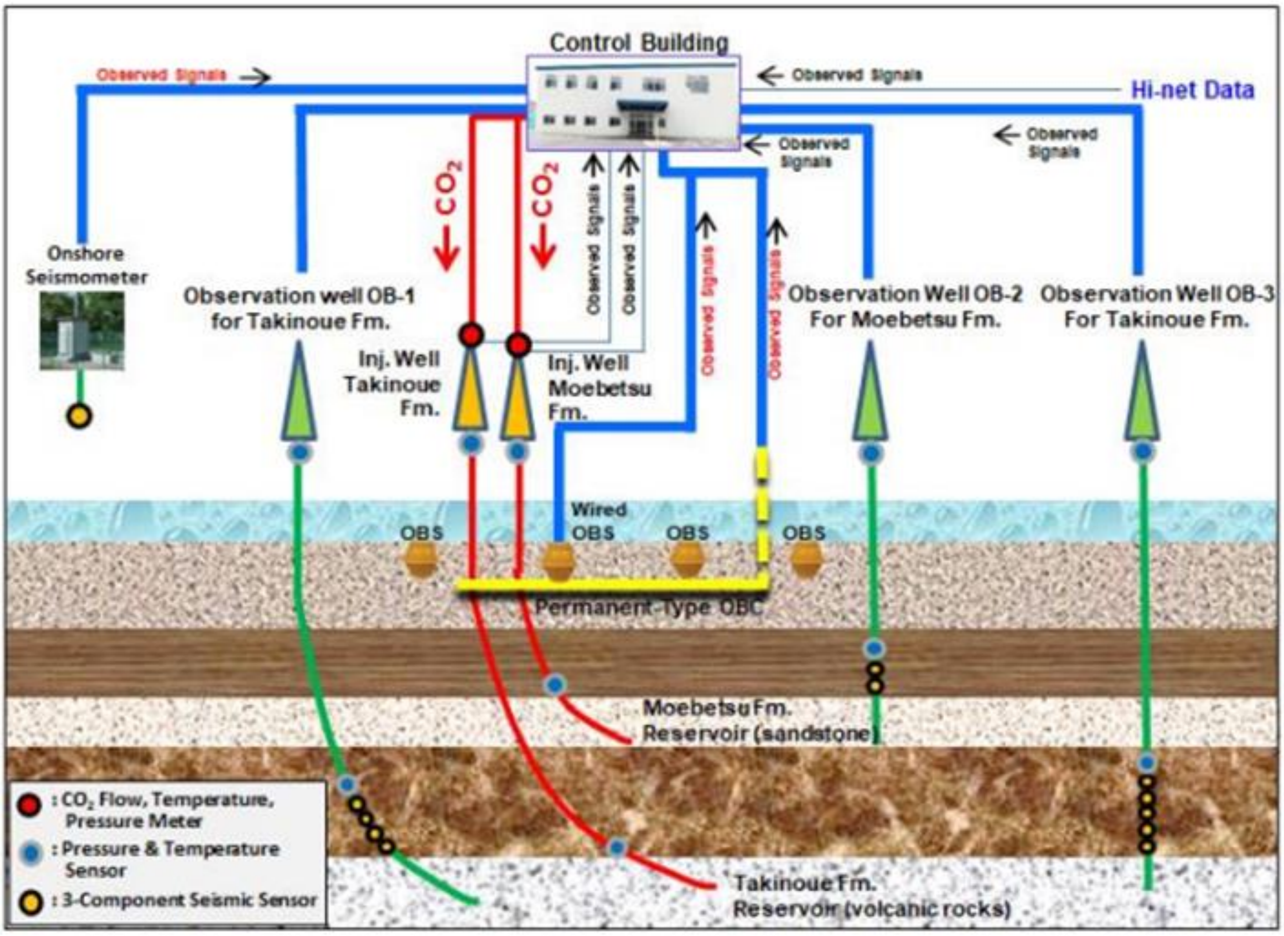


Schematic diagram of geologic layers and injection wells

Source: METI; NEDO; JCCS (2020)

The demonstration plants were commissioned in 2015. Since then, the behaviour of the injected CO_2 has been repeatedly monitored by 3D and 2D seismic measurements in conjunction with various seismic sensors (seabed cable, seabed seismometer and onshore seismometer). In advance, a survey of seawater and marine organisms was conducted in accordance with the Marine Pollution Prevention Act. Since the plant was commissioned in 2016, a total amount of 300,000 t CO_2 was injected into the ground by 22 November 2019. The injection was subsequently stopped for monitoring.

Figure 10: Schematic diagram of monitoring system



Source METI; NEDO; JCCS (2020)

Table 3: Monitored Items

Equipment/Work	Monitored Items
Injection wells, facilities	Downhole: temperature, pressure wellhead: injection temperature, pressure, CO_2 injection amount
Observation wells	Downhole: temperature, pressure, micro-seismicity, natural earthquakes
Ocean Bottom Cable (OBC)	Micro-seismicity, natural earthquakes, recording of 2D seismic surveys
Ocean Bottom Seismometers (OBS)	Micro-seismicity, natural earthquakes
Onshore seismometer	Micro-seismicity, natural earthquakes
2D seismic survey	Distribution of CO_2 in reservoir
3D seismic survey	Distribution of CO_2 in reservoir
Marine environmental survey	Marine data (physical, chemical properties, biological habitat, etc.)

Source: METI; NEDO; JCCS (2020)

4.2.2.2 BECCS in Omuta, Fukuoka

In October 2020, the demonstration operation of a CO_2 capture and recovery plant started at a 50,000 kW biomass power plant of Sigma Power Ariake Co. Omuta City (Fukuoka Prefecture/Kyushu). More than 500 t CO_2 are captured per day, which corresponds to about 50% of the plant's daily CO_2 emissions (MoEJ 2020c). 18 consortium partners, including major Japanese companies such as Toshiba Energy Systems, Chiyoda Corp. and Mitsubishi Materials are involved in the project.[20] It is the first plant in Japan (as of October 2020) that can recover more than 50% of the CO_2 emitted by a thermal power plant company's technology. It uses an amine solution to absorb CO_2 at low temperatures and releases it at high temperatures; CO_2 is absorbed by the amine solution, and then it is discharged from the stack. The CO_2 absorbed amine solution is then fed into the regeneration tower where it is heated in a boiler to separate the amine solution returned to absorption column where the separation and recovery process is repeated (Sankei Newspaper, 2021). In the future, possible storage of the recovered CO_2 will be considered (MoEJ 2020c).

4.2.2.3 CO_2 separation: Osaki CoolGen

In the city of Osaki (Kyushu), a project is underway to develop and test various HELE (high efficiency-low emission) technologies in thermal power generation project is being carried out by Osaki CoolGen Corporation, which was founded in 2009 by the J-Power and Chugoku Electric Power Company. The Osaki CoolGen project, as it is called, builds on the knowledge and findings of the EAGLE project which was completed in 2013. It aims to gradually demonstrate IGCC (Integrated Gasification Combined Cycle) technologies and CO_2 capture in coal- and gas-fired power plants on a large scale:

- Step 1: Oxygen-powered IGCC;
- Step 2: IGCC (Integrated Gasification Combined Cycle) + CO_2 Capture;
- Step 3: IGFC (Integrated Gasification Fuel Cell Cycle) + CO_2 Capture.

The power plant constructed in the first step has an efficiency of 40.8% HHV (gross calorific value), which means that the target of 40.5% HHV has been exceeded.[21] The objective for the second step is to achieve a CO_2 capture rate of more than 90% with a CO_2 purity of 99%. The implementation of step 2 and 3 took place from FY 2016 to FY 2022, FY 2018 to FY 2022.[22] However, the results have not been announced yet. The recovered CO_2 will be liquefied and transported to investigate ways to use it effectively. This includes, for example, using it in tomato vegetable gardens, promoting research into the production of biofuel from microalgae or developing environmentally friendly concrete.

4.2.2.4 Feasibility study for CCS in Australia

In October 2021, Japan Oil, Gas and Metals National Corp. (JOGMEC) and Mitsui & Co Ltd said they would jointly conduct a feasibility study for CCS using Mitsui's facilities in Western Australia. The study will focus on examining the possibilities for the production and export of ammonia. The

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20 Toshiba Energy Systems & Solutions Corporation (2021): Adopted for the Ministry of the Environment "FY2021 Project to Promote the Creation of Circular Carbon Society Model through CO_2 Recycling", https://www.toshiba-energy.com/en/info/info2021_0824.htm.

21 NEDO (2019): 世界初、石炭ガス化燃料電池複合発電（IGFC）の実証事業に着手. World's First Coal Gasification Fuel Cell Combined Cycle (IGFC) Demonstration Project Launched, https://www.nedo.go.jp/news/press/AA5_101103.html.

22 NEDO (2020): 石炭ガス化燃料電池複合発電実証事業. Coal gasification fuel cell combined cycle power generation demonstration project, https://www.nedo.go.jp/content/100932833.pdf.

basis for the production of the ammonia will be hydrogen, which is to be produced from the Waitsia natural gas field. In addition, the two partners are also considering storing the CO_2 is released into the nearby depleted gas field after ammonia synthesis. First, however, the study will examine the effectiveness of CCS in the depleted gas field before further steps follow (Reuters 2021).

4.2.3 Abatement costs: capture, transport, storage

The Japanese Ministry of Environment (MoEJ) estimates CCS costs based on a 750 MW thermal power plant depending on the CO_2 capture technology used (SC, USC, IGCC, NGCC) and the transport distance in km. For example, the following costs are estimated for a distance of 600 km between the emitter and the storage site, depending on the technology used. The costs listed refer to 2014 and include recovery, liquefaction, transport, injection, storage, containment, and overgrowth costs (Table 4).

Table 4: Cost ranges for capture, transport and storage

	Transport distance km	CCS costs USD/t CO_2	Avoidance costs USD/t CO_2
IGCC	185	68	123
	600	75	133
	970	80	142
SC	185	78	131
	600	85	140
	970	90	148
USC	185	80	127
	600	87	136
	970	92	143
NGCC	185	109	146
	600	115	153
	970	121	159

Source: MoEJ (2014)

On average, the estimated CCS costs are thus 90 USD/t CO_2, and abatement costs of 139 USD/t CO_2. It is striking here that the costs for the cheapest CCS technology IGCC are 55% lower than the costs of NGCC, but the total abatement costs are only 15% lower (MoEJ 2014).

Based on CCS data from the Tomakomai project (section 4.2.2.1), costs were estimated for a practical model with an annual capacity of 1 Mt for hydrogen and ammonia production through IGCC (Integrated Coal Gasification Combined Cycle). The estimated CCS costs for this model are 54 USD/t CO_2 with abatement costs of 64 USD/t CO_2 (METI; NEDO; JCCS 2020).

4.3 Comparison of Germany and Japan

The approaches for achieving climate neutrality and the role of CCS in this context are quite different for Japan and for Germany. Japan is focusing on both capturing CO_2 from fossil power plants and exploring storage capacity domestically but also abroad in Australia. Germany's new government aims at phasing-out electricity generation from coal by 2030 and considers natural gas power plants as a bridging technology which needs to be converted to green hydrogen as soon as possible. In addition, consideration of storing of CO_2 in domestic sites stalled more than 10 years ago and is being reconsidered in the context of negative emission for heavy-to-abate sectors based on a clear priority: 1) reducing GHG emissions, 2) CCS for heavy-to-abate point sources such as cement of lime and 3) compensating heavy to abate diffuse GHG emissions such as from agriculture through negative emission technologies.

5 Carbon Capture and Utilization

Carbon capture and utilization (CCU) is the separation of carbon dioxide (CO_2) and its subsequent use in further chemical processes.

Carbon-based energy sources and chemicals will play an important role in a future, defossilised industrial society, but they will then no longer be produced on the basis of oil, natural gas and coal, but on the basis of biomass or from CO_2 via power-to-X technologies (PtX). Possible carbon sources have already been listed and discussed in chapter 2; the energy for the production of PtX materials will in future generally be provided via electrolytically generated hydrogen. Important fields of application for PtX technologies are those sectors in which no more efficient, alternative technologies are available or in which carbon carriers are needed for material use, especially in the sectors of transport, basic chemicals and industry. Some PtX technologies are already developed to the point where they can be considered for use on an industrial scale, e.g. Fischer-Tropsch processes for the synthesis of hydrocarbons based on synthesis gas or olefin synthesis from methanol based on synthesis gas.

Apart from the metals sector, basic chemicals is the most energy-intensive industrial sector in Germany. A special feature here is that energy sources are not only used for energy, but also for material use. For a future sustainable basic chemicals industry, water and CO_2 will form the new raw material basis, which will be converted by means of PtX technologies using renewable electricity. Important **organic basic materials** in the chemical production chains are, for example, methanol and the high value chemicals (HVC) ethylene, propylene, butene and butadiene as well as the aromatics benzene, toluene and xylene.

In a broader sense, **synthesis gas** is a mixture of gases used for chemical synthesis, e.g. the mixture of nitrogen and hydrogen for ammonia synthesis. In a narrower sense, the term is used for mixtures of carbon monoxide and hydrogen (CO/H_2) in varying proportions (Arpe 2007). This synthesis gas, which is used e.g. for methanol synthesis, is conventionally obtained from natural gas by means of steam reforming, but also from coal and other carbon sources. In addition to the reverse water gas shift reaction (RWGS, see below), other processes for providing synthesis gas from CO_2 are currently under development, e.g. low-temperature electrolysis of CO_2 and high-temperature co-electrolysis (DECHEMA 2019). In low-temperature electrolysis, CO_2 is reduced to CO (cathode reaction) and H_2O is oxidised to oxygen (anode reaction). In small quantities, H_2 is also formed at the cathode. The desired H2/CO ratio can be adjusted by adding H_2. In high-temperature co-electrolysis, the two reactions of electrolytic hydrogen production and CO production by a reverse water-gas shift reaction (RWGS) are carried out simultaneously in one reactor. Different synthesis gas compositions can be produced by varying temperature, pressure, input and other operating parameters.

Methanol is one of the most important basic chemicals that serves as a starting material for numerous other applications in organic chemistry. Methanol is produced on a large scale from synthesis gas (CO/H_2) in a long-established process. The raw methanol produced is then purified from water and other by-products by means of distillation. Synthesis gas is also used for production of **synthetic methanol**. The process is long established and does not require a process change when using synthesis gas obtained from CO_2. A new approach is the direct methanol synthesis from the two feedstocks H_2 and CO_2 in a single-stage process without the generation of a synthesis gas. The direct process shows higher energy efficiency compared to conventional methanol synthesis (Anicic et al. 2014; LUT 2017) but is still in the development stage.

Synthetic methane (CH_4) is produced from hydrogen and carbon dioxide via a process called "methanation". This can be accomplished via a chemical synthesis with the help of a catalyst (Sabatier process) or biologically with the help of microorganisms (Oeko-Institut 2019). The chemical-catalytic methanation takes place in an exothermic reaction at a temperature of more than 200° C. The waste heat can be used, for example, for CO_2 capture from the air (LUT 2017). Biological methanation via microorganisms is carried out at 35 - 70 °C in an aqueous environment. Both technologies are not yet available on an industrial scale (Wuppertal Institut; ISI; IZES 2018; Prognos; Oeko-Institut; Wuppertal-Institut 2021).

There are currently two common processes for producing **synthetic fuels** from CO_2 and hydrogen: Fischer-Tropsch synthesis (FTS) and synthesis via methanol. In an FTS, a synthesis gas is produced with the RWGS at an operating temperature of around 1,000 °C, which is then converted into a mixture of different hydrocarbons. This mixture is then separated into the desired products in a refining process. The RWGS itself is an exothermic process that generates waste heat at a temperature level of approximately 220 °C. On the other hand, the RWGS reaction requires a heat supply at a temperature level of around 1,000 °C. This heat is provided via renewable electricity (IWES 2017). While FT synthesis is a long-established process that is nowadays mainly used to produce fuels from coal and natural gas, the RWGS reaction is predominantly still at a demonstration plant level (Timmerberg und Kaltschmitt 2019; UBA 2016). The future relevance of synthetic fuels is predominantly seen in the field of aviation and maritime transport and to a lesser extent possibly also for heavy-duty transport (DECHEMA 2019). For passenger car transport, electromobility is a much more cost-effective alternative to fossil fuels compared to synthetic fuels (Agora Verkehrswende 2018), which also requires significantly less renewable electricity, which is why the large-scale use of synthetic fuels in individual transport is considered unlikely.

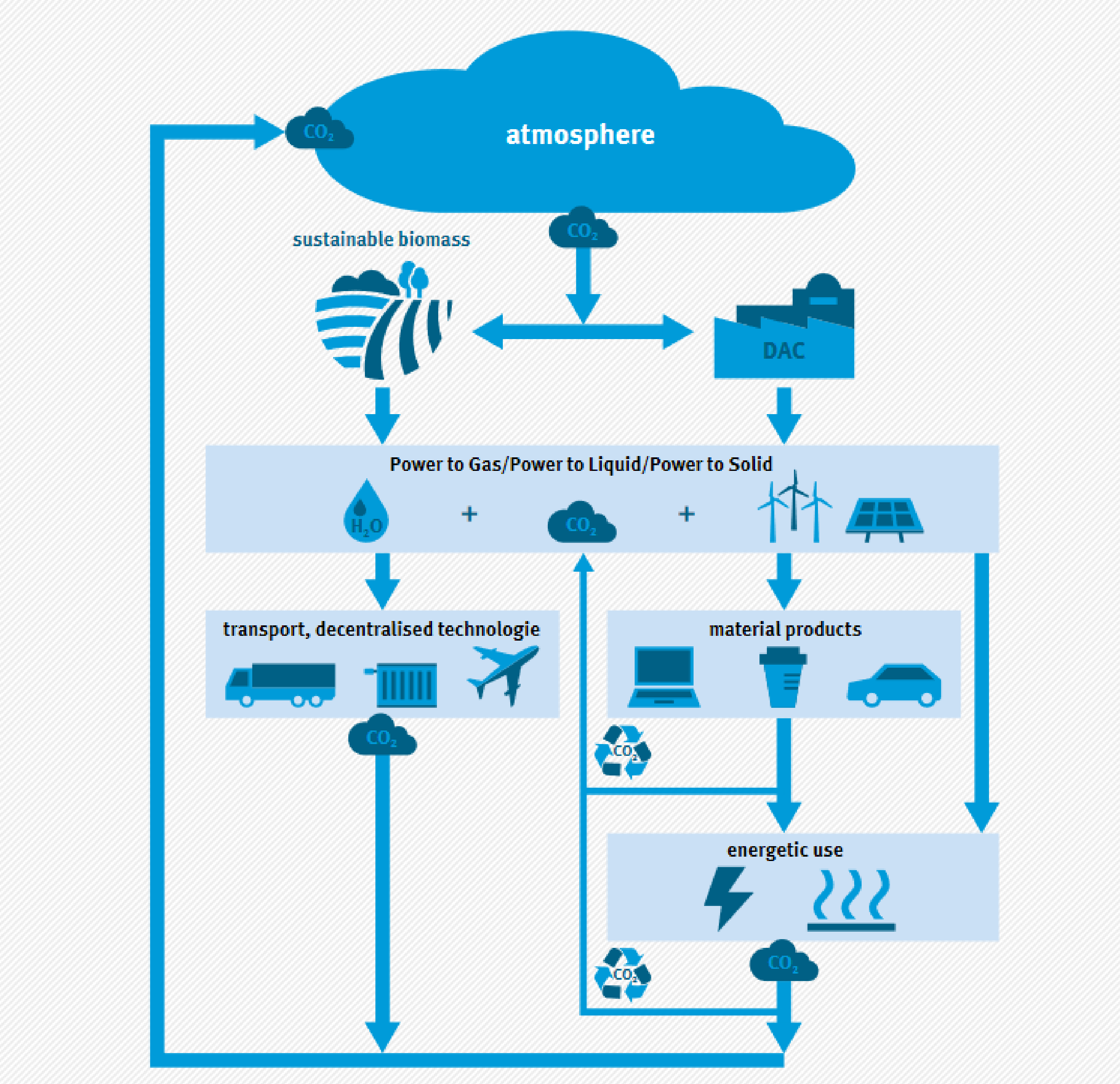
The climate neutrality of CCU processes is achievable in the long term on the condition that the carbon comes from air (DAC) or sustainable biomass[23] and all process energy is 100 % renewable. Carbon capture from air is in many cases still at the level of demonstration plants and is currently being scaled up to large-scale industrial use. This is a key technology in the use of PtX applications. Because biogenic processes cannot be scaled up to the same scale and because of the quantity limitation of sustainable biomass, the use of biogenic CO_2 in the production of PtX applications is limited. Industrial point sources based on fossil or geogenic carbon sources are not GHG-neutral CO_2 sources, especially since under the current framework conditions it is not ensured that the use of these CO_2 sources does not lead to a slowdown in emission reductions in these industrial sectors.

The German Federal Environment Agency (UBA 2021a) also does view CCU applications as a substitute for the reduction of fossil greenhouse gas emissions and emphasises that unavoidable greenhouse gas emissions, e.g. from cement and lime production, must be compensated in order to

[23] Since emissions from LULUCF can occur with cultivated biomass, this is strictly speaking only correct for waste biomass.

achieve greenhouse gas neutrality. CCU measures cannot contribute to compensation here.[24] Provided that CO_2 from the atmosphere is used as a carbon source, whether directly via DAC or indirectly via sustainable biomass, CCU technologies can in principle be operated in a greenhouse gas neutral manner. Figure 11 shows an overview of the greenhouse gas neutral use of CO_2 from the atmosphere for CCU.

Figure 11: Overview of the use of atmospheric CO_2 for CCU



Source: UBA (2021a)

Natural limitations

The actual production processes for PtX technologies do not require much **land**. At the same time, relevant land is required for CO_2 capture from the air and, above all, for the provision of renewable

[24] When used in building materials, a long-term bond of the carbon can be achieved.

electricity. The available land or the social acceptance for the use of land is a limiting factor for the expansion of PtX technologies in Germany and other densely populated countries (Oeko-Institut e. V. 2019). For this reason, and also because of the lower production costs, the production of synthetic fuels can be expected primarily at preferred locations in sparsely populated areas. PtX technologies have a much lower land use than the use of cultivated biomass as a feedstock: in the case of onshore wind power plants, some of the land used can continue to be used for agriculture and thus in the order of magnitude of other industrial processes. Some regions in the world, which are often discussed as preferred locations for the production of synthetic fuels due to their high solar radiation, e.g. the MENA region, South Africa, Australia or the southwest of the USA, are among the driest regions on earth (Schmidt et al. 2016). Agricultural land with nutrient-rich soils and good climatic conditions should not be claimed for power generation and CO_2 provision. With regard to the sustainability requirements for carbon storage in the soils and for biodiversity, assessment criteria such as High Conservation Value[25] (High Carbon Stock Approach)[26] and Key Biodiversity Areas[27] are suitable.

Hydrogen electrolysers require pure **water** as input. Solar energy plants have an additional and far greater water consumption than wind energy plants due to the necessary cleaning of the solar cells or the parabolic mirrors. Another water requirement arises from the cooling of the synthesis plants. For the production of synthetic fuels, this water requirement amounts to around 70 litres per litre of fuel (Malins 2017). From a sustainability perspective, it is therefore important that the use of new PtX plants should not negatively affect the availability, cost and quality of the drinking water supply at the production sites. Instead, the construction of new water infrastructure, e.g. a seawater desalination plant, could improve water availability for the local population, provided that negative environmental effects need to be addressed.

5.1 Situation in Germany

5.1.1 Overview

In Germany, there are a number of research and development projects involving large industrial companies and scientific institutes in which various processes for the use of CO_2 are being investigated and further developed. The public sector has been funding such projects very strongly in recent years, for example the Climate Protection Fonds or the Federal Ministry of Education and Research. In addition to projects that focus on synthetic fuels, especially synthetic kerosene, other projects focus on a variety of chemical intermediates and end products from the range of chemical applications.

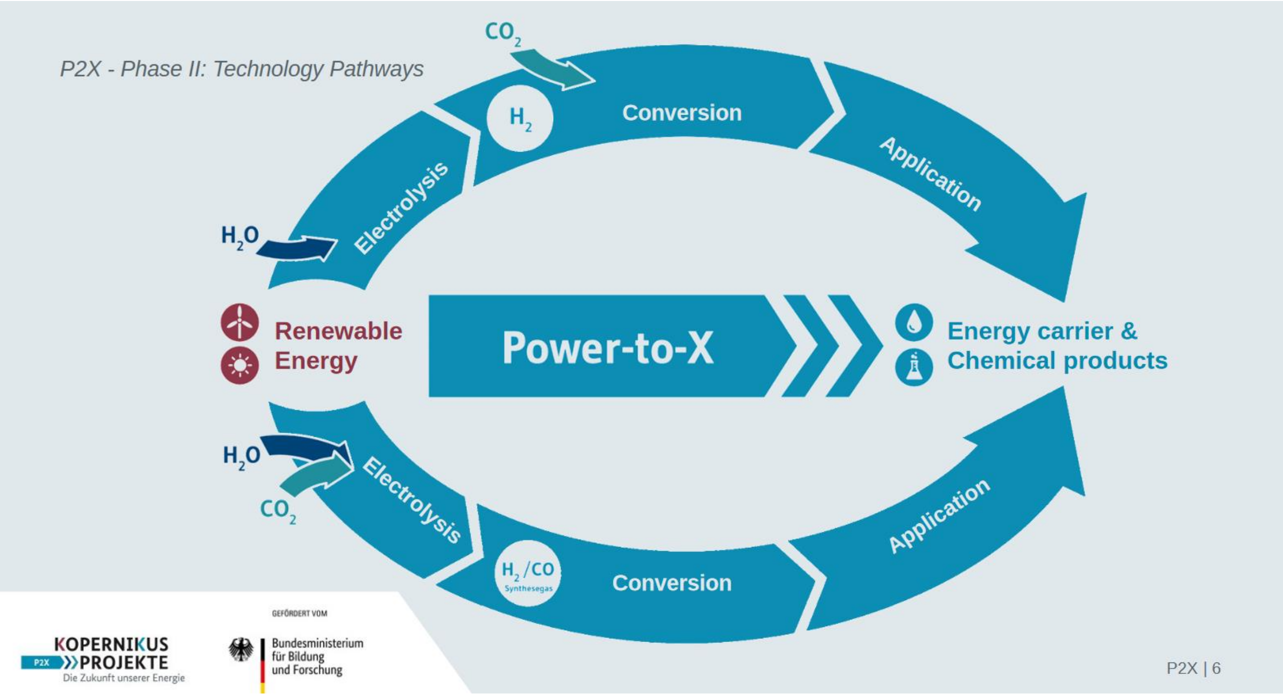
25 https://hcvnetwork.org.
26 http://highcarbonstock.org.
27 http://www.keybiodiversityareas.org/home.

5.1.2 Recent initiatives

5.1.2.1 Kopernikus P2X

In the joint project **Kopernikus P2X**[28], which is funded by the German Federal Ministry of Education and Research, various "Power-to-X" concepts are being researched and have been further developed since 2016. The aim is to implement selected technologies on an industrial scale. In Phase II since 2019, the project, which is coordinated by DECHEMA, RWTH Aachen University and Forschungszentrum Jülich, focuses on two technology paths: "hydrogen as an energy vector" and "synthesis gas as an energy vector" (Figure 12). Examples of products that are being targeted from CO_2 and H_2 in the joint project with the participation of numerous companies and research institutions are synthetic kerosene, polyurethane (e.g., for coatings, foams and adhesives) or hexanol and hexanoic acid, whose derivatives can be used as chemical value products for cosmetics.

Figure 12: Overview on the process routes of Kopernikus P2X



Source: Ausfelder and Dura (2021)

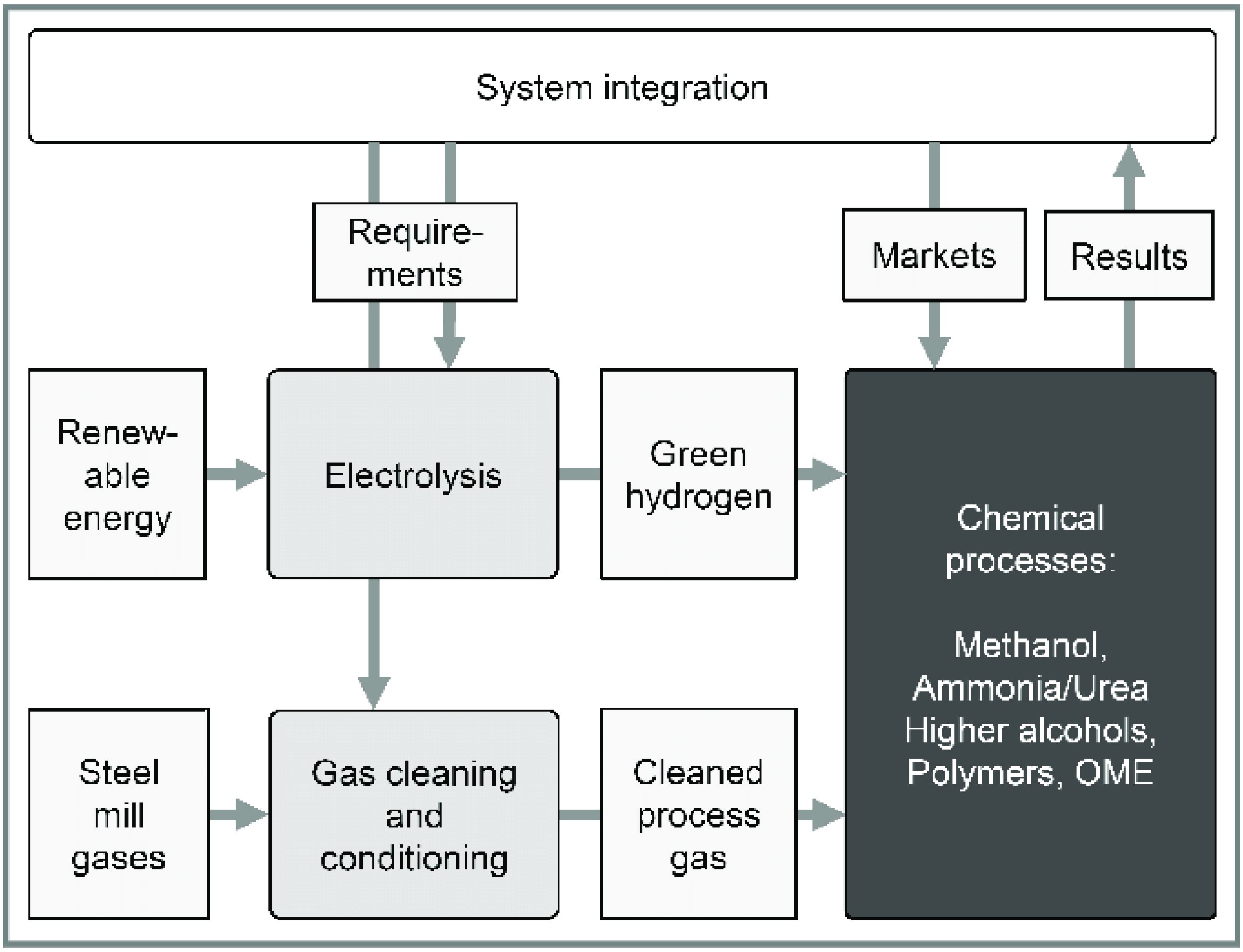
5.1.2.2 Carbon2Chem

The **Carbon2Chem**[29] project (coordination: thyssenkrupp AG, MPI-CEC and FhG-UMSICHT) is investigating how CO_2 from steelmaking gases can be converted into precursors for fuels, plastics or fertilizers. Since 2016, various industrial companies (including thyssenkrupp, Linde, Covestro, Evonik) have been working with the Max Planck Society, the Fraunhofer Society and universities to develop a solution that can be used worldwide to convert the waste gases from blast furnaces into precursors for fuels, plastics or fertilizers, e.g. methanol, urea or higher alcohols (Figure 13). The hydrogen required for this purpose is also produced by the companies from green electricity using

28 https://www.kopernikus-projekte.de/projekte/p2x.
29 https://www.fona.de/de/massnahmen/foerdermassnahmen/carbon2chem.php.

an electrolyser. In the second phase of the project, the focus will be on other CO_2 sources such as cement plants and waste incineration plants.

Figure 13: Process routes of Carbon2Chem



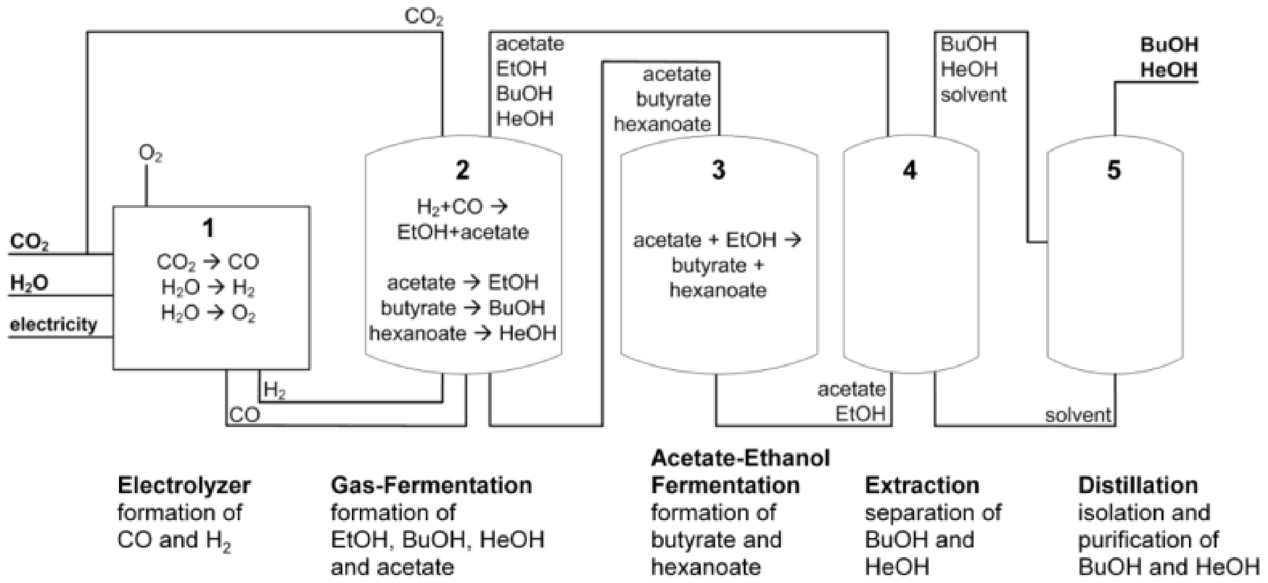
Source: Schlüter and Geitner (2020)

5.1.2.3 Rheticus

The **Rheticus**[30] research project (Figure 14) grew out of the Kopernikus P2X project. Project partners are Evonik Operations GmbH and Siemens Gas and Power GmbH & Co. KG. The aim of the project is to produce chemicals from CO_2 and water. In a first step, CO_2 and water are converted into hydrogen and carbon monoxide using renewable energy in a co-electrolysis process. In the second step, this synthesis gas is used as input for a fermentation process in which bacteria of the genus *Clostridium* extract is used to produce specialty chemicals such as butanol and hexanol from carbon monoxide.

[30] https://www.kopernikus-projekte.de/projekte/rheticus.

Figure 14: Overview of the Rheticus process



Source: Green Car Congress[31]

5.1.2.4 NAMOSYN

In the joint project **NAMOSYN,**[32] technologies for the production of synthetic fuels from CO_2 and H_2, in particular oxymethylene ether (OME) for use in diesel engines, are being researched and have been further developed since 2019. The project under the coordination of DECHEMA is funded by the German Federal Ministry of Education and Research and conducted with the participation of numerous companies and research institutions, including AUDI AG, BASF SE, BP Europa SE, Clariant Produkte (Deutschland) GmbH, Deutsches Zentrum für Luft- und Raumfahrt e.V., Evonik Technology & Infrastructure GmbH, Fraunhofer-Gesellschaft zur Förderung der ange-wandten Forschung e.V., Linde AG, Mitsubishi Hitachi Power Systems Europe GmbH, Robert Bosch GmbH, Ruhr-Universität Bochum, RWE Power AG, RWTH Aachen, Technische Universität Darmstadt, Technische Universität München and Umicore AG & Co. KG.

5.1.2.5 KEROSyN100

In the **KEROSyN100**[33] research project, a network of six partners from industry and science is investigating the production of synthetic kerosene and other synthetic fuels. Led by the Advanced Energy Systems Institute (AES) of the University of Bremen, the project involves Chemieanlagenbau Chemnitz GmbH (CAC), the industrial partners Raffinerie Heide GmbH and SKL Engineering & Contracting GmbH. Scientific partners are the TU Bergakademie Freiberg, the DLR - Institute for Networked Energy Systems e.V. and IKEM - Institute for Climate Protection, Energy and Mobility e.V. In a demonstration plant at the site of the project partner Raffinerie Heide, a synthesis gas is produced from CO_2 from direct air capture and hydrogen from water electrolysis using renewable energy

31 Green Car Congress (20/10/2019): Evonik and Siemens launch phase 2 of Rheticus: butanol, hexanol from CO_2 and water using renewable electricity and bacteria, https://www.greencar-congress.com/2019/10/20191020-rheticus.html.

32 http://namosyn.de/.

33 https://www.cac-synfuel.com/en.

from wind power. Synthetic fuels are produced from this synthesis gas via the intermediate step of methanol synthesis.

5.1.2.6 Production of synthetic kerosene in Werlte/Emsland

On 4 November 2021, a production plant for the production of synthetic kerosene for aircraft was inaugurated in Werlte/Emsland in northern Germany.[34] Here, an e-fuel is produced from water and CO_2 using renewable electricity, which is then transported from Emsland to Hamburg and processed into Jet A1 paraffin there. The project is based on a cooperation of the climate protection organisation Atmosfair with the Lufthansa Group and Kühne+Nagel.

5.1.2.7 Other initiatives

Within the funding initiative “CO_2 als nachhaltige Kohlenstoffquelle – Wege zur industriellen Nutzung (CO2-WIN)”[35] [CO_2 as a Sustainable Carbon Source - Pathways to Industrial Utilization] research and development projects are funded that focus on the use of CO_2 as a sustainable carbon source to broaden the raw material base of the German economy and safeguard it against supply crises.

The thematic focal points of the funding are

- Carbonation and mineralization: Production and evaluation of marketable products through the carbonation of CO_2 as well as the development of suitable carbonation processes for natural minerals, industrial slags or concretes.
- Artificial photosynthesis: direct use of solar energy for the chemical reduction of CO_2, for example by means of integrated systems for artificial photosynthesis
- Electrochemical conversion of CO_2: development of innovative electrocatalytic processes for the chemical reduction of CO_2 with a realistic perspective of transfer to industrial practice
- Chemical and biotechnological conversion of CO_2: Development of biotechnological or chemical-biotechnological processes for the material utilization of CO_2.

5.2 Situation in Japan

5.2.1 Overview

Like Germany, there are a number of CCU projects being realized in Japan, which are mostly at the scale of a demonstration plant.

5.2.2 Recent initiatives

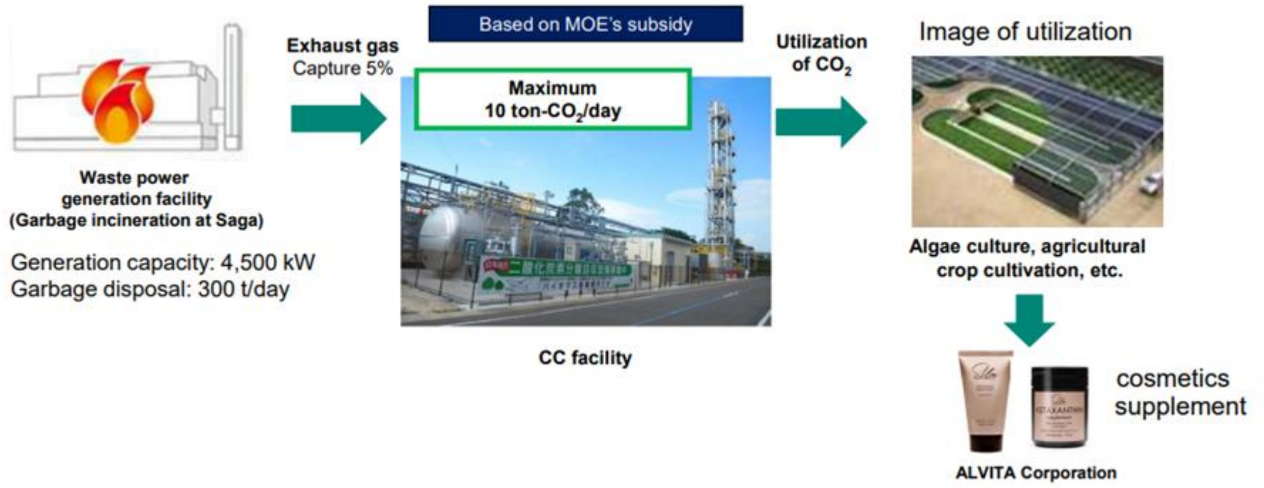
5.2.2.1 CCU from waste power generation

In Japan, a CO_2 capture and recovery system has been installed for the first time at a waste incineration plant in Saga city on Kyushu Island. The recovered CO_2 is sold to an algae grower who uses

[34] According to its own information, the world's first plant for the production of synthetic paraffin.
[35] https://www.fona.de/de/massnahmen/foerdermassnahmen/co2-als-nachhaltige-kohlenstoffquelle.php.

the CO_2 for photosynthesis of *Haematococcus algae*, which is used as an ingredient in cosmetics and dietary supplements (Figure 15).

Figure 15: Captured CO_2 as input for algae photosynthesis

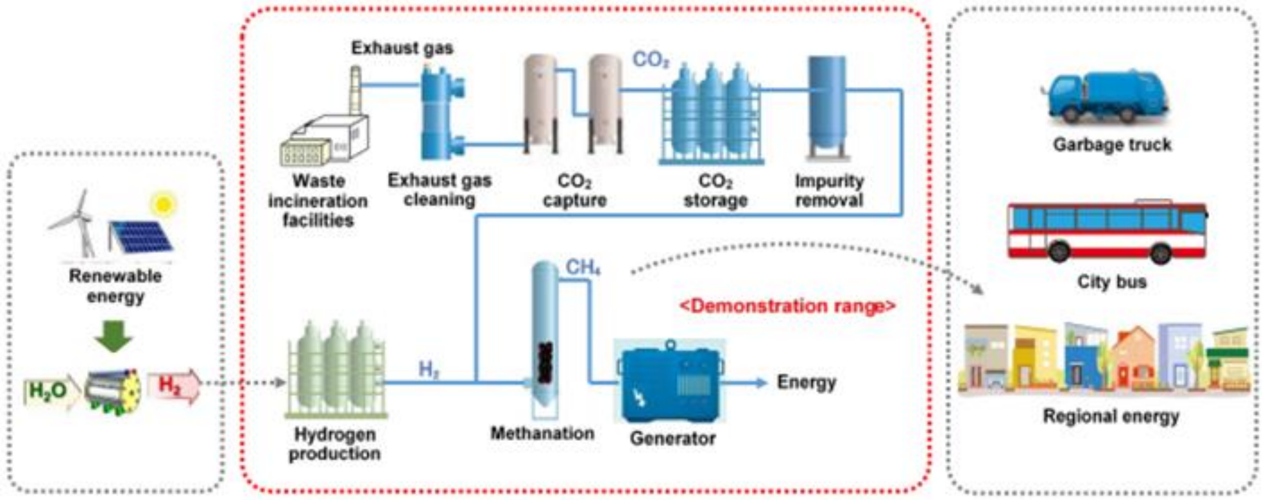


Source: (MoEJ 2020a)

5.2.2.2 Methane production from hydrogen and CO_2 by Hitachi Zosen Corporation

To produce synthetic methane, CO_2 from a waste incineration plant is converted with hydrogen from renewable energy sources (Figure 16). The project aims to establish commercial-scale CCU technologies by 2023. The demonstration plant will begin operation by 2022 (MoEJ 2020b).

Figure 16: Methane production by Hitachi Zosen Corporation



Source: Hitachi Zosen Corporation (2020)

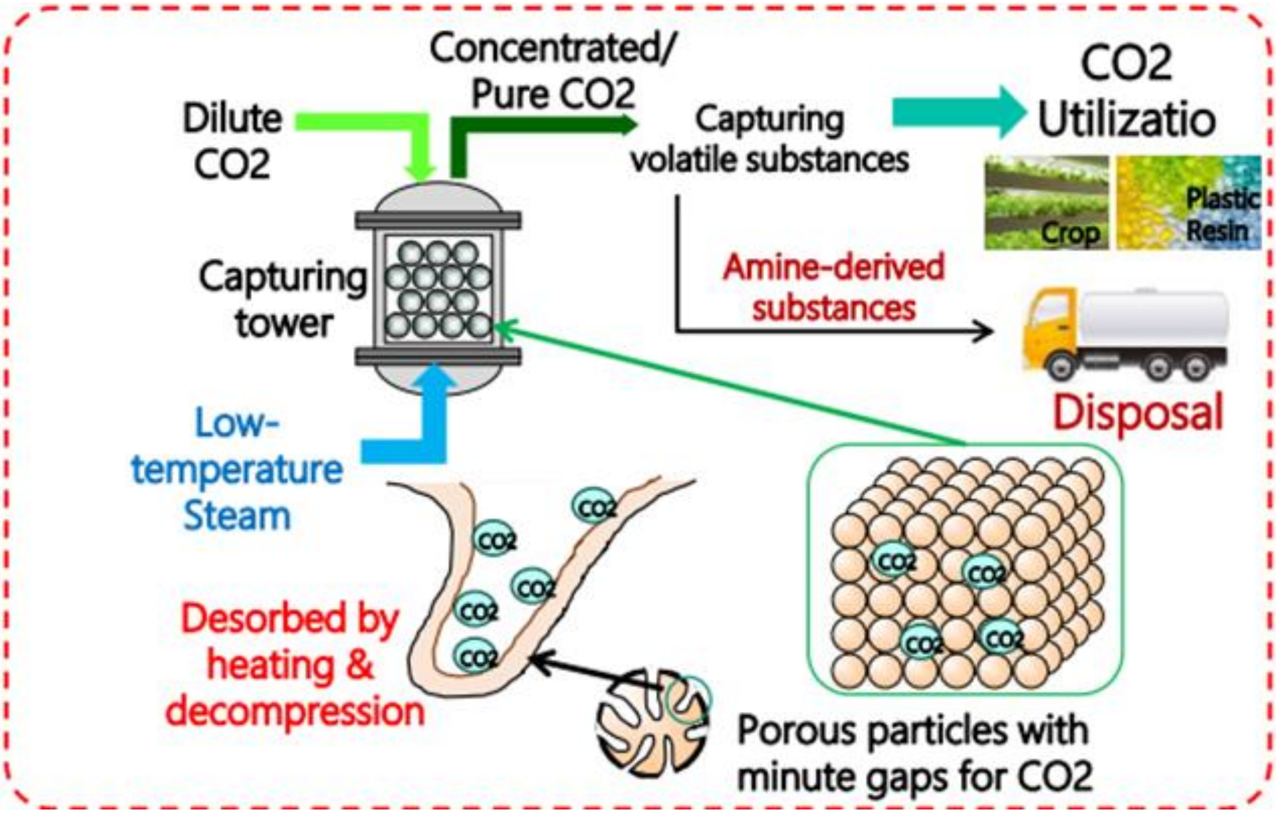
5.2.2.3 Ethanol conversion by using biocatalysts

Syngas is synthesised from CO_2 from waste treatment plants and hydrogen from renewable energy sources. Ethanol is then produced from this syngas using a microbial catalyst. This involves a special strain of microorganisms from Sekisui's cooperation partner, LanzaTech. These microorganisms ferment gases such as CO and H_2 and convert them into ethanol. The reaction rate of converting gases is more than 10 times faster than naturally occurring protists and no special heat or pressure is required. Toshiba Energy Systems & Solutions Corporation (Toshiba ESS) received an order from Sekisui Chemical, Co. Ltd. for the plant, which will be used in a bioenergy recycling test plant (ethanol conversion) in Kuji City in Iwate Prefecture. The plant is scheduled to begin operation at the end of FY 2021 (MoEJ 2020b).

5.2.2.4 R&D Project for DAC by Kawasaki Heavy Industries, Ltd.

Demonstration of a previously difficult-to-use carbon cycle model using a low-concentration CO_2 capture system and special solid absorbents to implement a direct air capture (DAC), see Figure 17. (MoEJ 2020b). Kawasaki Heavy Industries, Ltd. and the Research Institute of Innovative Technology for the Earth (RITE) have agreed with Kansai Electric Power Co., Inc. to construct a pilot-scale test facility (40 ton-CO_2/day scale) for the CO_2 separation/recovery system at Kansai Electric Power's Maizuru Power Station, and to start the test operation in FY 2022.[36]

Figure 17: DAC project by Kawasaki Heavy Industries, Ltd.



Source: MoEJ (2020b)

[36] Kawasaki Heavy Industries (2020): 石炭火力発電所における省エネルギー型二酸化炭素分離・回収システムのパイロットスケール実証試験を開始. Start of pilot-scale demonstration test of energy-saving carbon dioxide separation and capture system at coal-fired power plant, https://www.khi.co.jp/pressrelease/detail/20200924_1.html.

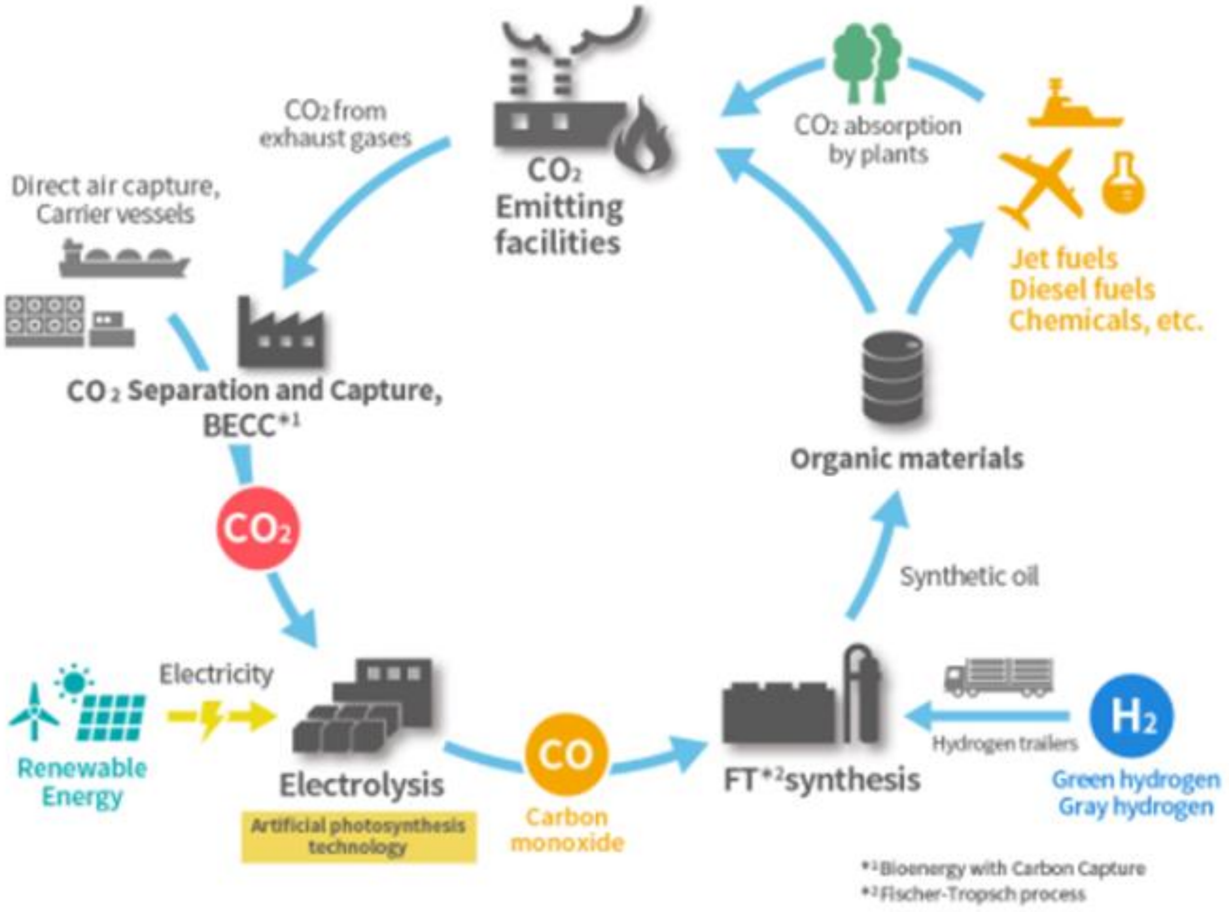
5.2.2.5 Creation of Circular Carbon Society Model through CO_2 Recycling

Toshiba Energy Systems & Solutions Corporation, Toyo Engineering Corporation, Toshiba Corporation, Idemitsu Kosan Co. Ltd., Japan CCS Co. Ltd., and All Nippon Airways Co. Ltd. have proposed a “Regional CO_2 Resource Utilization Study Business Through Electrolysis Utilizing Artificial Photosynthesis Technology” in response to the call for “FY 2021 Project to Promote the Creation of Circular Carbon Society Model through CO_2 Recycling” by MoEJ, the proposal for which was adopted as a commissioned project.

The six companies have previously cooperated to combine the CO_2 electrolysis technology developed by the Toshiba Corporate Research & Development Center for the conversion of carbon dioxide (CO_2) into carbon monoxide (CO) with the Fischer Tropsch synthesis (FTS) technology used to synthesize liquid fuel from CO and hydrogen to produce Sustainable Aviation Fuel (SAF) and to study carbon recycling business models using P2C (Figure 18). Toshiba Energy Systems and Solutions Corporation will build a prototype of a full-scale CO_2 electrolysis unit and conduct demonstration operation of the unit at the company’s Hamakawasaki Operations (Kawasaki City, Kanagawa Prefecture). Based on this, the companies will create a basic plan to utilize their knowledge, technology, related plant equipment, and other resources to demonstrate the entire process from the separation and collection of CO_2 to the production and consumption of SAF at potential sites in Japan including Tomakomai City in Hokkaido Prefecture.[37]

[37] Toshiba Energy Systems & Solutions Corporation (2021): Adopted for the Ministry of the Environment "FY2021 Project to Promote the Creation of Circular Carbon Society Model through CO_2 Recycling".

Figure 18: Regional Circular Carbon Society Model



Source: Toshiba Energy Systems & Solutions Corporation[38]

5.2.2.6 The Carbon Dioxide Capture & Conversion (CO_2CC) Program

As part of a NEDO project, in 2015 Asahi Kasei began construction of a validation plant at its Mizushima Works to verify its newly developed process to produce DPC (diphenyl carbonate) via DRC (dialkyl *carbonate*) to overcome these issues (Figure 19). Stability and operability as an industrial process was also confirmed through over 1,000 hours of continuous operation. Asahi Kasei has successfully established the non-phosgene process using CO_2 as a safe feedstock, enabling not only reduced energy consumption but also reduced CO_2 emissions. The project operated from FY 2014 to FY 2016.[39]

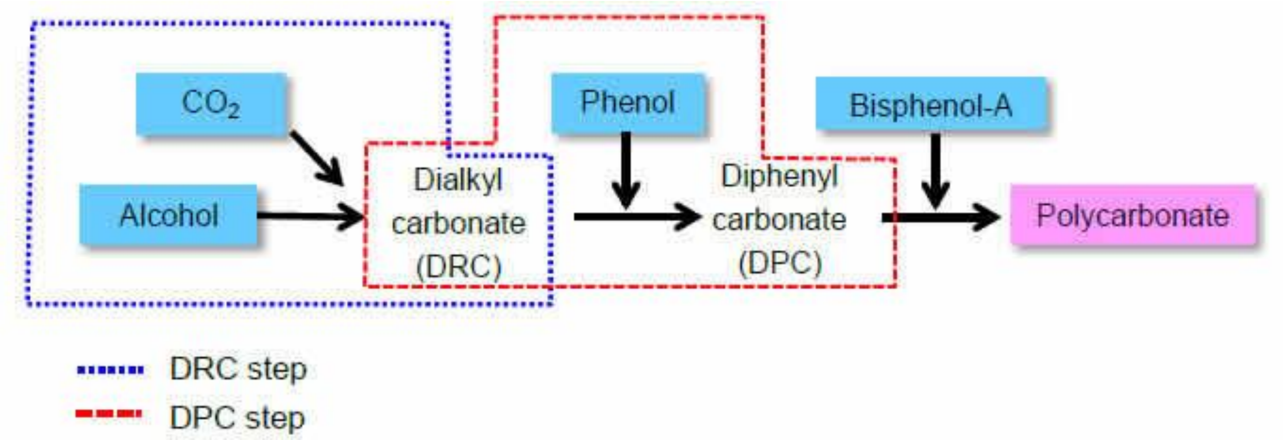
The DRC process for DPC is using catalysts to obtain DRC from CO_2 and alcohol, and then obtain DPC from DRC and phenol. They have validated the feasibility of the DRC process for DPC through continuous operation to assess catalyst cycling and catalytic performance in both the DRC step,

[38] Toshiba Energy Systems & Solutions Corporation (2021): Adopted for the Ministry of the Environment "FY2021 Project to Promote the Creation of Circular Carbon Society Model through CO2 Recycling",https://www.toshiba-energy.com/en/info/info2021_0824.htm(24/08/2021).

[39] Asahi Kasei (2017): Demonstration of validation plant for DRC process to produce DPC, a monomer of PC, https://www.asahi-kasei.com/news/2017/e170807.html (07/08/2017).

which produces DRC from CO_2 and alcohol, and the DPC step, which produces DPC from DRC and phenol, as well as reactor performance and the system to recycle unreacted feedstocks.[40]

Figure 19: Diphenyl carbonate production from CCU



Source: Asahi Kasei[41]

The outcomes of the projects are as follows

1) Confirmed stability and operability as an industrial process through over 1,000 hours of continuous operation.

2) Achieved reduced energy consumption and CO_2 emission compared with the conventional process for PC.

3) Established a production process using CO_2 as a safe feedstock instead of highly toxic phosgene. The carbonyl group of polycarbonates is obtained from CO_2 rather than from phosgene as with the conventional process.

5.2.3 Potentials and limits for Carbon Capture and Usage (CCU) in Japan

At the Davos Economic Summit in January 2019, then Japanese Prime Minister Shinzo Abe explicitly expressed interest in CCU, marking the beginning of METI's promotion of carbon recycling. The mentioned *Roadmap for Carbon Recycling Technologies* (METI 2021c) was created as a direct result of PM Abe's declaration. The aim is to disseminate basic technologies by 2030 that are already established as technologies, such as polycarbonate and biojet fuel. Other products such as chemicals, including olefins, benzene, toluene and xylene, which are not yet in use but promise high CO_2 recycling rates, are to be introduced in practice by 2050, according to the roadmap.[42]

Although the application of CCU expected to generate revenue through the sale of CO_2-based products, it is difficult to achieve cost advantages over existing products on the market due to the still

[40] Asahi Kasei (2017): Demonstration of validation plant for DRC process to produce DPC, a monomer of PC, https://www.asahi-kasei.com/news/2017/e170807.html.

[41] Asahi Kasei (2017): Demonstration of validation plant for DRC process to produce DPC, a monomer of PC, https://www.asahi-kasei.com/news/2017/e170807.html.

[42] Mizuho Research and Technologies (2020): CO_2 有効利用（CCU）の国内外の動向. National and international trends in the effective use of CO_2 (CCU), https://www.mizuho-ir.co.jp/publication/report/2020/mhir20_ccu_03.html.

high production costs. Therefore, to become competitive in the market, costs of CO_2 capture, hydrogen procurement and other process steps need to be significantly reduced.

5.3 Comparison of Germany and Japan

In both Germany and Japan, there are many efforts in the industry to move away from fossil and towards sustainable carbon sources. In both countries, there are projects that use industrial point sources or direct air capture as a starting point for the CO_2. There is a lot of research at the laboratory level, but also more and more applications are reaching the scale of a pilot plant or even a demonstration plant. Neither in Germany nor in Japan has the level of large-scale industrial production been reached so far. Projects based on chemical synthesis as well as those based on biological processes are being developed in both countries. As the costs for CO_2 capture and especially the costs for hydrogen supply are still very high, CCU production processes are not yet economically viable.

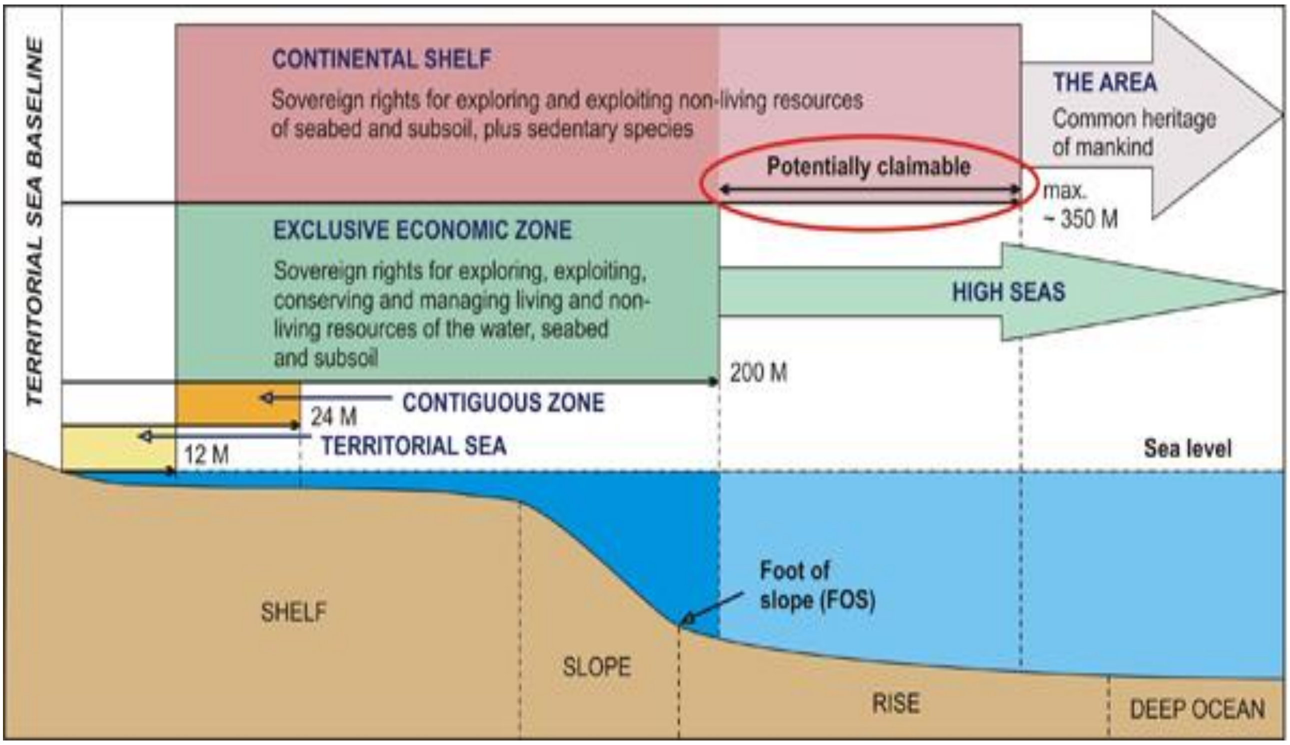
6 Regulatory framework

CCS is partially regulated in international law, with regards to CCS activities under the sea. Other than that, the regulatory framework is country-specific; in Germany the framework is strongly influenced by the EU. The utilization part of CCU does not have a specific regulatory framework (yet).

6.1 International regulatory framework

The United Nations Convention on the Law of the Sea, 1982 (UNCLOS) permits states to exploit the sea outside of their territorial waters within 200 nautical miles (exclusive economic zone, EEZ), though there are certain environmental obligations specified in the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter (London Convention) and its Protocol (London Protocol). Japan and Germany, as well as most European countries are parties to the London Protocol (IMO 2019). The London Protocol's Annex I was amended to explicitly allow for "*Carbon dioxide streams from carbon dioxide capture processes for sequestration*", but only in sub-sea-bed geological formations, the storage in the water column is therefore not permitted (Stoll und Lehmann 2008). The London Protocol further specifies that it must consist "*overwhelmingly of carbon dioxide*" and "*no wastes or other matter are added for the purpose of disposing of those wastes or other matter*". Furthermore, the "*Objectives and General Obligations of this Protocol set out in articles 2 and 3*" must be followed. That includes inter alia a waste prevention audit and consideration of waste management options, an assessment of potential effects, a permit process by the State and the obligation to put in place a monitoring and mitigation plan. The Protocol's Members agreed in 2012 on very specific guidelines that need to be followed (IMO 2012).

Figure 20: Illustration of maritime zones



Source: BGR[43]

Art. 6 of the London Protocol forbids "*the export of wastes and other matter to other countries for dumping or incineration at sea*". This strict ban of the use of other countries sub-seabed storage was softened in recent years. In 2009, some contracting parties tried to amend the Protocol to allow the export of carbon for CCS, but as only few countries have ratified the amendment, it is not in force yet.[44] In the following years, specific issues with the transboundary movement of carbon were clarified until in 2019, the Contracting Parties to the London Protocol adopted a resolution to allow provisional application of the 2009 (IEAGHG 2021). Therefore, the export is now allowed if,

> *"2 Notwithstanding paragraph 1, the export of carbon dioxide streams for disposal in accordance with Annex 1 may occur, provided that an agreement or arrangement has been entered into by the countries concerned. Such an agreement or arrangement shall include:*
>
> *2.1 confirmation and allocation of permitting responsibilities between the exporting and receiving countries, consistent with the provisions of this Protocol and other applicable international law; and*
>
> *2.2 in the case of export to non-Contracting Parties, provisions at a minimum equivalent to those contained in this Protocol, including those relating to the issuance of permits and permit conditions for complying with the provisions of Annex 2, to ensure that the agreement or arrangement*

[43] Implementing the United Nations Convention on the Law of the Sea (UNCLOS), https://www.bgr.bund.de/EN/Themen/Zusammenarbeit/TechnZusammenarb/Projekte/Abgeschlossen/Archiv/Sektorvorhaben_Ueberregional/1018_2006-2122-7_Ueberregional_SeerechtskonventionenUNCLOS_en.html.

[44] https://www.imo.org/en/OurWork/Environment/Pages/CCS-Default.aspx.

does not derogate from the obligations of Contracting Parties under this Protocol to protect and preserve the marine environment.

A Contracting Party entering into such an agreement or arrangement shall notify it to the Organization."[45]

The Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention), of which Germany is a member, has the same regulations for CCS as the London Protocol (Stoll und Lehmann 2008).

6.2 Situation in Germany

6.2.1 Historical development and EU legislation

Two attempts to regulate CCS in Germany failed, due to very diverse interests and opinions across parties, federal states as well as a strong public opposition (BMWi 2018; Dieckmann 2012). In 2009, the EU issued a directive for the storage of CCS (CCS Directive).[46] Existing environmental framework was changed to allow for sequestration and transport of carbon, changes were made inter alia in Large Combustion Plants Directive, Environmental Impact Assessment (EIA) Directive and the Industrial Emissions Directive.[47] For the storage of carbon, the Directive sets new procedural requirements throughout the lifetime cycle of CO_2 storage facilities (exploration, operation, closure), and requirements regarding geological formations and changed EU water and waste legislation.[48] Member States are able to opt-out of CCS altogether or designate certain sites. Germany used the later and is therefore required to conduct assessments regarding the available storage capacity within its territory (Kohls et al. 2015). In 2019, Germany reported 75 Gt storage capacity in major gas fields and between 20-115 Gt in saline aquifers, though 80% of those aquifers are not accessible as they belong to federal states that ban CCS (EC 2019).

The Directive needed to be transferred in national law by 2011, thus providing political pressure to reach a political compromise. The third attempt for a CCS law in August 2012 worked. It covers all aspects of the CCS chain, changing the German Federal Immission Control Act (BImschG) and providing a law for carbon dioxide storage (KSpG).

45 See text of "Resolution on the amendment to Article 6 of the London Protocol" at https://www.imo.org/en/OurWork/Environment/Pages/CCS-Default.aspx.

46 Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006 (Text with EEA relevance) OJ L 140, 5.6.2009, p. 114–135, https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32009L0031.

47 https://ec.europa.eu/clima/eu-action/carbon-capture-use-and-storage/legal-framework-safe-geological-storage-carbon-dioxide_en.

48 https://ec.europa.eu/clima/eu-action/carbon-capture-use-and-storage/legal-framework-safe-geological-storage-carbon-dioxide_en.

Table 5: Policy mechanisms and regulations of Germany

Category	Main law(s)
Regulation of CO_2 sequestration	Federal Immission Control Act (BImschG)
Regulation of CO_2 transport	KSpG (permit)
Regulation of CO_2 injection and post- injection site care and closure	KSpG, CCS Directive. The KSpG puts three limits on the sequestration (1) amount of carbon, (2) possibility for federal states to opt-out and (3) deadline for application requests. The most important federal states opted out and the deadline has passed, no project was realized
Management of liabilities, including long-term storage liability	Regarding Liability to the Environment: Eu Environmental Liability Directive[49] and national laws, regarding liability to property and health: KSpG (Dieckmann 2012)
Other significant regulations	ETS Directive[50]

Source: Authors' own compilation

6.2.2 Situation in Germany today

All aspects of the CSS chain are covered by German law (Dieckmann 2012). There is no special law for utilization; however, it is covered by current environmental law.

6.2.2.1 Sequestration and Transport

The most important law for sequestration is the Federal Immission Control Act, that was changed by the German CCS law (Dieckmann 2012). It regulates the permit system for building new plants with carbon sequestration or refurbishing existing. Whenever large plants (300 megawatts or more) are build or refurbished, it needs to be checked whether they are already CCS compatible or whether space can be reserved for building sequestration or transport facilities later on. The KSpG regulates the permit system for transport pipelines. Permits for cross-border pipelines depend inter alia on the observance of the of the EU-CCS Directive by the other state. Environmental impact assessments are necessary (Dieckmann 2012). While the German CCS law has a deadline for the application for CCS storage permits, this does not apply to new sequestration or transport facilities (BMWi 2018). The German and EU legislation did not take CCU into account; as a result, the wording of the KSpG, for example, only refers to transport pipelines for storage.

6.2.2.2 Storage

The KSpG regulates carbon storage in Germany as well as in the explicit economic zone in the sea.

The KSpG foresees a two-step process for site identification: first by the agencies of the federal states and then by private companies. In the first step, potential environmental impacts need to be assessed on a precautionary basis (Kohls et al. 2015). It sets extensive prerequisites for the permit

49 https://ec.europa.eu/clima/eu-action/carbon-capture-use-and-storage/legal-framework-safe-geological-storage-carbon-dioxide_en.

50 http://data.europa.eu/eli/dir/2003/87/oj.

process, such as an environmental impact assessment, a safety demonstration, a monitoring concept, a decommissioning and aftercare concept. It sets extensive liability requirements regarding damages to persons or property. In case of harm, the company needs to prove that the facility ran according its permit, and that it is plausible something or someone else is responsible for the harm that occurred. That is stricter than general German environmental civil liability law. The law also requires the company to prove financial security, in the form of an insurance or security.

The KSpG puts three limits on the sequestration: (1) amount of carbon, (2) possibility for federal states to opt-out and (3) deadline for application requests. The amount of carbon is limited to 4 Mt of carbon per year in Germany, and 1.3 Mt/a per plant. This would have amounted to 3 medium-sized CCS facilities (BMWi 2018). But those federal states with the most potential for carbon sequestration used the opt-out clause (like Niedersachsen and Schleswig-Holstein) or previously passed laws to discourage any CCS activities (Mecklenburg-Vorpommern) (BMWi 2018). The deadline for the application for permits was 31/12/2016; no applications for a permit were made (BMWi 2018).

6.2.3 EU Emissions Trading System

Since 2015, sequestration, transport and storage installations have been included in the EU Emissions Trading System (ETS), carbon that is safely stored is considered as "not emitted" under the EU ETS.[51] In general, this does not apply to CCU facilities. In 2017 the European Court of Justice ruled that carbon dioxide which was "*transferred to another installation for the production of precipitated calcium carbonate"* could not be included *"in the emissions of the lime combustion installation"* .[52] It reasoned that "emissions" under the EU ETS Directive are only those that are released to the atmosphere.[53] This led some scholars to believe that all CCU installations would be exempted from EU ETS as well (Ehrmann 2017). But the Emissions Trading System Monitoring and Reporting Regulation was only changed with regard to this specific case.[54]

6.2.4 Planned policies

The Coalition Agreement of the new government contains no statements regulation of CCS and CCU activities, especially nothing on changing the laws to permit storage in Germany. Part of the coalition

51 https://ec.europa.eu/clima/eu-action/carbon-capture-use-and-storage_de.

52 https://eur-lex.europa.eu/legal-content/de/TXT/?uri=CELEX:62015CJ0460 "*The second sentence of Article 49(1) of Commission Regulation (EU) No 601/2012 of 21 June 2012 on the monitoring and reporting of greenhouse gas emissions pursuant to Directive 2003/87/EC of the European Parliament and of the Council and point 10(B) of Annex IV to that regulation are invalid in so far as they systematically include the carbon dioxide (CO_2) transferred to another installation for the production of precipitated calcium carbonate in the emissions of the lime combustion installation, regardless of whether or not that CO_2 is released into the atmosphere."*

53 https://eur-lex.europa.eu/legal-content/de/TXT/?uri=CELEX:62015CJ0460 See 32 *" According to Article 3(b) of Directive 2003/87, 'emissions' are, for the purposes of that directive, defined as the release of greenhouse gases into the atmosphere from sources in an installation. It follows from the very wording of that provision that, for there to be an emission within the meaning of that provision, a greenhouse gas must be released into the atmosphere."* and 42 *"Those provisions thus lead to the CO_2 transferred in such circumstances being regarded as falling under the definition of 'emissions' within the meaning of Article 3(b) of Directive 2003/87, despite not always being released into the atmosphere. By the second sentence of Article 49(1) of Regulation No 601/2012 and point 10(B) of Annex IV to that regulation, the Commission therefore broadened the scope of that definition."*

54 https://www.europarl.europa.eu/doceo/document/E-9-2020-000634_EN.html.

is strongly in favour.[55] Others are very critical and see CCS as a “last resort”.[56] The coalition plans to “actively follow” the EU Commission's debate on the Carbon Removal Certification Guidelines.[57] This encompasses natural as well as technical solutions.[58] A call for evidence will be launched in January, the legislative proposal by the EU Commission is planned for the end of 2022.[59]

A number of new legislation pieces proposed by the EU Commission shall improve the demand for CCU technology. The EU Commission proposed:

- Changing the ETS Directive
  - Reg. synthetic fuels based on CCU to avoid the double counting of emissions
  - Reg. CCU products that permanently bind carbon
- Increasing the demand for synthetic fuels for the aviation sector (ReFuelEU)
- Setting a sub-target for renewable fuels from non-biological origin in the renewable energy directive (EC 2021).

The EU Commission outlines its plans to achieve 5 Mt removal of carbon annually by 2030 in its Communication on “Sustainable Carbon Cycles” (EC 2021).

6.3 Situation in Japan

Japan modified and ratified the Marine Pollution and Disaster Prevention Act in 2007. This established a permitting system for the disposal of CO_2 below sea level and enabled the capture and storage (CCS) of CO_2 in subsea formations in Japan. With the approval of the Tomakomai demonstration project (section 4.2.2.1), the law was applied for the first time.

Under the permit system, an operator must submit results of a preliminary assessment of the impact of CCS on the marine environment and monitoring plans. The operator must take care not to harm the marine environment. The following elements need to be included:

- Routine monitoring for a range of factors such as the quantity of stored carbon dioxide, CO_2 characterization and injection data (pressure, velocity and temperature), as well as site characteristics including geological characteristics, location and range of stored CO_2, chemical characteristics of the seawater overlying the storage site, marine life and ecosystems, and utilization of marine life, environmental and resources (e.g. fishing grounds)
- Precautionary monitoring in order to detect any CO_2 leakage as soon as it occurs. Monitoring is required to cover time dependent changes in pressure in the storage formation, the location and range of stored CO_2 and chemical characteristics of the overlying seawater.
- Emergency monitoring if a leak occurs. It must include time-dependent changes in pressure in the storage formation, detailed conditions of the CO_2, the location and range of stored CO_2, chemical

55 https://www.fdp.de/forderung/carbon-capture-and-storage-ccs-deutschland-endlich-moeglich-machen.
56 https://www.faz.net/aktuell/wissen/erde-klima/was-halten-die-parteien-von-negativen-emissionen-17541852.html.
57 https://www.cleanenergywire.org/factsheets/future-german-governments-key-climate-and-energy-plans-2021-coalition-treaty.
58 https://www.reuters.com/markets/commodities/eu-set-up-scheme-encourage-co2-removal-atmosphere-2021-12-15/.
59 https://ec.europa.eu/commission/presscorner/detail/en/ip_21_6687.

characteristics of the seawater overlying the storage site, impacts on marine life and ecosystems, together with social impacts (including impacts on fishing grounds)

Under the Marine Pollution Prevention Law, where leakage occurs the permit holder is required to take corrective action. The permit holder must report immediately to the MOE any results outside the permitted ranges for CO_2 migration or seawater/marine ecosystem impacts, together with remediation plans for remedy the situation. Regular monitoring is then required until results settle within the expected range.[60]

Table 6: Policy mechanisms and regulations of Japan

Category	Main law(s)
Regulation of CO_2 transport	Under consideration by Japanese government
Regulation of CO_2 injection and post- injection site care and closure	In Japan, the permitting provisions for underground storage of CO_2 are found in the Marine Pollution Protection Law and only cover offshore, sub-seabed storage. There are no provisions covering onshore geo-sequestration. Under the Marine Pollution Protection Law, the provisions applicable to the subsea bed storage of CO_2 are focused on protecting the marine environment from any adverse impacts of sub-seabed storage activities and are not specifically aimed at promoting CCS as a low-carbon technology. This reflects the fact that the CCS provisions were enacted in 2007 in order to comply with Japan's international obligations to implement the amendment to Annex I of the London Protocol that included CO_2 streams as wastes or other matter that may be considered for ocean dumping. For example, an application for sub-seabed CO_2 storage is made to the Minister of the Environment and is assessed, largely, from an environmental perspective. Re-permit is required every 5 years. Other than the regulations above, existing regulations are applied for METI's Tomakomai CCS Demonstration project operation but there is no regulation for post injection and closure.
Management of liabilities, including long-term storage liability	Under consideration by Japanese government
Other significant regulations	None identified

Source: GCCSI (2020)

Since there are no specific laws and regulations for CCS in Japan, the "Law on the Safety of High-Pressure Gases" and the "Law on Safety and Health in Industry" apply to carbon capture and recovery plants.

There are also no specific safety standards for injection drilling; the Mining Safety Act applies here. It is still being examined whether the right to use the earth should be defined in a similar way to the

[60] Global CCS Institute (2016): Japan's legal and regulatory framework for CCS, https://www.globalccsinstitute.com/news-media/insights/japans-legal-and-regulatory-framework-for-ccs/.

mining law. In general, long-term responsibilities are not defined in Japan. The only exception is the Marine Pollution Prevention Act, which provides for continuous monitoring of the storage site by the operator; or over the period in which CO_2 is stored (METI; NEDO; JCCS 2020).

The lack of specific legislation and the complex application of existing laws make CCS cumbersome and time-consuming. The review of a possible unification of laws for CCS has started with Japan's declaration of climate neutrality by 2050 and is therefore expected to take some time.[61]

6.4 Comparison of Germany and Japan

There are some similarities between Germany and Japan due to common international law obligations. Those projects that are within, or rather, under the sea, have quite similar regulations. The London Protocol’s Obligations and Guidelines are quite extensive. As there are no current CCS projects in Germany, it cannot be determined whether practical application of these guidelines is similar.

Germany has an extensive framework for CCS, especially for the storage of carbon, which is currently not used. This is not due to the laws being overly strict or complicated, but due to the possibility of political opt-outs of CCS on a federal level. Japan, meanwhile, has few specific CCS regulations. Those that do exist are due to international obligations (London Protocol). In Germany/the EU, these international obligations were transferred into the CCS Directive, creating a unified permitting process for both land and seabed storage facilities, while giving special considerations to the circumstances on land (e.g. change of the EU water legislation) and other existing obligations e.g. regarding environmental impact assessments. Regarding the sequestration of carbon, Germany/EU adjusted their existing environmental framework and permit system.

7 Conclusions

Both countries are committed to climate neutrality. Japan envisages achieving this goal by 2050 while Germany has recently enhanced its ambition and now plans to achieve climate neutrality by 2045. Japan plans to increase the share of renewable energies to electricity production to almost 40% by 2030, while Germany’s new government increased the 2030 target from 65% to 80%. This corresponds with different strategies in terms of power generation from fossil source. While Germany aims at decommissioning the last coal power plant by 2030, it is planned that coal power will contribute 19% to Japan’s electricity generation.

On the way towards a decarbonized economy, both countries also envisage important contributions of Carbon Capture and Storage (CCS) and Carbon Capture and Utilization (CCU), though with somewhat different roles.

Carbon capture and storage

Japan has developed a roadmap for capturing CO_2 and is focusing on both capturing from large point sources including fossil power plants and exploring storage capacity domestically but also

[61] Sa.nkei Biz (2021): ＣＯ２地下貯留へ新法 政府法律一本化を検討 民間参入、普及に弾み. New Law on CO_2 Underground Storage: government considers consolidating the legislations, https://www.sankeibiz.jp/business/news/210103/bsc2101032253001-n1.htm.

abroad with the view to establish supply chains for 'blue' hydrogen and to extend fossil power generation beyond 2050.

Germany does not have a similar roadmap yet because the consideration of CO_2 storage in domestic site stalled more than 10 years ago. CCS is currently being reconsidered in the context of negative emissions for balancing GHG emissions from heavy-to-abate sectors based on a clear priority: 1) reducing GHG emissions, 2) CCS for heavy-to-abate point sources such as cement of lime and 3) compensating heavy-to-abate diffuse GHG emissions such as from agriculture through negative emissions technologies.

Carbon capture and utilization

In both countries, Germany and Japan, there are many research projects for the use of CO_2 at the laboratory level. More and more of these projects are now reaching the scale of pilot or even demonstration projects. However, neither in Germany nor in Japan has the level of large-scale industrial production been reached yet. Projects based on chemical synthesis as well as those based on biological processes are being developed in both countries. As the costs for CO_2 capture and especially the costs for hydrogen supply are still very high, CCU production processes are not yet economically viable.

Regulatory framework

There are some similarities between Germany and Japan due to common international law obligations. Those projects that are within the territory of the countries including maritime sovereign zones have quite similar regulations. The London Protocol's Obligations and Guidelines are quite extensive. As there are no current CCS projects in Germany, it cannot be determined whether practical application of these guidelines is similar. Germany has an extensive framework for CCS, especially for the storage of carbon, which is currently not used. This is not due to the laws being overly strict or complicated, but due to the possibility of political opt-outs of CCS at the regional level. Japan, on the other hand, has few specific CCS regulations, mainly those that do exist are due to international obligations (London Protocol). In Germany, those international obligations were transferred in the EU's CCS Directive, creating a unified permitting process for both land and seabed storage facilities, while giving special consideration to the circumstances on land (e.g., change of the EU water legislation) and other existing obligations e.g. regarding environmental impact assessments.

The considerations illustrate that CCS and CCU are being actively discussed in both countries. Deliberations of these technologies started earlier in Japan than Germany. From a German perspective it would be worthwhile scrutinizing the experiences gained so far in Japan in this respect. From a Japanese perspective, it may be interesting to assess Germany's approach on the expansion of renewable energies in a country with similar resource endowments and the role envisaged for negative emission technologies.

Overall

Beside the differences and similarities of both countries' approaches to CCS and CCU, we can draw the following more general conclusions from the deliberations above:

- CCS and CCU processes overlap to some extent: Under the CCS route, CO_2 will be stored for the long term while under the CCU route it will be used stored in products and prevent a contribution to global warming throughout the lifetime of the product. Therefore, CCS can contribute to negative emissions while CCU can contribute to maintaining climate neutrality, provided that all energy used in the upstream stems from renewable energies and does induce global worming indirectly and provided that the CO_2 used does not stem from fossil sources but only from the ambient air.

- If mitigation instruments are not sufficient, CCS as a negative emission technology can be a way of achieving climate neutrality by 2050 or, if targets are missed, can help to reduce the CO_2 concentration in the atmosphere in the second half of this century to bring the temperature back down to 1.5° Celsius.
- The abatement costs of CCS and CCU are relatively high compared to other abatement options. In this respect, emission reductions should take priority. They should therefore be applied primarily to the hard-to-abate sectors, e.g. cement, lime (CCS), aviation and maritime transport (CCU).
- CCS and CCU are dependent on resources (storage capacity, land) whose theoretical potential is large but nevertheless limited and partly claimed by other uses. Beyond the high costs, a focused use of both technologies is also required for this reason.

Individual process steps of the technologies are already used on an industrial scale, but others are at the beginning of their technological development cycle. Therefore, no significant reduction contribution of these technologies can be expected by 2030.

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