acatech POSITION PAPER

CCU and CCS – Building Blocks for Climate Protection in Industry

Analysis, Options and Recommendations

acatech (Ed.)

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NATIONAL ACADEMY OF SCIENCE AND ENGINEERING

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The acatech POSITION PAPER SERIES

This series comprises position papers from the National Academy of Science and Engineering, providing expert evaluations and future-oriented advice on technology policy. The position papers contain concrete recommendations for action and are intended for decision-makers from the worlds of politics, science and industry as well as interested members of the public. The position papers are written by acatech members and other experts and are authorised and published by the acatech Executive Board.

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Executive Summary

The Paris Climate Agreement came about as a result of numerous scientific findings about the causes of climate change and the increasingly apparent serious impact of the human contribution to climate change. However, the steps the signatory states will have to take to achieve the self-imposed targets of the agreement also themselves have serious consequences. In Germany's case, these go far beyond the successful start which has been made to its energy transition that has so far primarily concerned the electricity sector. Major challenges remain in relation to heating, agriculture, transport and energy-intensive industries, specifically iron and steel production as well as the chemicals and cement industries. The direct impact on the population will be highly diverse: heating and insulation costs, diet, private transport, additional costs for building materials, metal products and chemicals, changes to the labour market.

This position paper focuses on German industry. The sector target for energy-intensive industries, which in 1990 accounted for around one fifth of Germany's greenhouse gas (GHG) emissions, is to cut emissions in half to 140 to 143 million tonnes of carbon dioxide equivalents (CO_2 equivalents) by 2030.[1,2] Emissions from this sector had already been cut to 188 million tonnes of CO_2 equivalents by 2016 thanks to many different measures. Further distinct reductions, however, remain to be made over the years to 2050. This raises important questions: are our societies, in Germany and the other signatory countries, ready for the necessary cuts which will arise from the goals agreed in Paris and specified in national Climate Action Plans? How can energy-intensive industry meet its challenges by 2030 and 2050? Have sufficient lead times been allowed for researching, planning, trialling and implementing technologies on the necessary scale? What changes can be expected on the labour market? There has so far been very little wide-ranging public debate about the consequences for each individual.

All options for reducing GHG emissions must be considered for industry. Essentially, the following options for avoiding CO_2 emissions can be identified and should be provided in this order of priority: firstly, avoidance of CO_2 emissions through higher efficiency, greater electrification and the use of alternative energy sources, processes and materials, secondly (re)utilisation of emitted CO_2 by extending material use, namely Carbon Capture and Utilisation (CCU), and thirdly long-term geological storage of otherwise unavoidable residual CO_2 emissions by Carbon Capture and Storage (CCS). It should, if required, be possible to re-extract stored CO_2 as a raw material.

It is generally assumed that emission reductions up to 2030 will be essentially achievable by material and energy efficiencies and by increased use of renewable energy sources. From 2030 onwards, when these potential savings will already to a great extent have been made, there will be an increasing need for new methods, materials and technologies which, in addition to using CO_2-free or -neutral energy sources, new processes and further electrification, also include CCU and optionally CCS. Both CCU and CCS are technically feasible and some approaches have already trialled at various scales, but there are substantial differences in terms of their strategic potential, how they can be integrated into CO_2 reduction scenarios and how feasible they are to implement depending on the outcome of prior debates regarding acceptability. The motives underlying the selection of CCU and CCS are also different.

CCU is primarily used for carbon circulation and GHG-neutral production with the concomitant climate protection effect being a welcome addition. There would appear to be potential for making repeated use of considerable volumes of industrially emitted CO_2 in conjunction with the production of synthetic motor and combustion fuels using renewable energy sources. However, there has not yet been any public discussion about the consequences, for instance a greater need to expand renewable energy considerably in the short term.

With CCS comparatively large volumes of CO_2 can be put into permanent geological storage in deep underground strata. There is a huge disparity between the levels of acceptance and the evaluation of the possible risks of CCS among the general public and in specialist circles. A politically successful protest movement has arisen against "CO_2 disposal sites", for which reason CCS is seldom openly discussed as an option even in political circles, so complicating the development of technology agnostic GHG neutrality strategies. CCS measures have previously mainly been discussed in connection with reducing CO_2 emissions from coal-fired power stations. The present position paper objects the idea that CCS makes sense for the power generation sector and limits itself to evaluating CCS for technologically unavoidable process-related CO_2 emissions from energy-intensive industries.

1 | Cf. BMUB 2016.

2 | Accounting as it does for around 86 per cent of total GHG emissions, CO_2 is the most significant greenhouse gas. Converting the global warming climate effect of other greenhouse gases into that of CO_2 allows total emissions to be stated as CO_2 equivalents.

The chemicals industry is dependent on carbon, currently predominantly obtained from fossil resources (oil, natural gas, coal), in many different ways. CO_2, like biomass, is an alternative carbon source and offers the possibility of at least partially closing the carbon cycle loop for industrial use. The potential offered by CCU applications in terms of sustainability essentially involves savings in fossil resources. In Germany, large-scale use of CCU technologies will to a great extent depend on its economic viability and on the availability of renewable electrical energy in terms of timing, location and volume. Technological innovations might in future expand the use of these technologies but the resultant climate protection effect will only be available on a large scale at some indeterminate time in the future. It would appear questionable whether industry will be able to meet its obligations arising from the Paris Agreement up to 2050 solely by applying all the above-stated CO_2 avoidance and reduction options and by utilising CO_2.[3] The fundamental political decisions which have yet to be taken in the present legislative period should therefore extend beyond the portfolio of these measures.

In contrast with the reticence towards CCS among some groups of the population, experts in engineering and geosciences can point to numerous years of experience in safe CO_2 storage, including beneath the North Sea, the Norwegian Sea and in Canada and the USA. In the light of the progress which has been made in safety engineering and if climate protection targets are to be achieved, even CCS sceptics should be able to regard CCS technology as a feasible way forward, especially since stringent testing and authorisation procedures ensure the risks are slight. In Germany, 2012's Carbon Dioxide Storage Act (KSpG) created no incentives to use CCS. The Federal States were given the option of an opt-out clause which has been widely exercised. It would be good to find out for the future whether they would be willing to review their decision in relation to using CCS for otherwise unavoidable industrial emissions.

As levels of CO_2 savings increase, further GHG reduction measures in industry will become more technically challenging which means that we have yet to face the more difficult stages of achieving climate targets. If CCS is ruled out as an option and full use has already been made of the other options or they can no longer be pursued or expanded at reasonable cost, little room for manoeuvre remains. It is therefore doubtful whether it makes sense to maintain Germany's current absolute prohibition of CCS.

Just as at the start of the debate about the use of CCS around a decade ago, there is still no clear roadmap for large-scale use of CCU and CCS technologies. Numerous national and international scientific studies view both approaches, CCU and CCS, to be conceivable building blocks, if not an essential mainstay, for cost-effectively achieving the climate policy targets of the Paris Agreement.

Successfully achieving CO_2 reductions in industrial processes using CCU and CCS technologies will only be possible if these technologies enjoy broad support from civil society and major players from industry, politics, interest groups and science. CCS technology in particular will only be an option for further CO_2 reductions if it is accepted by Germany's citizens. The technologies which, on the basis of current knowledge, will be required, especially from 2030 onwards, will have to be further developed and brought to market maturity in the near future if they are to be available in time. The necessary infrastructure must be planned, approved, funded and built, preferably in industrial regional clusters, spanning corporate and sector boundaries. Given the long lead times involved, it is vital to pay attention now to issues around suitable business models and the funding of the necessary infrastructure.

In the case of CCU, the priority is to further develop technically, environmentally and economically implementable technologies and to have them recognised as sustainable CO_2 reduction methods for the purposes of the national climate protection targets.[4] In the light of the widespread reservations regarding CCS technology, there is an urgent need for a thorough debate with all stakeholders to establish whether, in which sectors and to what extent CO_2 storage might be applied. In order to create a willingness to use CCS, any deep underground CO_2 storage should be limited to otherwise unavoidable CO_2 emissions from industry. It must moreover be clarified to which energy-intensive industry emitters CCS should be available as a priority, for how long (if it is a bridge technology), who will provide the infrastructure for transporting and storing CO_2, how can this be achieved at the lowest possible cost while ensuring the highest safety standards, where should storage preferably be located (onshore and/or offshore) and who will bear the costs? Devising planning principles, creating social consensus and the administrative and engineering implementation require a focused and thorough approach.

3 | Global climate protection scenarios accordingly indicate that achieving the 2 degree target will probably, and certainly in the case of the 1.5 degree target, entail removing CO_2 from the atmosphere ("negative emissions"). In January 2018, the European Parliament resolved to cut CO_2 emissions to zero by 2050 and afterwards to ensure net removal of CO_2 from the atmosphere (European Parliament 2018). Even optimistic scenarios assume that some 14 million tonnes CO_2 equivalents from industry, especially the cement and lime industry, are unavoidable (UBA 2015).

4 | Uniform assessment criteria and standards over the entire life of any CCU products are required for this purpose (Life Cycle Assessment).

Overall, it is also necessary to come to an understanding as to how far CCU and CCS are or will have to be elements of an overarching GHG neutrality strategy. Publicly funded innovation programmes and financial assistance in the construction of transport and storage infrastructure will play a vital role in development and market introduction. It should also be established whether and to what extent CCU and CCS will in future be capable of contributing to Germany's industrial competitiveness. German companies are contributing to climate protection around the world with their innovative products and systems and so create growth and jobs in engineering and plant construction, in the electrical industry or with smart control engineering. Given appropriate adaptation, it should be possible to maintain existing value chains and successful industry clusters and to reconcile GHG neutrality with industrial competitiveness. Early development of the necessary infrastructure can bolster belief in the survival and future success of industrial production lines and clusters and also help to maintain Germany's position as a model of technological innovation.

It is obvious that we need a new, unprejudiced debate about whether we wish to make use of CCU and CCS as options for significantly reducing CO_2 emissions from industry and, if so, under what conditions. If we take the Paris Agreement seriously, we must make a start today.

The intended audience for this acatech POSITION PAPER primarily includes political actors and interested members of the general public, decision makers and experts from all areas of the industries concerned as well as possible funding providers and investors. The position paper is intended to inject impetus in three ways:

- Firstly, the position paper is intended to make a scientifically well-founded contribution to the further development of Germany's climate protection strategy and address fundamental issues of broad use of CCU and, for technologically unavoidable emissions from essential industrial processes, of CCS as possible climate protection building blocks. The Federal Government's coalition agreement commits it to the 2020, 2030 and 2050 climate targets agreed in the Paris Climate Agreement and to being technology agnostic.[5] Pointing out the opportunities, risks and limitations of CCU and CCS with regard to CO_2 reduction options and their public perception is intended to provide important indications regarding the possible use of these technologies in energy-intensive industries.
- Secondly, the position paper indicates the technological significance of and the possible contribution to climate protection by CCU and CCS in reducing CO_2 emissions from energy-intensive industries. The industries in question, including chemicals, iron and steel as well as cement, are of huge significance to the economy. Research and development into emission reduction measures boost Germany's ability to innovate and create value.
- Thirdly, the paper hopes to kindle a broad social debate about possible approaches to reducing emissions from industrial processes by means of CCU and CCS and their implications. Cooperation between science, industry and society would appear to be absolutely essential with regard to the use of CCU and CCS due to their highly interdisciplinary nature, great technological complexity and the significance of the industries involved to employment.

5 | Cf. German Federal Government 2018.

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6 | Now Federal Office for the Safety of Nuclear Waste Management.
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1 Greenhouse Gas Neutrality of Industry and CCU/CCS in Accordance with the Paris Agreement

Climate change is one of the greatest challenges facing humanity. The Paris Climate Agreement commits the international community to keeping global warming well below 2 degrees Celsius and to endeavouring to ensure that warming does not exceed 1.5 degrees Celsius. The intention is to achieve the objective of greenhouse gas (GHG) neutrality in the second half of this century.

1.1 The Task of the Paris Climate Agreement

Climate research has shown that global warming has been progressing in line with the cumulative total volume of CO_2 emissions since the start of industrialisation. It may be concluded from this that there is a limit to the permitted total budget of CO_2 emitted into the atmosphere if a specified target worldwide temperature rise is not to be exceeded. Just short of 800 billion tonnes of CO_2 now remain for the 2 degree limit, a volume which corresponds to 25 times current global annual emissions.[8] If the 1.5 degree limit is to be observed, the permitted total budget is of course still lower.[9] The desired climate stabilisation can only succeed if global CO_2 emissions are greatly reduced as soon as possible.[10]

The decision taken at the Paris Conference in December 2015 injected a new sense of urgency into the climate protection debate in Germany and the EU too. German climate protection targets have been readjusted in the light of the Paris Agreement and the intentions stated in the German 2010 Energy Plan should now be considered the minimum targets for Germany's contribution to complying with the 2 degree limit. The Climate Action Plan 2050, adopted by the Federal Government in late 2016 and aiming to achieve substantial GHG neutrality, relative to the year 1990, by 2050, is the cornerstone of Germany's compliance with the commitments it has entered into.

The major new feature of the Climate Action Plan is that it has for the first time stated emission reduction targets for greenhouse gases for all major economic sectors by 2030 in order to achieve the goal, set in the Federal Government's Energy Plan 2010, of reducing GHG emissions by at least 55 per cent by 2030 in comparison with 1990.[11] While Germany's contribution to the global emission budget is currently "only" 2.2 per cent,[12] missing the targets stated in the Paris Agreement could, however, also result in other states not pursuing their climate protection commitments with the appropriate seriousness. In addition, the provision of emission reduction or avoidance technologies would have a climate protection effect beyond Germany.

Germany's stated *sector target for industry*[13] specifies, starting from 283 million tonnes CO_2 equivalents[14] in 1990, a reduction to 140 to 143 million tonnes CO_2 equivalents by 2030, amounting to a 49 to 51 per cent reduction. By 2050, Germany and other industrialised nations must have achieved or exceeded the upper end of the 80 to 95 per cent reduction corridor for 2050 in order to demonstrate the feasibility of stabilising the climate to a rise in temperature of around 2 degrees Celsius while simultaneously permitting sustainable economic development on other continents. Greater energy and material efficiencies and electrification using an increasing proportion of renewably generated electrical energy will have to make substantial contributions to reducing industry emissions. By themselves, however, these levers will not be enough to make some processes in the basic materials industry climate-neutral even in the long run. Innovative technologies which have not yet been available on the necessary scale will additionally be required.

8 | Cf. MCC 2018.
9 | Cf. Climate Home News 2018.
10 | Cf. Luderer et al. 2018.
11 | The Federal Government does, however, emphasise that these targets are not set in stone; their breakdown by sector (but not the total quantity) is set to be regularly adjusted, for the first time in 2018.
12 | Cf. Statista GmbH 2018.
13 | According to the Climate Action Plan, the industrial sector includes all emissions from combustion processes and on-site power generation by manufacturing as well as emissions from industrial processes and product use of fluorinated gases. At 188 million tonnes CO_2 equivalents, this sector was Germany's second largest emitter in 2016.
14 | Measure of a substance's greenhouse gas effect converted into volumes of CO_2.

1.2 Achieving GHG Reductions in Industry

In its Climate Action Plan 2050, the Federal Government has laid an emphasis on a technology agnostic approach and the necessity of innovation. Increases in efficiency, fuel switching (use of biomass or energy sources with lower CO_2 emissions) and electrification of energy demand can be put into practice even in the short term in some areas of industry and so make a considerable contribution to medium-term reduction targets as soon as 2030. New processes, materials and technologies, which are now already at the research and development stage, will be required for the considerable GHG reductions desired beyond 2030. A reliable frame of reference must be established as soon as possible in order to enable commercial use in the medium term.

Industrial emission balances (cf. section 2) would suggest that a systematic reduction in energy and material consumption, electrification using electricity from renewable energy sources, use of suitable alternative materials, fuel switching, improved recycling and even an increasing changeover to low-carbon processes (e.g. direct reduction steel) will probably not be enough to achieve GHG neutrality in industry.[15] For remaining emissions, energy-intensive industries should thus give consideration to processes for the capture and utilisation or storage of CO_2, i.e. Carbon (Dioxide) Capture and Utilisation (CCU) and Carbon (Dioxide) Capture and Storage (CCS).

CCU involves capturing CO_2 from industrial processes, primarily for chemical (re)utilisation of the CO_2 (see section 4).[16] CCS is a climate protection measure in which CO_2 captured from such processes is securely stored deep underground in rock formations (section 5); it should, if required, be possible to re-extract the CO_2 as a raw material.[17] This position paper does not envisage using CCS in the energy sector, but solely for the purpose of reducing otherwise unavoidable CO_2 emissions from industry. Other reports sometimes also consider the utilisation of CO_2 for boosting plant growth to be a CCU measure.[18] This option is not taken into consideration in the context of the present explanations and nor is the utilisation of often large quantities of captured carbon dioxide to increase yields from hydrocarbon deposits (Enhanced Oil Recovery, EOR, or Enhanced Gas Recovery, EGR).[19]

1.3 Timely Availability of All Options

The technologies required after 2030 will in particular have to be brought to market maturity in the short term if they are to be able to contribute to climate protection in good time. The necessary infrastructure has to be designed, approved, planned, built and funded, frequently spanning corporate and sector boundaries. Issues relating to possible multi-sectoral business models and their funding are already of relevance now due to long lead times. Where CCU and CCS are used, issues also arise in relation to society's willingness, the reduction potential inherent in the system, environmental sustainability and the practicality of associated market models.

If CCU technologies are to have a significant climate protection effect, there must be social and political acceptance of a rapid, huge expansion of power generation from renewable energy sources, since virtually all CCU processes are highly energy-intensive and have no climate protection effect with Germany's current power mix.

CCU has a climate protection effect only if the electrical energy used originates from renewable sources. This entails ensuring that the generation of renewable energy is expanded to such an extent that it is capable of meeting the considerable additional demand for CCU processes, in addition to other demand for electrical energy which will in any event rise due to more electromobility and heat pumps.[20]

An integrated approach, including uniform assessment criteria and standards for CO_2 reduction over the entire life of the resultant products (Life Cycle Assessment), is also required for any kind of CCU product. A reasonably high, globally increasingly harmonised CO_2 price which is reliable over the long term can potentially provide climate-friendly technologies with a competitive advantage over conventional CO_2-intense production processes and make currently uneconomic processing pathways economically

15 | Cf. McKinsey & Company 2018.
16 | Cf. Zimmermann/Kant 2017.
17 | For example for promoting the growth of exploitable algae (as a future option).
18 | Cf. Chowdhury et al. 2017.
19 | In this method, which has frequently been used in particular in North America, the great majority of the CO_2 used remains permanently in the deposit.
20 | The expansion targets for renewable energies must to this end be adapted to the additional demand. The expansion corridors specified in the 2017 Renewable Energy Act are in all likelihood too small (acatech/Leopoldina/Akademienunion 2017).

viable. Another significant factor for any kind of CCU business model is to define which participant in the CO_2 user chain is considered to be CO_2-free or -neutral and who furthermore is deemed to be a CO_2 emitter, an issue which is yet to be conclusively settled.[21]

The possible use of CCS technology must be the subject of a thorough debate with all social stakeholders as to whether and in which regions and to what extent the storage of CO_2, whether onshore or offshore, should play a part in Germany's or indeed the EU's climate protection efforts. Plans for the safety, long-term reliability and sustainability of CCS solutions are essential documents which require approval from government mining authorities. The funding structures of CCS infrastructure for transporting and storing CO_2 must be clarified. Technical standards for CO_2 transport and CO_2 storage are also of great significance to practical feasibility and must be developed in good time; substantial progress has already been made (see section 6.3).

1.4 CCU and CCS as Components of an Overarching GHG Neutrality Strategy

All options for reducing GHG emissions must be considered for industry. Priority must here be given to avoiding CO_2 emissions by higher efficiency, greater electrification and use of alternative energy sources, processes and materials. Considerable research effort and innovation are still required for some of these options.[22] However, given the stated intention of focusing on the debates around CCU and CCS technologies which are to be conducted in society, they will not be addressed in greater detail here. If CCU and CCS are also be effective climate protection measures, it is important to reach an understanding about the extent to which these technologies are to be components of an overarching GHG neutrality strategy and to be understood as such by all stakeholders. Publicly funded innovation programmes, general conditions in line with market requirements and financial assistance for building new infrastructure will play a decisive role in the development and market introduction of CO_2 reduction options. Additional interdisciplinary research effort, where possible involving both industry and civil society, will be required in order to come to a largely consensual assessment of the contribution made to the climate protection targets by the various reduction options. Not only must particular attention be paid to economic viability and acceptance but clarification is also required about which priorities the Federal Government and other public institutions should pursue by providing suitable incentives.

Decisions and resolutions need to be made soon in order to ensure appropriate security for the planning of and investment in new climate protection technologies. Only in this way can it be ensured that the introduction of these technologies will contribute simultaneously to climate protection and to maintaining industrial competitiveness.

21 | For example, the (re)utilisation of CO_2 for producing motor fuels involves industry, which captures CO_2, and the transport sector, which uses motor fuel.

22 | Cf. for instance McKinsey & Company 2018.

Fundamentals

2 CO_2 Emissions from Industrial Processes in Germany

2.1 Emissions Balance in Industry

Germany's total GHG emissions, converted into CO_2 equivalents, were 909 million tonnes in 2016, corresponding to a 27 per cent decline in comparison with 1990. CO_2 is the most significant greenhouse gas, accounting for some 86 per cent of total GHG emissions. Industry accounted for some 21 per cent of German GHG emissions in 2016 (figure 1). After the energy sector, industry is thus the second largest emitter in volume terms at 188 million tonnes CO_2 equivalents. The source balance according to the UNFCCC system[23] which is used here takes account of all emissions arising in the respective sectors, i.e. industry values include not only emissions from the combustion of the fossil energy sources coal, oil and natural gas but also process-related emissions; biomass is recorded as CO_2 neutral. Emissions from the use of secondary energy sources such as electrical energy or district heating, on the other hand, are allocated to the energy sector, even if the electricity is used in industry.[24] All subsequent GHG emission values are based on this source quantification method.

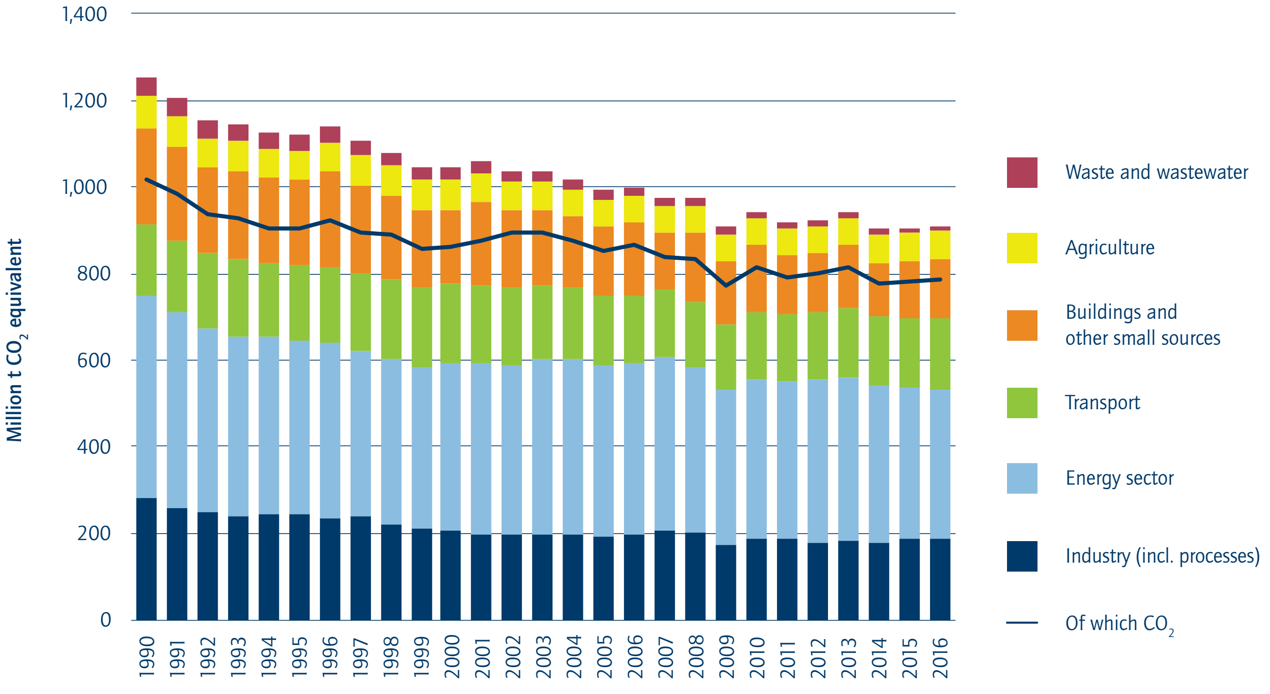


Figure 1: Trend in GHG emissions in Germany by sector. Industry is defined as in the Climate Action Plan (sources: UBA 2018a, UBA 2018b).

23 | GHG emissions can be quantified in various ways. On the one hand countries report their emissions in accordance with the UNFCCC Common Reporting Framework (CRF). On the other hand, emission balances are available from EU emissions trading. Both data sets quantify on a source balance basis which means that emissions arising from the use of electrical energy or district heating are not stated in the balance for industry but instead for power generation. The data sets differ significantly with regard to industry breakdown. The UNFCCC balance, for example, differentiates between process- and energy-related emissions and emissions from on-site power generation and combined heat and power generation, the EU emissions trading emissions registry separates out activities or sectors such as iron and steel, oil refineries, cement clinker etc. and permits a spatial representation. Due to the many different definitions used, the two data sets are not directly comparable, but they do include the large emission sources and together draw a relatively detailed picture of GHG emissions from industry in Germany.

24 | Final energy consumption by industry amounted to 29.0 per cent of total German energy consumption in 2015; 29.5 per cent were accounted for by the transport sector, 25.8 per cent by private households and 15.7 per cent by commerce, trade and services (BMWi 2017).

Figure 2 shows the trend in Germany's GHG emissions for industry in accordance with the definition of the sector target for 2030 (according to the Climate Action Plan). The industrial sector substantially contains emissions from processes, heat generation, combined heat and power generation and own power generation. Demand for industrial process heat varies greatly depending on the production process and sector involved. While food processing, for example, makes use of low-temperature hot water and steam, some processes in the basic materials industry (steel, glass, cement, lime etc.) require temperatures of over 1,000 degrees Celsius.

Major sources of process-related emissions are iron and steel, ammonia and cement production (figure 3). Steel production gives rise to process-related emissions by iron ore reduction, for which carbon is required. Cement production gives rise to CO_2 by the deacidification of limestone and by the use of combustion fuels. The approx. 34 per cent decline in GHG emissions in industry between 1990 and 2016 is largely attributable to a reduction in process-related emissions in the chemicals industry (primarily nitrous oxide (N_2O) emissions in the production of adipic and nitric acid), a decline in the use of coal and oil for heat generation (combined heat and power generation) and an increase in energy efficiency.

The spatial distribution and size of the individual point sources play an important role when it comes to the possible use of CCU and CCS. Table 1 shows the average GHG emissions of individual plants in Germany in 2014. Refineries have the highest average emissions per plant, at around 0.87 million tonnes CO_2, followed by iron and steel (each approx. 0.35 million tonnes CO_2) and cement works (0.30 million tonnes CO_2). It should, however, be noted that these are mean values for all plants registered in the EU Emission Trading Scheme (EU ETS). There is a wide range of variation in emissions from individual plants in every area.

More meaningful is the ranking shown in figure 4 of Germany's 50 highest emitting industrial plants in 2014 according to the EU ETS. These plants are responsible for around 68 per cent of industrial emissions in the EU ETS, with only those plants with minimum annual emissions of 0.2 million tonnes CO_2 equivalents being included. Individual plants with annual emissions exceeding 1 million tonnes CO_2 equivalents are particularly well represented in the iron and steel, basic chemicals and refinery sectors. Many cement works emit between 0.2 and 1 million tonnes CO_2 equivalents per year, while the glass, paper and non-ferrous metals sectors have only a few plants emitting over 0.2 million tonnes CO_2 equivalents per year. Across all sectors, 25 plants had emissions of at least 1 million tonnes CO_2 equivalents in 2014.

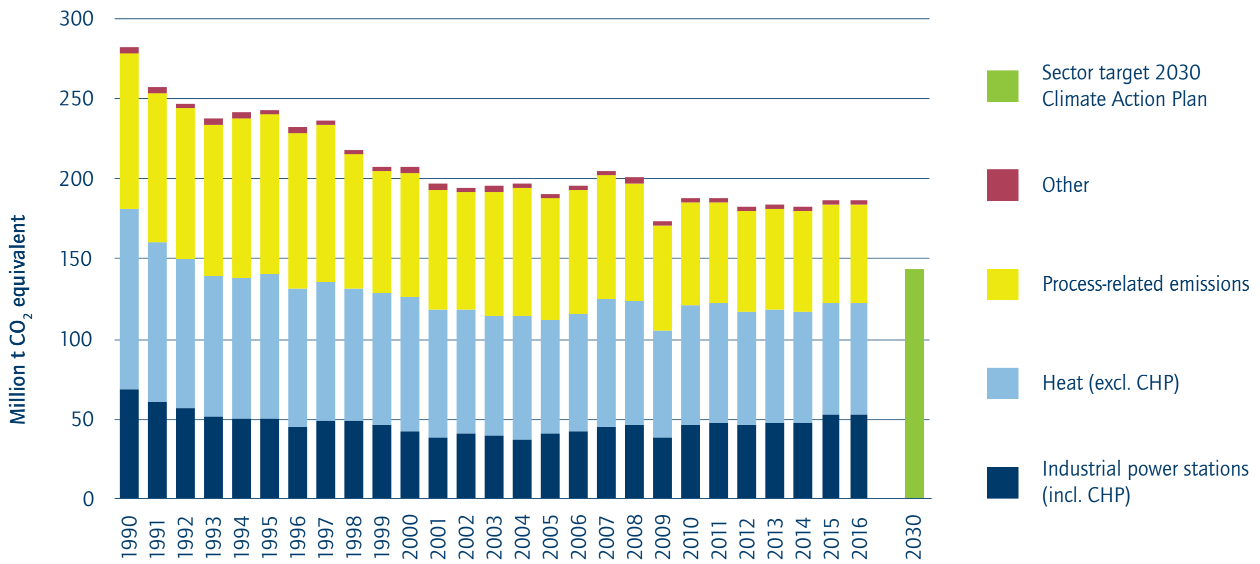


Figure 2: Trend in GHG emissions from industry in Germany by source type without biomass emissions and 2030 sector target according to Climate Action Plan; CHP = combined heat and power generation (sources: UBA 2018a, UBA 2018b)

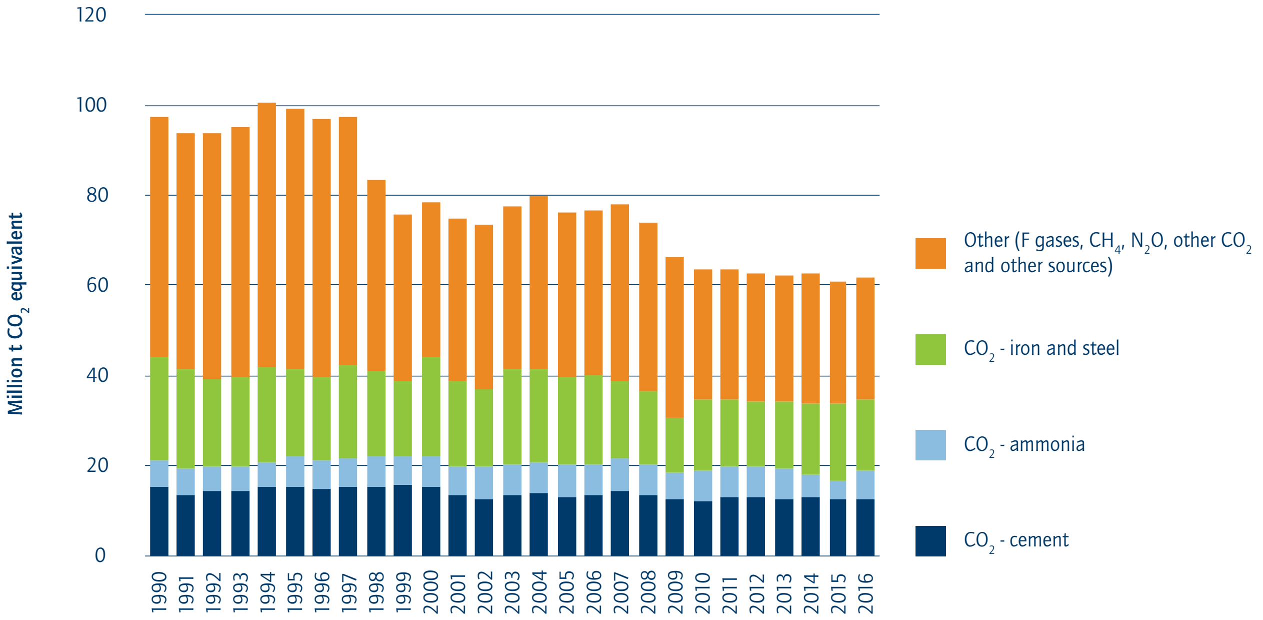
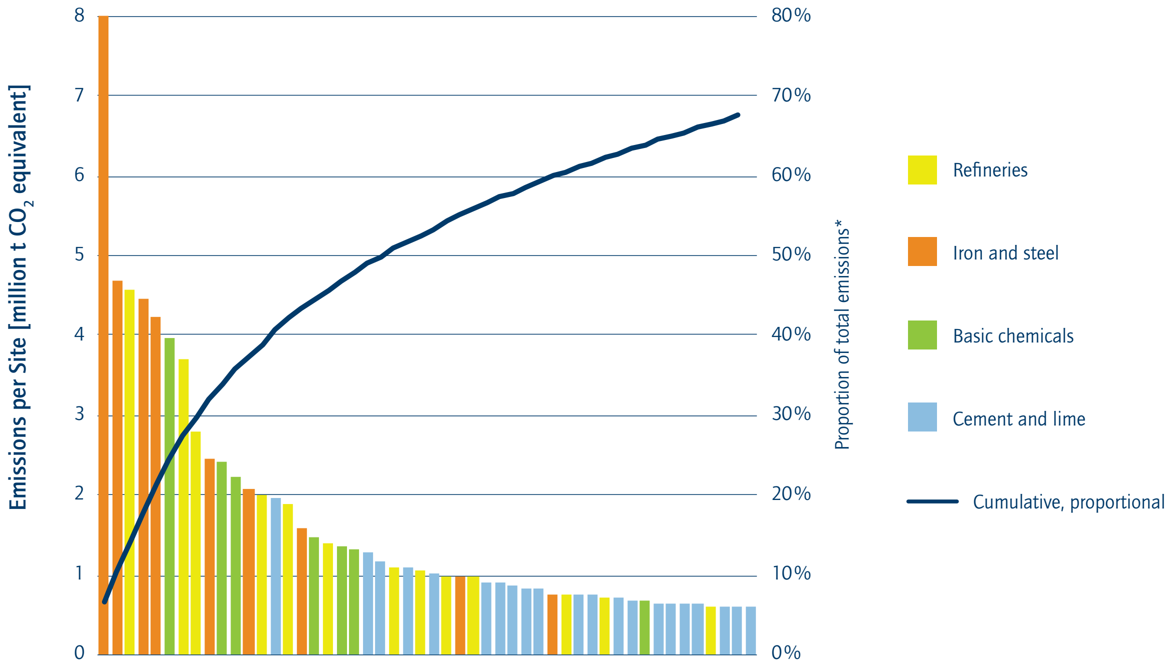


Figure 3: Trend in process-related GHG emissions from industry in Germany (sources: UBA 2018a, UBA 2018b)

	GHG emissions [million t CO_2 equiv./a]	Number of plants	Average emissions per plant [kt CO_2 equiv./a]	Maximum emissions [kt CO_2 equiv./a]
Iron and steel	36.2	105	345	8,016
Cement and lime	29.0	97	299	1,965
Refineries	23.5	27	871	4,569
Basic chemicals	18.1	129	140	3,974
Paper and pulp	5.6	148	38	343
Glass	3.9	84	46	243
Ceramics, brick, gypsum etc.	2.7	171	16	84
Non-ferrous metals	3.0	42	71	415

Table 1: Overview of 2014 GHG emissions by sector and number of plants in Germany (source: EUTL 2017)

Figure 5 shows the geographic distribution of significant German industrial sites in EU emissions trading. Some branches of industry are located in very narrowly defined regions (e.g. iron and steel production) while others are distributed relatively uniformly across the whole of Germany (e.g. lime and cement).



*Proportion of total emissions in 2014 (~122 million t) from industry in EU emissions trading for Germany

Figure 4: Verified GHG emissions of the fifty German industrial sites with the highest GHG output in EU emissions trading in 2014 (ranked by emission volume) and cumulative proportion of total emissions; only sites with an annual GHG output of at least 0.2 million tonnes are included (source: own presentation based on EUTL 2017).

2.2 Avoidance Options in Current Reduction Scenarios

Achieving comprehensive GHG neutrality in industrial production by 2050 will entail fundamental changes to the structure of production, energy supply and the use of raw materials and products in the basic materials industry. As with industrial production itself, there is great variety in GHG avoidance options, which arise not only at the production site but also right along the entire value chain. Although an exact classification is frequently not possible, the following avoidance options can broadly speaking be distinguished for industry:

- **Energy efficiency**: reducing energy consumption by investing in more efficient plants or optimising operating procedures;
- **Circular economy**: increasing the recycling rate and extending material flows in the loops (reuse, remanufacturing);
- **Material and resource efficiency** along the value chain: making more efficient use of basic materials in the downstream value chain including extension of product lives;
- **Use of alternative products and materials** along the value chain: using less energy-intensive materials in the downstream value chain;
- **Fuel switching**: changing over to energy sources with lower CO_2 emissions; this can also include using renewable energy for Power-to-Heat (PtH) or Power-to-Gas (PtG) processes;
- **CCU**: capture and utilisation of CO_2;
- **CCS**: capture and permanent storage of CO_2.

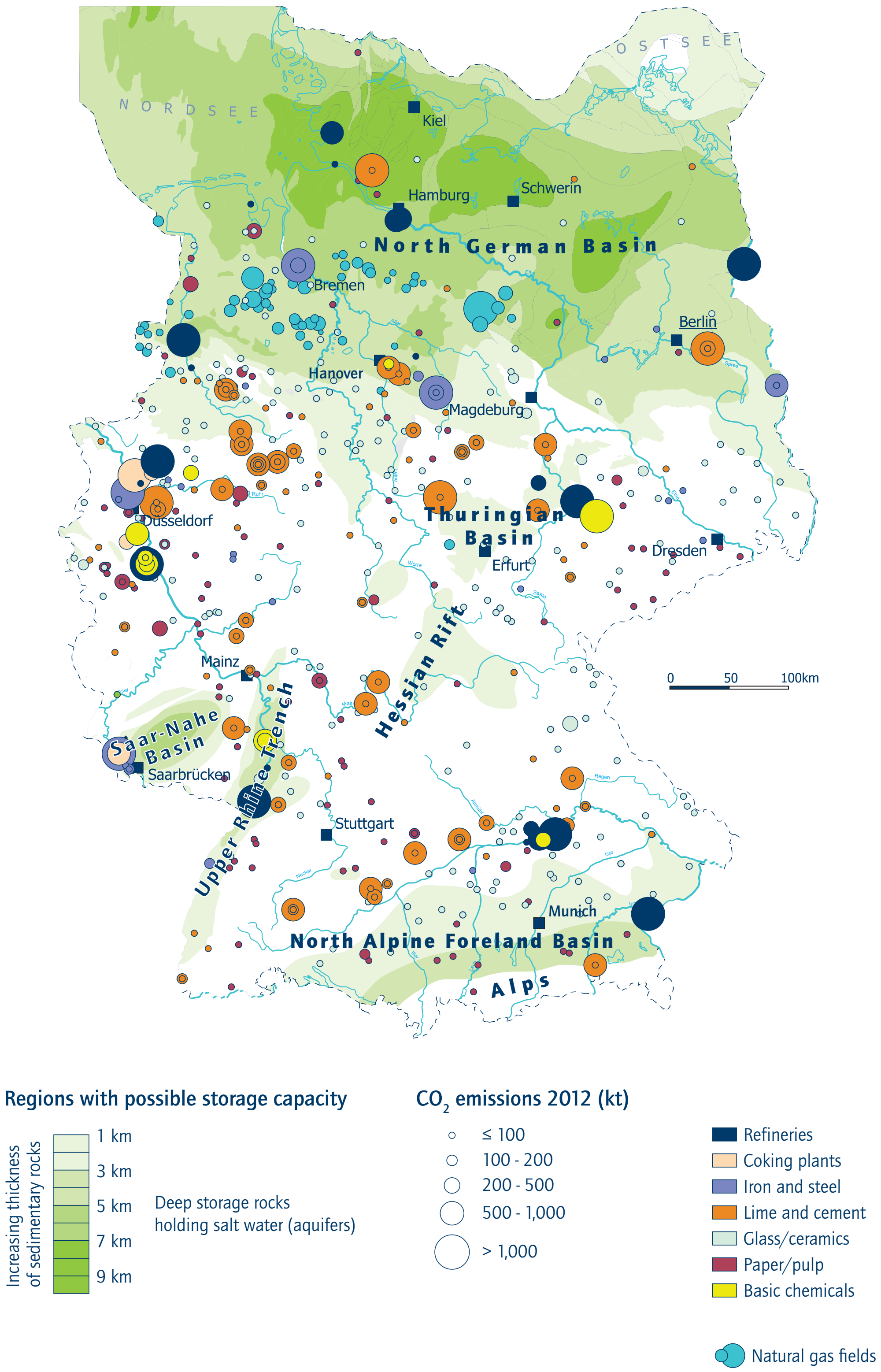


Figure 5: Geographical distribution of GHG emissions verified by EU emissions trading from industrial point sources in Germany and location of sedimentary basins and natural gas fields as geologically possible underground CO_2 storage sites. At present, onshore storage of CO_2 is largely impossible for legal reasons (sources: Gerling et al. 2009, DEHSt 2013).

Scenario	Published by	Year	Industry reduction 2050 in comparison with 1990
Climate protection scenario 2050, round 2: 95% scenario (BMUB KS95)	BMUB	2015	99%
GHG-neutral Germany (UBA GHGND)	UBA	2014	95%
Climate pathways for Germany, 95% scenario (BDI 95% pathway)	BDI	2018	95%
Long-term scenarios for the transformation of Germany's energy system, 80% scenario (BMWi long-term)	BMWi	2017	84%
Climate protection scenario 2050, round 2: 80% scenario (BMUB KS80)	BMUB	2015	75%
Climate pathways for Germany, 80% scenario (BDI 80% pathway)	BDI	2018	65%

Table 2: Overview of compared scenarios for GHG reduction for industry in Germany (ranked by reduction target level; source: own presentation)

Analysis of scenarios can reveal the contributions made by the various reduction options, for example until mid-century, and which targets are achievable under the assumptions made in each case.[25,26,27,28] Table 2 lists scenarios for industry which have high technological resolution and are included in the following comparison (sorted by the achieved reduction in annual emissions to 2050). While the most ambitious scenario "Climate protection scenario 2050, round 2: 95 per cent scenario" (BMUB KS95) for industry specifies a 99 per cent reduction in comparison with 1990, the reduction in the "Climate pathways for Germany: 80 per cent scenario" (BDI 80 per cent pathway) is only some 65 per cent. The need to have recourse to CCS as a reduction option also varies depending on the level of ambition of the scenario.

A comparison of the scenarios reveals not only major differences but also some common features. For instance, all scenarios include very major progress in efficiency. In this respect, the most ambitious scenarios in particular are approaching the limits of what is technically feasible. CCU does not play a major role as an avoidance option in most scenarios because the quantities of renewably generated electrical energy which may be required are considered to be unrealistically high or the overall emission reduction potential is not considered to be sufficiently significant. Material efficiency and the use of alternatives are also taken into account in only two scenarios and then at a low level (see table 3).

"Climate pathways for Germany: 95 per cent scenario" (BDI 95 per cent pathway) argues that a GHG-neutral energy system for Germany can only include those CCU applications which bind the CO_2 in products for the very long term, or alternatively that PtG and/or Power-to-Liquid (PtL) products can only be imported from countries with high proportions of renewable energy. This is not the case, for example, in the production of methane in PtG plants. In scenarios with a 95 per cent reduction, some isolated CO_2 streams are still available which could be used for CCU (for example in cement production).

Two scenarios with a reduction level of below 80 per cent remain which depend solely on faster progress in energy efficiency, fuel switching (use of biomass) and further progress in the circular economy, above all on an increase in the proportion of electric steel. Scenarios with reduction levels of over 80 per cent also make use, in addition to new production processes, of processes such as PtH (for example electric steam boilers), PtG (for example producing methane or hydrogen) and CCS which are operated with renewable energies. The scenarios focus on different priorities. For instance, the "GHG-neutral Germany" (UBA GHGND) scenario makes no use of either biomass or CCS.[29] As a consequence, there is a very high requirement for CCU in the form of PtH and PtG and new production processes are moreover of central significance. The other three scenarios use a similar portfolio of reduction options, albeit with considerably higher volumes of biomass, as well as with PtH in steam generation and the use of CCS. Except for the

25 | Cf. Fleiter et al. 2013.
26 | Cf. Arens/Worrell 2014.
27 | Cf. Brunke/Blesl 2014.
28 | Cf. Zuberi/Patel 2017.
29 | Only a small quantity of biomass with an energy content of less than 20 terawatt-hours, arising as a by-product of papermaking, is used.

Scenario	Reduction	Energy efficiency	Biomass	PtH	PtG	CCS	New processes	Circular economy	Mat. eff. + use of alt.
BMUB KS95	99%	+++	++	+	0	++	+	++	+
UBA GHGND	95%	+++	0	++	+++	0	++	++	0
BDI 95% pathway	95%	++	+++	0	+	+++	0	+	0
BMWi long-term	84%	++	++	+	0	++	+	++	+
BMUB KS80	75%	++	++	+	0	0	0	+	0
BDI 80% pathway	65%	++	+++	0	0	0	0	+	0

Table 3: Comparison of reduction options used in the scenarios (+++: very major use; ++: major use; +: less major use; 0: zero use). Power-to-Gas (PtG) is a form of CCU (source: own presentation).

BDI 95 per cent pathway scenario, all the scenarios above an 80 per cent reduction use new production processes. CCS is used for large point sources with highly concentrated CO_2 streams; these include iron and steel works, cement and lime works and plants for producing basic chemicals such as ammonia, ethylene or methanol. The volume of CO_2 stored underground each year by CCS is set to increase in the three scenarios from 35 to 73 million tonnes by 2050. The BMUB KS95 scenario uses biomass CCS (BECCS) in cement works, which results in "negative emissions" and enables a reduction of 99 per cent for the entire industrial sector.

The scenarios not only make different assumptions in terms of economic growth, energy prices and technological parameters but also use different methodological approaches. Although the number of scenarios compared is too low to be able to make generally applicable statements, some conclusions may nevertheless be drawn. Assuming continuous economic growth (0.5 to 1.5 per cent annually) until 2050 and an approximately constant industrial structure, it may be stated that

- a reduction of the order of some 70 per cent in comparison with 1990 would appear to be possible solely by ambitious progress in energy efficiency, increased use of biomass and a more completely circular economy;
- a reduction of over 80 per cent entails further reduction options which are either associated with higher costs or uncertainties in terms of public acceptance (CCS) or require new technologies which are today still at the demonstration or pilot scale (CCU);
- a reduction of over 80 per cent without CCS is only achieved by using new production processes and/or CCU in the form of PtG.

The impacts of an ambitious material efficiency and circular economy strategy have not yet been investigated in depth. The conclusions are correspondingly more rigorous in relation to a GHG reduction of 95 per cent in comparison with 1990. In each case, CCU plays a subordinate role.[30]

30 | Studies which focus on the analysis of an integrated energy system (power, heat and transport sector) in contrast in some cases reveal considerable use of CCU. The synthetically produced combustion and motor fuels may for example be used to supply energy during extended periods with little wind and sun which cannot be solely bridged by battery storage systems. It would seem to be particularly suitable to produce synthetic combustion and motor fuels by using excess electrical energy which is not required by other consumers and arises during generation which is dominated by wind and photovoltaics (acatech/Leopoldina/Akademienunion 2017; this study does not consider CCS).

3 Capture and Transport of CO_2

3.1 Capture Technologies

CCU and CCS technologies share the first two steps, namely CO_2 capture and transport (see figure 6). The CO_2 arising from industrial processes must be captured suitably in terms of costs, purity of the captured gas, efficiency and energy requirement of the process and the space requirement for the plant and equipment. From an economic point of view, using CO_2 capture technologies is primarily appropriate for large, stationary CO_2 sources where purity levels are already high. Over the last two decades, research for developing, trialling and implementing capture technologies has mainly been carried out in the power generation industry.

Existing technologies can be subdivided into three process pathways which differ in principle and can also be applied to other industrial processes,[31] namely post- and pre-combustion capture and the oxyfuel process. In some cases, research activities into the specific use of the various capture technologies for CO_2-intensive processes, for example in petroleum processing, the production of pig iron and steel including coking plants, the production of cement clinker and lime and of chemical products are still at the pilot scale in Germany. Post- and pre-combustion capture processes are commercially mature with the large scale industrial production of CO_2 for chemical processes or use in the food processing industry being standard practice.

3.1.1 Post-combustion Capture

CO_2 is captured from the flue gas after combustion or after the industrial process. A post-combustion capture unit for capturing CO_2 can accordingly be retrofitted to an existing industrial process. The CO_2 is captured from the flue gas by means of chemical absorption methods (scrubbing), for example using liquid solvents containing amines, ammonia or alkali, by means of "carbonate looping" (dry sorption), in which carbonation of calcium oxide (CaO) is combined with calcination of the calcium carbonate $CaCO_3$ or by means of membrane-based processes.[32] While chemical absorption processes and carbonate looping are also suitable for use at a low CO_2 partial pressure in the exhaust gas stream, membrane-based processes are in particular suitable for a high CO_2 partial pressure in the exhaust gas stream. Earlier plans for using the CCS process led to the construction of post-combustion capture pilot plants which are operated by the energy companies EnBW, RWE and Uniper at their Heilbronn, Niederaußem and Wilhelmshaven sites. The cement industry is researching post-combustion technology in the CEMCAP project.[33,34] Further research projects have been funded by the Federal Ministry for Economic Affairs and Energy.[35]

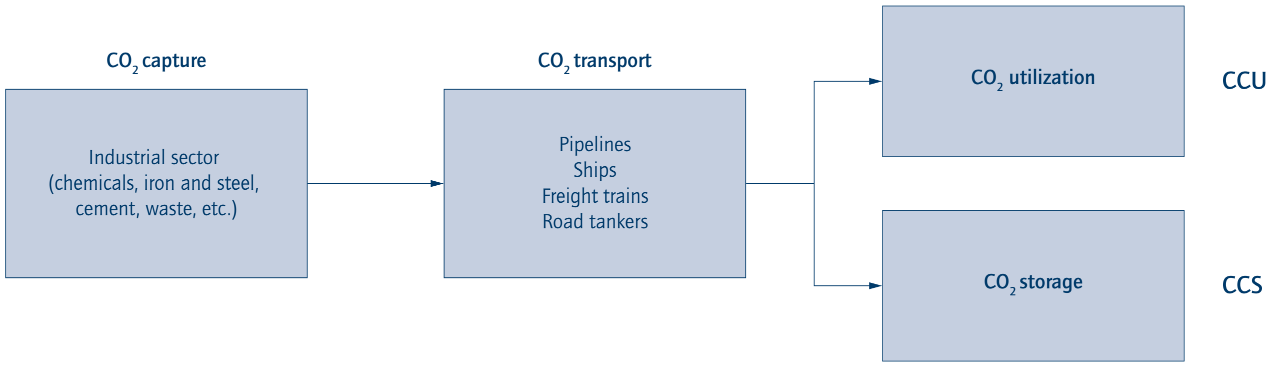


Figure 6: CCU and CCS technology process chains. CO_2 is a raw material which can be utilised in various applications; CO_2 in underground storage can be re-extracted if necessary (source: own presentation).

31 | Cf. Kuckshinrichs et al. 2010.
32 | Cf. Abu-Zahra et al. 2013.
33 | Cf. Hornberger et al. 2017.
34 | Cf. Perez-Calco et al. 2017.
35 | Cf. FIZ 2018.

3.1.2 Oxyfuel Process

In the oxyfuel process, combustion proceeds with pure oxygen. The oxygen is currently produced on a large industrial scale using cryogenic air fractionation plants. Alternative oxygen production processes include membranes, chemical looping and water electrolysis during hydrogen production. Combustion with pure oxygen results in distinctly higher CO_2 contents in the flue gas of some 89 per cent by volume in comparison with 12 to 15 per cent by volume in conventional power stations. A large proportion of the CO_2-rich flue gas is recirculated into the combustion chamber in order to reduce the distinctly higher temperatures which occur during combustion with pure oxygen. Unreacted oxygen is thus resupplied to the oxidation process and the residual oxygen content in the flue gas reduced. One energy company has investigated the oxyfuel process in a 30 megawatt thermal oxyfuel pilot plant on the Schwarze Pumpe site. In addition to the post-combustion process the cement industry is also investigating the possible use of the oxyfuel process in the CEMCAP project.[36,37]

3.1.3 Pre-combustion Capture

The pre-combustion process is based on integrated gasification of the actual energy feedstock (coal or biomass) and the production of a synthesis gas which consists of hydrogen, carbon monoxide and CO_2. In a second step, the carbon monoxide is converted into CO_2, which is then separated from the synthesis gas which has been formed. The actual combustion process is carried out with synthesis gas containing little to no carbon. Since only two power stations are so far being operated with this technology in Europe, the focus of CCS development in the power generation sector has been on the two previously described process pathways (post-combustion and oxyfuel processes). The pre-combustion process is not ideally suited to capturing CO_2 from industrial processes since it is incapable of capturing any process-related emissions, as occur for example in the deacidification of limestone. Furthermore, the conventional production process would have to be modified in order to implement this technology.[38]

3.2 Transport

Once captured, the CO_2 can be put to further chemical use or placed in a deep geological storage site to keep it permanently out of the atmosphere. For large volumes of CO_2, transport into storage should be by pipeline for reasons of safety and economy. To this end, the captured CO_2-rich gas mixture must firstly be sufficiently purified of any accompanying substances. The COORAL[39] research project determined the compositions of the CO_2-rich gas mixture arising from CO_2 capture from coal-fired power stations and investigated the corrosive effects on pipeline transport. The CLUSTER[40] follow-on project involves combining CO_2 capture technologies not only with power station processes but also industrial steel and cement production and oil processing processes and defining minimum requirements for the composition of the CO_2-rich gas mixture. If reliable pipeline operation involving little corrosion is to be economic, the water content in the CO_2-rich gas mixture must, for example, be reduced to below 0.005 per cent by volume (50 ppmv). In a maritime context, it is possible to envisage carrying CO_2 by ship to an offshore storage site, complemented, where required, by an inland waterway leg, in addition to CO_2 transport by pipeline[41]. Road and/or rail transport may be considered for land transport from smaller volume CO_2 sources (see figure 7).

Irrespective of the selected transport system, the CO_2-rich gas mixture must first be greatly reduced in volume by compression and/or refrigeration. In pipeline transport, the CO_2 is compressed to values above the critical pressure of 73.77 bar (for pure CO_2) so that it can be transported in the supercritical or liquid phase and unwanted phase transitions during transport can be ruled out. For ship transport, the CO_2 is cooled to a temperature of approx. –52 degrees Celsius. The minimum pressure for the tank here corresponds to the respective boiling pressure of the CO_2-rich mixture at –52 degrees Celsius (6.5 bar for pure CO_2). The above-stated pressure and temperature values will have to be adjusted depending on the nature and quantity of the remaining accompanying components.

36 | Cf. Lemke 2017.
37 | Cf. Mathai 2017.
38 | Cf. Fischedick et al. 2015.
39 | Cf. Rütters et al. 2015.
40 | Cf. BGR 2018.
41 | Cf. ISO 2016.

The USA has already gained considerable experience in transporting CO_2 by pipeline and this knowledge served as a major basis for the subsequent standardisation of CO_2 transport by pipeline (see section 6.3). Road and rail transport of CO_2 are standard practice.

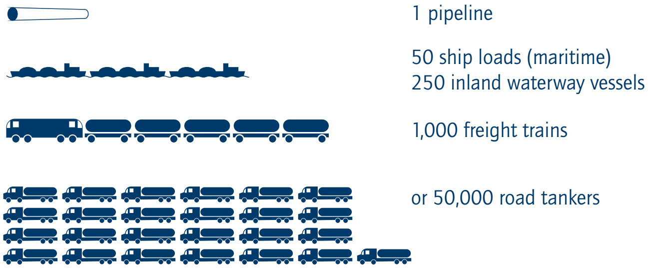


Figure 7: Comparison of resources used for transporting 1 million tonnes of CO_2 by pipeline, ship, rail or road tanker (source: own presentation)

4 CCU Technology

CCU involves capture of CO_2 from industrial processes, fossil fuel-fired power stations and biogenic sources or direct removal from the atmosphere with subsequent material use of the resultant CO_2, for example as a synthesis building block or carbon source in (petro-)chemical and biotechnological processes. Examples are the (re)utilisation of CO_2 in plastics and construction materials and the use of CO_2 in the production of synthetic motor fuels. CCU provides additional raw materials options for chemical processes and can contribute to reducing GHG emissions in two ways:

1. Reusing the CO_2 postpones the time at which the CO_2 enters the atmosphere. This is of relevance to climate protection for very long-lived products such as construction materials with a product life of a century or more.

2. If CO_2 is converted using renewable electrical energy into carbon-containing energy sources, short-lived synthetic products are obtained which can be used in the same way as energy sources obtained from fossil resources. As a result, either the industrial process from which the reutilised CO_2 is captured or the combustion process which is operated with synthetic motor fuel becomes virtually emission-free.[42]

CO_2 is a thermodynamically stable molecule. Reactions with CO_2 therefore in most cases require the input of considerable quantities of energy, either directly or in the form of energy-rich reactants such as hydrogen.

4.1 CO_2 as a Raw Material

The chemicals industry is dependent on carbon for the production of organic products. This carbon demand is currently predominantly met by the fossil resources oil, natural gas and coal. Captured CO_2, like biomass, is an alternative carbon source and offers the possibility of partially closing the carbon cycle loop for industrial use. Worldwide, approx. 120 million tonnes of CO_2 per year are already reacted in syntheses, 115 million tonnes of which in urea synthesis in which the CO_2 arising from gas and coal during ammonia synthesis is directly put to further use. Methanol synthesis makes use of 2 to 3 million tonnes of CO_2 for adjusting the hydrogen to carbon monoxide ratio. CO_2 is used to a lesser extent among other things for producing cyclic carbonates as solvents and for producing salicylic acid.

In principle, much greater volumes of CO_2 could be used. New synthetic routes are being intensively investigated in research and development projects. The availability of hydrogen produced by processes with a small CO_2 footprint, for example by renewable energy, is fundamental to tapping the greatest potential. Options starting from CO_2 and hydrogen include:

- conversion into methane (methanation, Sabatier process);
- conversion into formic acid;
- production of synthesis gas with subsequent methanol synthesis or production of hydrocarbons via the Fischer-Tropsch process.

All the pathways open up the possibility of subsequent synthesis of the most important petrochemical products based on these primary products.

The chemicals industry in Germany used some 17.9 million tonnes of fossil resources (petroleum products, natural gas and coal) in 2016,[43] the majority of which can in principle be replaced by CO_2 using the described routes. The essential prerequisite is the use of very large quantities of renewable energy for producing hydrogen (see figure 8). Using energy from today's power mix would make the CO_2 balance for the production of methane and methanol from CO_2 harmful to the climate, i.e. more CO_2 would be emitted from the process and due to energy input than would be bound in material form in synthetically produced methane or methanol. On the other hand, using electrical energy entirely originating from renewable sources might in future equalise the CO_2 balance.

Energy-rich reactants other than hydrogen are in principle also suitable for reaction with CO_2. For instance, CO_2 can be used as a co-monomer in polymerisation reactions with epoxides. Depending on the catalyst system, this gives rise to polycarbonates or polyether-polycarbonate polyols, a polyurethane precursor. Both classes of product have an annual production volume of several million tonnes.

Wide-ranging research is being conducted into further direct

42 | It must be ensured that sufficient renewable energy is available for the overall system in order to meet the demand for electricity from CCU in addition to that for other purposes.

43 | Cf. VCI 2018.

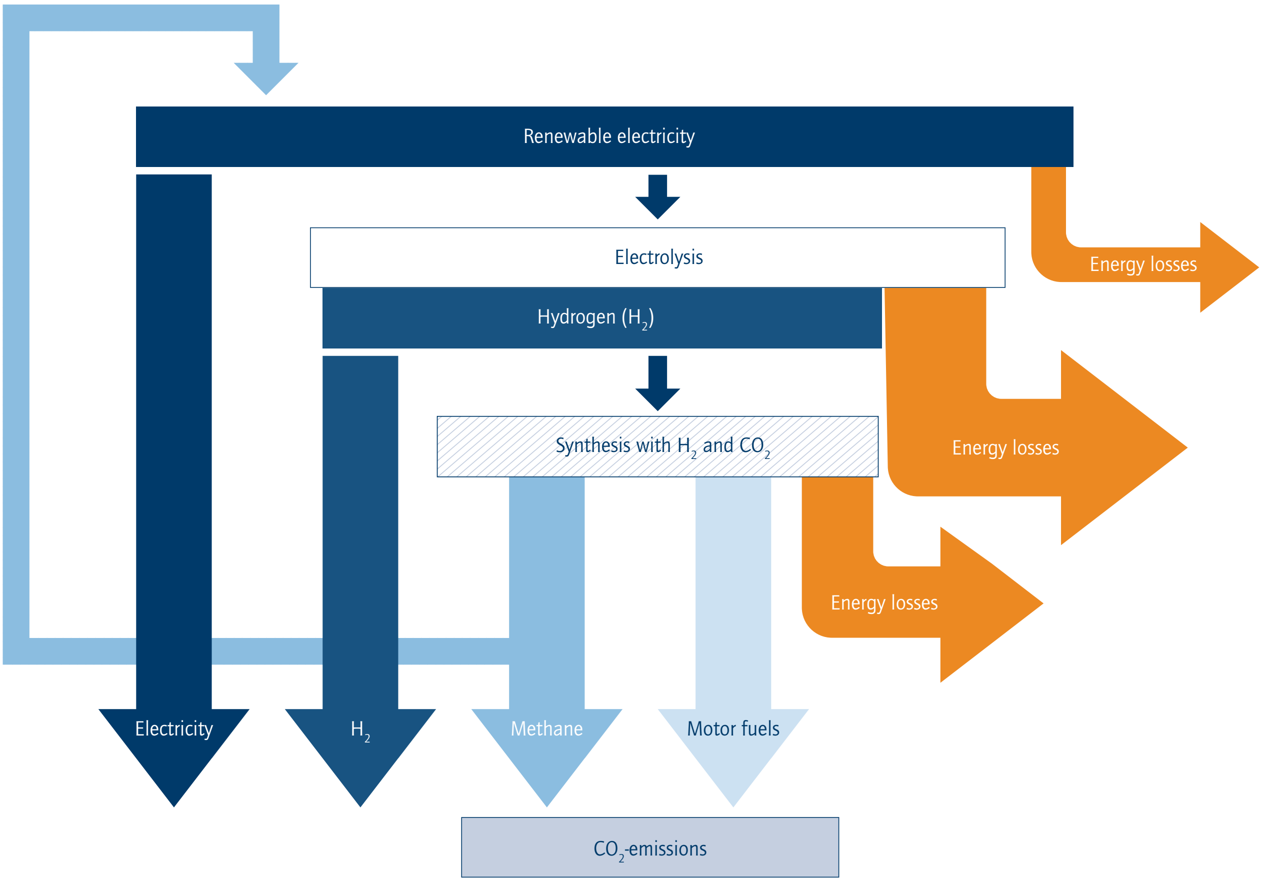


Figure 8: Qualitative presentation of energy flow and the role of CO_2. The pathway leading back from methane to renewably generated electrical energy indicates the possible circulation of energy using CO_2 which would involve accepting considerable energy losses (source: own presentation on basis of Piria et al. 2016).

synthetic routes starting from CO_2 (see figure 9). The following approaches being pursued in Germany may be mentioned by way of example:

- the production of acrylic acid from CO_2 and ethylene;[44]
- the direct electrocatalytic reduction of CO_2 to ethylene;[45]
- the production of formaldehyde from CO_2;[46]
- the synthesis of valeraldehyde, a large-volume intermediate for producing a new generation of plasticisers, from n-butane and CO_2.[47]

Carbon2Chem is another BMBF-funded initiative for the material use of CO_2 in which 17 partners from industry and science are working on producing raw materials from metallurgical gases.[48] In North America, pathways for CO_2 mineralisation in cement and concrete production are being investigated.[49,50]

4.2. Economic Viability

The economic viability of the production of products based on CO_2 is essentially dependent on the value creation of the resultant products and on the regulatory environment. For instance, the production of polyols which is being pursued by one

44 | Cf. ACER project: Bazzanella/Krämer 2017.
45 | Cf. CO_2 to value project: Siemens AG 2018.
46 | Cf. BMBF 2016.
47 | Cf. Valery project: Bazzanella/Krämer 2017.
48 | Cf. BMBF 2018.
49 | Cf. Solidia Technologies 2017.
50 | Cf. CarbonCure Technologies 2018.

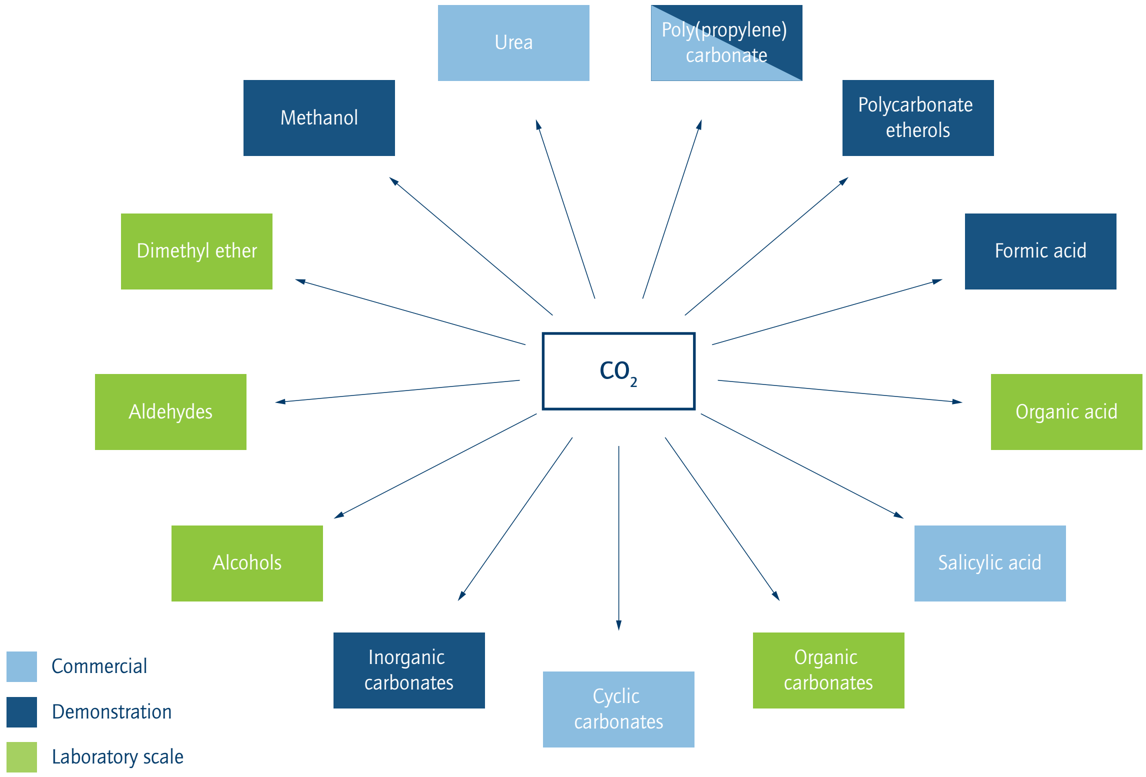


Figure 9: Possible chemical industry CCU products. The production of urea, cyclic carbonates and salicylic acid is already under way on a commercial scale while the other CO_2 products are at the demonstration or laboratory scale (source: own presentation on basis of Bazzanella/Ausfelder 2017).

chemicals company is already considered competitive; a demonstration plant inaugurated in 2016 is intended to confirm this presumption. The plants for methanation and methanol production or for producing motor fuels via Fischer-Tropsch synthesis are currently not economic. The fundamental problems are the high costs of producing hydrogen by electrolysis, which involves the consumption of electricity, in comparison with the low costs of fossil carbon sources. Process costs are substantially dependent on electricity purchase costs and the annual number of electrolysis full load hours. The Power-to-Gas[51] potential atlas published by the German Energy Agency (dena) estimates current production costs for electrolysis-based hydrogen at between €0.23 and €0.35 per kilowatt-hour, corresponding to €7.7 and €11.7 per kilogram. The production costs for synthetic methane are around 50 per cent higher. At €0.03 to €0.04 per kilowatt-hour, the industrial gas price is many times lower. The same applies to the production of methanol or synthetic motor fuels, even if the cost difference for these products is smaller due to their higher value added (e.g. approx. 11.5 megawatt-hours per tonne of methanol[52]). For methanol, even under favourable conditions, i.e. 8,000 full load hours per year and electricity purchase costs of €30 per megawatt-hour, production costs are at least twice the market price of methanol derived from fossil raw materials. For synthetically produced motor fuels, this would thus result in a cost premium of at least 100 per cent.

51 | Cf. Schenuit et al. 2016.
52 | DECHEMA calculations.

Costs can only be reduced by considerably lower electricity costs or reduced capital costs for electrolysis and by enabling continuous operation, for example by holding buffer stocks of hydrogen or renewably generated electrical energy.[53] These are the priority development targets for implementing large-scale CCU applications. Nevertheless, renewable routes cannot be expected to achieve cost comparability with fossil routes within the foreseeable future because the extraction costs for fossil resources will, for the long term, be lower than the production of methanol and other raw materials from electrical energy, water and CO_2. Universal use of synthetic motor fuels would also appear to be only a theoretical possibility and then only as a result of a massive, unprecedented expansion of electricity generation from renewable sources.[54] A study carried out by dena and Ludwig-Bölkow-Systemtechnik (LBST) on behalf of the German Automotive Industry Association (VDA) in 2017 calculated that Europe's currently available renewable electricity generation capacity would have to be increased seven to ten fold by 2050 merely to enable the production of synthetic motor fuels according to the corresponding scenarios.[55] A study from the Academies' Project "Energy Systems of the Future" (ESYS) concludes that power generation from wind and photovoltaics in Germany would have to be multiplied six fold by 2050 in order to meet the rise in electricity demand from electromobility, power-to-heat and the production of hydrogen and synthetic motor fuels.[56] On the basis of the experience gained in the course of the energy transition and various scientific analyses, such an expansion of renewable energy sources would also not lead to distinctly lower electricity costs and thus economic viability for synthetic motor fuels.[57] No account has, however, been taken here of the impact of a higher CO_2 price. It has not yet been settled whether the emission reductions arising from the use of synthetic motor fuels will be allocated to the industrial process or to the end user of the motor fuels, i.e. for instance the transport sector, or proportionately to both.

4.3 Impact on Infrastructure

The methanisation route has the advantage that the existing natural gas grid can be used for storing and transporting the synthesis gas. No additional infrastructure would be necessary and transport of methanol and liquid motor fuels would also be straightforward. Limits currently apply to the use of methanol as a motor fuel additive, the admissible rate of addition to petrol in Europe being up to three per cent by volume. Synthetic motor fuels, the production of which involves a high energy input, have physico-chemical properties which are largely comparable with fossil motor fuels.[58] For reasons of transport economics, large-scale industrial CCU plants should preferably be located where large volumes of CO_2 are available (iron and steel works, refineries or cement works; see section 2). If such locations have no link to renewable energy sources, there will also be a need for power transmission system expansion.

4.4 CO_2 Footprint

Evaluating the CO_2 reduction potential of CCU measures is no easy task. In particular, product life cycle assessments must be carried out, since the time for which the CO_2 is bound by CCU can range from a few days (for example in heating, combustion and motor fuels) up to many decades (for instance in building materials). The driver of research into the material use of CO_2 has in the past often been the prospect of cutting GHG emissions by (re)utilising fossil-based emissions. Assessing the CO_2 footprint here assumes the highest priority. It must be borne in mind that generally large volumes of energy are firstly required in order to enable material use of CO_2. Therefore, if the overall process is not to emit more CO_2 than is put to material use, it is necessary to use energy sources which have been assessed as GHG-neutral. Ultimately, a life cycle assessment must provide information about the size of the CO_2 footprint of a technology or product. ISO standard 14040/44 contains instructions for carrying out a life cycle assessment, but there is no standardised approach to assessing CCU processes. Many issues remain unresolved, in particular how the impact of GHG should be divided between multiple products ("co-products"). Experts are currently working

53 | H_2 can also be produced with a much lower energy input by methane (or natural gas) pyrolysis with carbon then occurring (DECHEMA 2013).
54 | Cf. Assessment of GHG reduction scenarios, section 2.2.
55 | Cf. Siegemund et al. 2017.
56 | Cf. acatech/Leopoldina/Akademienunion 2017.
57 | Cf. Abanades et al. 2017.
58 | There may be slight differences in density and the characteristic values of relevance to engine combustion.

on developing a common standard for assessing the CO_2 footprint in the material use of CO_2.[59]

Nevertheless, initial specific case studies are already available. In the course of the above-mentioned chemicals company's use of CO_2 to produce polyols (see section 4.2), RWTH Aachen calculated the CO_2 savings potential in a life cycle assessment: the CO_2 footprint of the overall process is distinctly lower than that of a reference process. This is substantially attributable to the partial replacement of the fossil-based epoxide by CO_2 in the synthesis.[60]

A life cycle assessment of a Power-to-Liquid pilot plant "Fuel 1" on the Dresden site, in which hydrogen from the electrolysis of water is converted with CO_2 into motor fuels (petrol, diesel, kerosene) reveals that synthetic diesel production by Power-to-Liquid (PtL) has the potential to save emissions in comparison with fossil diesel, providing the electrical energy originates from renewable sources.[61] The main effect is achieved by the small well-to-wheel footprint of the synthetic motor fuels in comparison with fossil-based motor fuels.

If CO_2 is removed from the atmosphere by means of renewable energy and converted into synthetic combustion or motor fuels, its use is climate-neutral. If, on the other hand, the CO_2 originates from an industrial process in which carbon from a form in which it was bound as a solid (for instance from fossil resources or limestone in cement production), the release of this CO_2 must be taken into account in the overall assessment. The generated quantity of CO_2 must therefore be allocated to either the industrial process or the combustion of the synthetic motor fuels. If CCU is deemed to be a climate protection measure for industry (the industrial process thus being recorded as climate-neutral), combusting the synthetic motor fuel has just the same CO_2 impact as combusting a fossil fuel.[62] In addition to the CO_2 neutralisation of the industrial process and the avoided use of fossil energy sources for the synthetic motor fuel, release of the CO_2 is also delayed for a short time.[63]

An analysis of potential by DECHEMA[64] investigated the CO_2 reduction potential of CCU for the five largest volume petrochemicals (methanol, ethylene, propylene, urea, BTX) in various scenarios until mid century. Conventional production currently consumes considerable quantities of fossil resources. It is also apparent from these scenarios just how enormous is the challenge of replacing the energy currently generated on a fossil basis by large quantities of renewable energy.[65] Assuming annual investment of €27 billion, Europe's chemical industry could theoretically utilise at most 210 million tonnes of CO_2 per year from 2050 by using CO_2 as a replacement for fossil-based carbon sources.[66] This would result in demand for 4,900 terawatt-hours of electricity from renewable energy sources, which is 1.6 times the entire power generation of the EU-28 states in 2015[67] or six times the quantity of electricity renewably generated in the EU in 2015.[68,69,70]

59 | Cf. von der Assen/Bardow 2014.
60 | Cf. von der Assen/Bardow 2014.
61 | Cf. Universität Stuttgart 2015.
62 | On the assumption that the electrical energy used for producing the synthetic fuel originates from renewable sources.
63 | Namely from CO_2 capture from the industrial process to combustion as motor fuel. This development is nevertheless a way of also integrating renewable energies into transport applications (trucks, aircraft, ships and others). IEA estimates project pan-European demand for liquid motor fuels in the transport sector to be some 10,200 petajoules by 2050. If these motor fuels were completely replaced by synthetic motor fuels, Europe could save up to 750 million tonnes per year of CO_2 emissions. However, achieving this would entail massively expanding electricity generation from renewable sources to 11,700 terawatt-hours per year which, in comparison with 2015, is 3.8 times the total power generation of the EU-28 or 15 times the quantity of renewably generated electrical energy (which would have to be used solely for motor fuel production). An effective alternative in climate protection terms might be the extensive electrification of the transport sector, possibly using fuel cell technology.
64 | Cf. Bazzanella/Ausfelder 2017.
65 | It may be advisable on economic grounds to produce synthetic motor fuels at international locations with lower costs than Germany and to import them (cf. Ausfelder et al. 2017).
66 | By way of comparison, in 2015 total output of GHG emissions in the EU-28 was approx. 4,450 million tonnes CO_2 equivalents, corresponding to approx. 3,830 million tonnes CO_2 (EEA 2018).
67 | Cf. Statistics Explained 2017a.
68 | Cf. Statistics Explained 2017b.
69 | The largest proportion are hydroelectric power stations.
70 | The associated additional load on the power grid and adjustment to current grid expansion projects would also have to be taken into account.

5 CCS – Technical and Geological Requirements

One option for keeping CO_2 emissions from the various parts of the basic materials industry permanently out of the atmosphere is to capture CO_2 and place it in deep geological storage (CCS). According to current scientific understanding, the negative emissions[71] considered necessary in the latter half of this century might also most readily be achieved with the assistance of permanent geological storage of the CO_2 removed from the atmosphere.[72] CCS does not mean that the CO_2 stored underground might not subsequently be reextracted and used as a raw material.[73]

5.1 CO_2 Storage Technology

There are in principle four options available for the geological storage of CO_2: deep saline aquifers, depleted oil and gas deposits, deep, unminable coal seams and basalt. The first two options permit the storage of CO_2 in the pore space of a storage rock while storage in coal seams is based on the sorption of CO_2 on coal. Storage in basalt likewise makes use of the pore and fissure space in the rock but, in contrast with conventional pore storage, is intended to achieve comparatively rapid mineralisation of CO_2 thanks to the high reactivity of the rock. A further option, which has previously been investigated only on the laboratory scale, is CO_2 storage in (methane) hydrates, with the methane being displaced and replaced by CO_2.[74] The injection of CO_2 into oil or gas deposits (Enhanced Oil Recovery/EOR, Enhanced Gas Recovery/EGR) for increasing the yield of hydrocarbon resources, in which the majority of the CO_2 remains permanently in the deposit, is not considered here. This method has been widely used in North America where considerable volumes of CO_2 are permanently bound underground (several tens of million tonnes of CO_2 per year; see section 5.2).

CO_2 storage in deep coal seams is not feasible in Germany due to the grades of coal involved and the associated low injection rates. Basalt likewise has no role to play in Germany due to its low prevalence. Depleted oil deposits in Germany are generally too small, often broken up into compartments by faults and in many cases are also at too shallow a depth to provide secure and effective CO_2 storage. Depleted gas deposits and deep saline aquifers thus essentially remain as the available storage options for Germany. Storage in former gas deposits amounts to returning carbon to formations from which fossil carbon/hydrocarbons were previously extracted.[75]

The following conditions must be met for a geological formation to be considered as a CO_2 storage site:

- A sufficiently porous and permeable storage rock must be present which is as thick and wide as possible (large storage capacity).
- The storage rock must be covered by an impermeable cap rock which effectively prevents vertical migration of the CO_2 out of the storage site.
- The storage and cap rocks should form a geological trap structure which limits lateral expansion of the stored CO_2.
- The storage rock should have a minimum depth of some 800 to 1,000 metres so that the CO_2 efficiently fills the available pore space in the storage site with high density and low intrinsic volume.

5.1.1 Storage Mechanisms

A combination of physical and chemical storage mechanisms combine to ensure permanent and secure storage of CO_2, this essentially involving four storage mechanisms:

- Structural, lithological: free CO_2 rises upwards by buoyancy forces and is physically restrained below a cap rock.
- Residual: CO_2 remains in the pore space along migration pathways due to capillary forces.
- Solution: CO_2 dissolves chemically in the formation water.
- Mineralisation: CO_2 reacts with the constituents of the formation water and the storage rocks and is precipitated in the form of stable minerals (carbonates).

The interactions and relationships between storage mechanisms are many and varied and depend on the prevailing local geological conditions and the selected injection profile. During the injection

71 | Cf. Gasser et al. 2015.
72 | Cf. EASAC 2018.
73 | Cf. ENOS 2018.
74 | Cf. TechnologieAllianz 2018.
75 | Previously used natural gas, substantially consisting of methane (CH_4), is replaced by CO_2.

phase, CO_2 which is bound by physical storage mechanisms predominates in the storage site. The proportion of CO_2 bound by slow chemical reactions becomes more significant only once the injection phase is over. Intrinsic storage safety increases over the course of time because CO_2 increasingly dissolves in the formation water and the quantity of free, upward-rising CO_2 phase declines (see figure 10). In addition, CO_2-saturated formation water sinks down in the storage site because its density is higher than that of the CO_2-free formation water. Finally, storage safety is further increased by the CO_2 being permanently incorporated into the solid storage rock matrix in the form of carbonates.[76]

Storage sites with a natural geological trap structure are considered necessary for keeping large volumes of CO_2 underground. Relatively small volumes of CO_2, for example from individual industrial plants, might manage with residual binding and dissolution in the formation water without the stream of CO_2 moving away from the injection well. This opens up further local storage options in addition to the regions which have previously been considered worthy of investigation.

In addition to the mechanisms operating in the vicinity of the CO_2-enriched storage rock, the injection of CO_2 into saline aquifers also brings about effects in the wider environment surrounding the injection sites. For instance, placing CO_2 into storage results in an increase in pressure and partial displacement of the formation water. Numerical simulations have revealed that a pressure rise may occur in a region of ten kilometres around the injection site. This may be associated with slight surface heave (of a millimetre order of magnitude) and induced microseismic activity. In general, neither effect is perceptible without specialist geoscience measurements. Monitoring of the effect is nevertheless necessary and makes sense in order to track propagation of the CO_2 in the storage site. A further point to be considered is how the CO_2 to be stored interacts with the fluids present in the storage rock and with the solid framework of the storage rock. Where possible, geochemical reactions associated with rapid, geotechnically relevant material transformations, such as drops in porosity and permeability due to precipitates or the decomposition of storage rocks (framework breakdown due to the dissolution of minerals in the vicinity of the wells), should be avoided.[77] If the CO_2 is to be introduced into the storage rock, an injection pressure which is higher than the prevailing reservoir pressure must be applied. This injection pressure must not exceed the fracture limit of the storage and cap rock. If the compressed CO_2 is injected into saline aquifers, it rises in the pore space as a result of buoyancy forces until it is stopped from rising any further by the overlying, impermeable cap rock. Buoyancy is the result of a lower specific density of the undissolved CO_2 relative to the formation water present in the pore space.

5.1.2 Gas Deposit Storage Option

Depleted gas deposits are the ideal option for storing CO_2 for a number of reasons (see figure 5). Their overlying strata have been demonstrated to be capable of retaining liquids and gases over millions of years. In addition, given a deposit's extraction history, its geological characteristics are very well understood. It may even be possible to reuse some of the natural gas extraction infrastructure which is still present for CO_2 storage operation. Depleted gas deposits furthermore have the advantage that they typically have subhydrostatic pressure conditions. Firstly, this means that the injection pressure required is lower than in the case of storage in saline aquifers and secondly the inwardly directed pressure gradient causes the formation water with an increased concentration of CO_2 to flow into the storage site. An increase in reservoir pressure and the associated long-range propagation of pressure, as are to be expected in the case of storage in saline aquifers, therefore play only a subordinate role.

On the other hand, it must be borne in mind that numerous old wells may be present in the region of natural gas fields. These provide potential migration pathways for the injected CO_2 to the earth's surface. For use as a CO_2 storage site, old wells, whether extant or already filled in, must be identified and possibly resealed.

In principle, it ought to be possible to refill the depleted deposits and so reestablish the original pressure conditions in the reservoirs. The cumulative extracted volume of hydrocarbons should here be replaced 1:1 by a corresponding volume of CO_2 (parts by volume under reservoir conditions). The actual replacement ratio and thus also the potential storage volume of a deposit are determined by further geological factors of the reservoir: displacement behaviour and compressibility of the formation fluid, pore space compressibility, pressure propagation in the reservoir and in the adjacent rocks and the structural integrity of the storage and cap rock.

5.1.3 Saline Aquifer Storage Option

Of the geological storage options present in Germany, saline aquifers have the largest storage potential in volume terms due to their broad geographic distribution. Saline aquifers are deep underground rock strata which are porous and permeable (for

76 | Cf. Kühn 2011.
77 | Cf. Wolf et al. 2016.

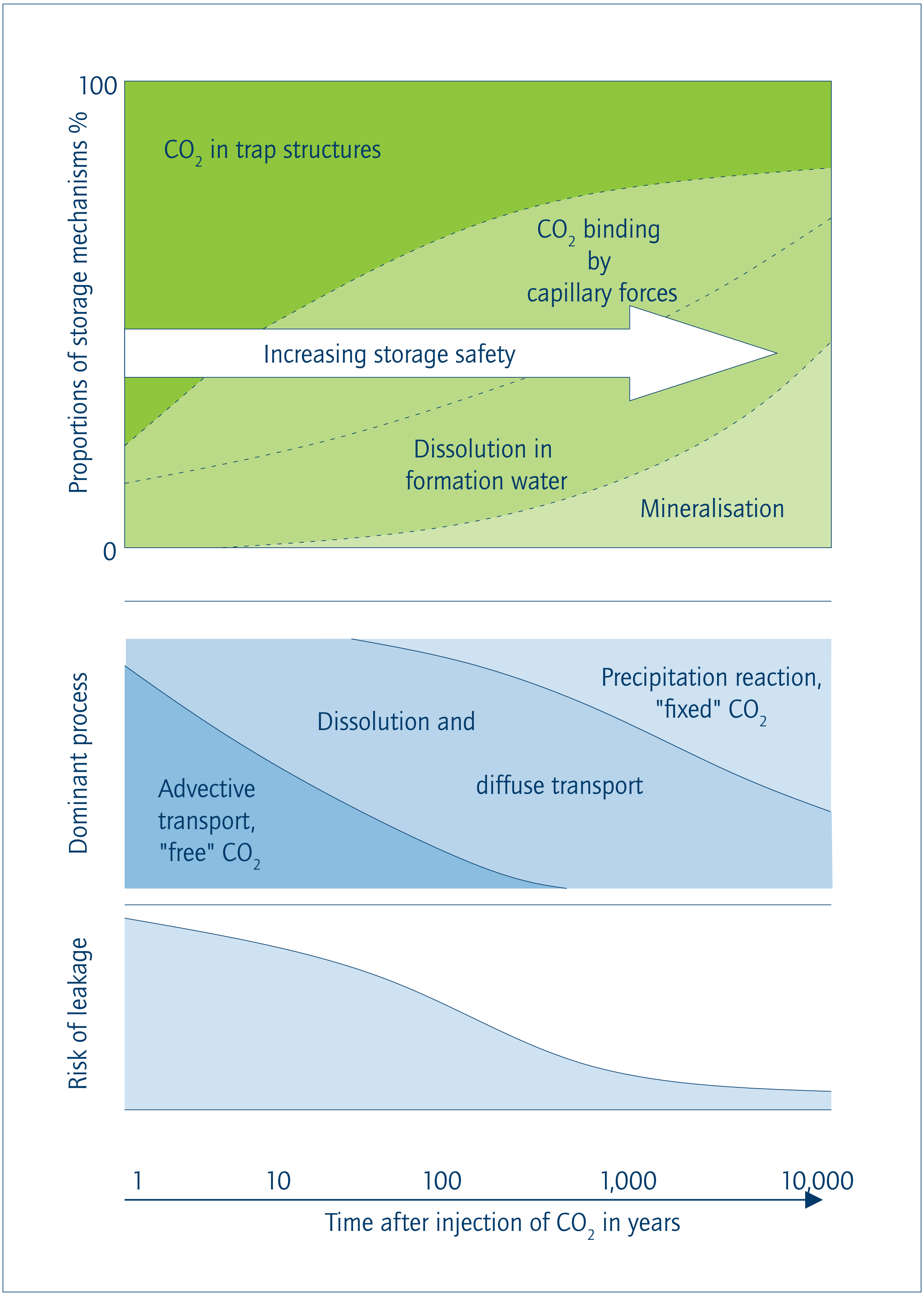


Figure 10: Storage mechanisms with time axis and decline in natural leakage risk over time (source: own presentation on the basis of Kühn et al. 2009)

the most part sandstone), the pore spaces of which are filled with highly saline formation water. The water is not suitable for drinking water extraction but some deep, salt-rich water is used in spas and as a carrier for geothermal energy. Overall, there has previously been little economic interest in saline aquifers, so they have been much less thoroughly explored than for example natural gas and oil deposits. The storage of CO_2 in saline aquifers demands an analysis and assessment of geological characteristics such as the situation in terms of structural geology, the type of aquifer, geological storage conditions and overburden density. Identifying suitable aquifer storage sites will therefore entail additional exploratory work.

5.2 Experience with CO_2 Storage

There is considerable international experience with the geological storage of CO_2, firstly from projects using CO_2 to increase yield from oil deposits (EOR) and secondly from projects for permanent CO_2 storage. The current CCS status report of the Global CCS Institute[78] lists 13 industrial EOR projects (predominantly in North America) with some 27.5 million tonnes of injected CO_2 per year and four industrial, pure CO_2 storage projects (Sleipner and Snovhit, Norway; Decatur, USA; QUEST, Canada) with approx. 3.7 million tonnes of CO_2 per year. In Germany, underground geological CO_2 storage was investigated from 2004 to 2018 at the Ketzin pilot site in Brandenburg. In addition to the injection of CO_2, propagation of the CO_2 underground was monitored and reextraction tested. Overall, 67,000 tonnes of CO_2 with a degree of purity of over 99.9 per cent were placed in storage over five years.[79,80] Together with the experience from various international storage sites, the findings obtained demonstrate that the geological storage of CO_2 is also ready for use on an industrial scale. The ongoing projects have, however, also revealed that, in the absence of a sufficient CO_2 price, at present CO_2 storage is only economically viable in the context of increasing yield from oil deposits (EOR).

From the standpoint of storage efficiency, it must be ensured that the gas to be stored is of the highest purity. In practice, the use of CCS technology, in particular in industry, will result in intermittent CO_2 streams which may vary in composition. The CLUSTER research project is currently establishing what consequences this will have on CO_2 storage requirements (e.g. necessity of buffer stores in the transport network, cluster solutions).[81]

5.3 Storage Capacity under the North Sea, the Norwegian Sea and in Germany

From a European standpoint, significant storage capacity is in particular available under the North Sea and the Norwegian Sea where there are projections of ample CO_2 storage capacity of some 165 billion tonnes of CO_2 in saline aquifers and some 38 billion tonnes of CO_2 in natural gas and oil deposits (see figure 11). The validity of these figures is, however, limited in so far as the capacity estimates from neighbouring countries differ in terms of the quantity and quality of the input data and also with regard to scale. One scenario in Great Britain assumes that by mid-century the country will each year be placing 75 million tonnes of CO_2 into storage in formations under the North Sea, 13 million tonnes of which will originate from industry.[82] The current government in the Netherlands intends to use CCS for the underground storage of 20 million tonnes of CO_2 annually from 2030.[83] The Norwegian government is funding a CCS demonstration project, currently set to run until 2022, for storing around 1.3 million tonnes of CO_2 annually in strata under the Norwegian Sea.[84]

The Federal Institute for Geosciences and Natural Resources (BGR) has determined the storage potential of gas deposits in Germany, taking account only of those natural gas fields from which cumulatively at least two billion cubic metres of natural gas had been extracted by 2008.[85] Storage capacity was estimated on the basis of production figures and published reserves. On this basis, the storage capacity of Germany's 39 known natural gas fields, almost all of which are located in north-west Germany, is put overall at some 2.75 billion tonnes of CO_2.[86]

78 | Cf. GCCSI 2017.
79 | Cf. Martens et al. 2014.
80 | Cf. Liebscher et al. 2012.
81 | Cf. BGR 2018.
82 | Cf. CCSA 2017.
83 | Cf. Bellona Foundation 2017.
84 | Cf. Ministry of Petroleum and Energy 2016.
85 | Measured under standard conditions, corresponding to some 5 million tonnes CO_2 under storage conditions which is in turn considered to be the minimum for economic capture and storage of CO_2.
86 | Cf. Gerling 2008.

Over the past 15 years, BGR has also calculated possible volumes of CO_2 storage capacity in saline aquifer structures in various regions of Germany in the course of project studies and updated Germany's possible storage volume. The investigation has recorded some 75 per cent of the area of the three sedimentary basins "North German Basin" (including the German sector of the North Sea), "Upper Rhine Trench" and "North Alpine Foreland Basin" (see figure 5) and included the spatially bounded trap structures identified there.[87] Calculation parameters were varied with the assistance of statistical simulations in order to assess uncertainties in the results, suggesting storage capacities of 6.3 (at 90 per cent probability), 9.3 (at 50 per cent probability) and 12.8 billion tonnes of CO_2 (at 10 per cent probability) with an average capacity of some 2.9 billion tonnes of CO_2 being located in the German sector of the North Sea.[88] Areas for investigation which, on the basis of current knowledge, best meet the conditions for storing CO_2 are primarily located in northern Germany[89]

Overall, there is sufficient storage capacity for many decades for anticipated future emissions from industry and likewise for achieving negative emissions by possible linkage with direct air capture in the latter half of the century (see table 4). If CCS technology is used for smaller CO_2 sources, further, less extensive storage structures can be considered in addition.

Until the issue of public acceptance of onshore CO_2 storage in Germany has been clarified, undersea storage, which may possibly be transboundary, would appear overall to be the costlier but more feasible option in the immediate future.

	10 million t CO_2 annually	20 million t CO_2 annually	50 million t CO_2 annually	100 million t CO_2 annually
(a) Offshore German North Sea, 2.9 billion t CO_2	290 years	145 years	58 years	29 years
(b) Onshore Germany 9.1 billion t CO_2	910 years	455 years	182 years	91 years
(c) Offshore North Sea and Norwegian Sea, 10% proportion, approx. 20 billion t CO_2	2000 years	1000 years	400 years	200 years

Table 4: Storage potential in years in the event of placing 10, 20, 50, 100 million tonnes of CO_2 in storage in the regions (a) offshore German North Sea, (b) onshore Germany, (c) offshore North Sea and Norwegian Sea, in this latter case in a proportion of 10 per cent of the estimated storage volume (source: own presentation; total size of storage potential rounded on the basis of figure 11)

87 | Cf. Knopf et al. 2010.
88 | For example field A6/B4 in the German "Entenschnabel" ("Duck's Bill") sector of the North Sea (TU Clausthal 2018).
89 | However, to date, the Federal States of Mecklenburg-West Pomerania, Schleswig-Holstein and Lower Saxony have availed themselves of the opt-out clause in the Carbon Dioxide Storage Act (KSpG) to adopt state legislation, or in the case of Brandenburg a state parliament decision, prohibiting CO_2 storage in their sovereign territory (including coastal waters).

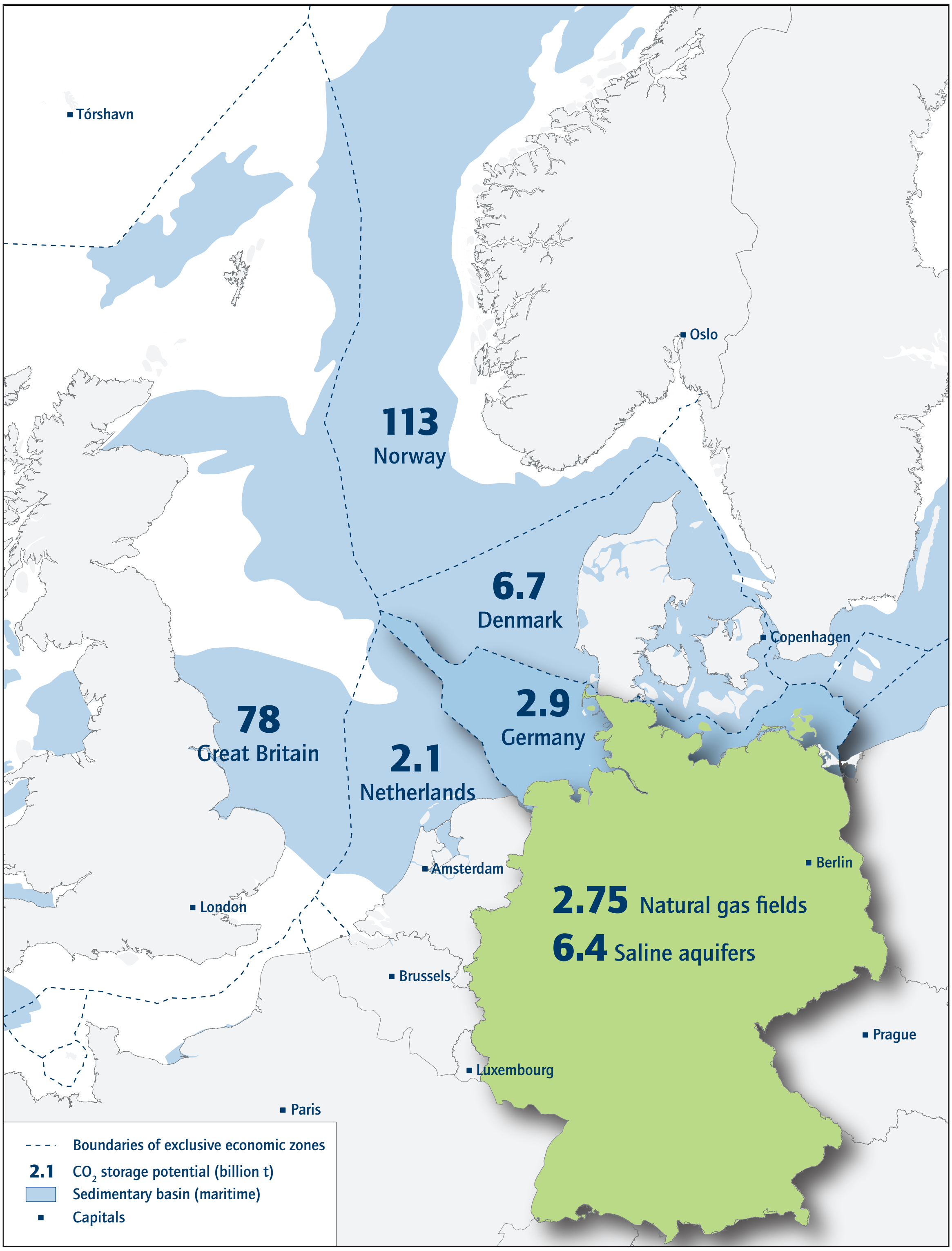


Figure 11: Projected CO_2 storage potential in formations beneath the North Sea and Norwegian Sea and in Germany; undersea values are aggregated for saline aquifers and hydrocarbon deposits (source: Bentham et al. 2014; Riis/Halland 2014; Anthonsen et al. 2013; Anthonsen et al. 2014; Knopf et al. 2010; Neele et al. 2012)

6 Legal Framework, Political Context, Technical Standards

6.1 Legal Framework

The European Directive on the geological storage of CO_2 entered into force in 2009.[90] After several years of an arduous legislative process including an arbitration procedure and threatened EU breach of treaty action, the CCS Directive was implemented in Germany in 2012 by the Act on the Demonstration and Application of Technology for the Capture, Transport and Permanent Storage of CO_2, known as the CCS Act. The central pillar of the omnibus act is the Act for Demonstration of the Permanent Storage of CO_2 (Carbon Dioxide Storage Act/KSpG).[91]

6.1.1 Aims and Scope of the Carbon Dioxide Storage Act

KSpG was drafted in Germany's 16th legislative period initially for comprehensive, large-scale industrial use of CCS technology but in the light of increasing resistance from the Federal States it was finally adopted as a "demonstration" act in the course of the 17th legislative period. Accordingly, the total admissible annual storage volume in Germany is limited to 4 million tonnes of CO_2 overall, with a maximum annual storage volume of 1.3 million tonnes of CO_2 per storage site. Applications for storage site authorisations had to be made by 31 December 2016, so new storage sites can no longer be permitted as the legislation stands at present. The act does, on the other hand, allow planning permission for CO_2 pipelines which means that the capture and subsequent transport by pipeline or alternatively also by ship or truck are not restricted by the current legal situation in Germany. By 31.12.2018, the Federal Government will report to the Federal Parliament about the application of the act, the experience gained internationally and the current status of scientific and technical knowledge.

During the legislative procedure, controversy focused above all on the opt-out clause for the Federal States which allows them to exclude specific areas from the CO_2 storage trial or to permit storage only in specific areas. The Federal States of Lower Saxony, Schleswig-Holstein, Mecklenburg-West Pomerania and the city states availed themselves of this clause and barred their entire territory, including all coastal waters in the North and Baltic Seas.[92] The Exclusive Economic Zone is excepted from the opt-out clause but, due to the expiry of the deadline at the end of 2016, no further applications for CO_2 storage can be made there either.

6.1.2 CO_2 Capture

Articles 7 and 8 KSpG add capture plants to the relevant pollution control regulations: plants for capturing CO_2 from plants which are subject to formal approval pursuant to the Federal Pollution Control Act (BImSchG) themselves require approval. If a capture plant is constructed in the course of the construction of a new plant which requires approval as an integral part[93] of the plant or as an ancillary facility, it is covered by the approval for the overall plant.

6.1.3 Transport of Captured CO_2

Under KSpG, planning permission is required for the construction, operation and substantial modification of CO_2 pipelines. The provisions of energy legislation relating to the construction of gas pipelines apply to the approvals procedure, which allows it to be considerably accelerated. In addition to the actual pipelines, this arrangement also applies to the compressor and pressure booster stations required for transport.

The restrictions of waste legislation are not applicable to (transboundary) transport of the captured CO_2 since the German Resource Cycle Management Act explicitly excludes the CO_2 which is captured, transported and stored for permanent storage or research purposes from the scope of waste legislation. In contrast, it has not yet been clarified how to deal with Article 6 of the London Protocol to the "London Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter" of 1972. While the amendment of the article does indeed permit transboundary transport for undersea storage purposes, the regulation does not come into force until at least thirty protocol members have ratified the amendment and with only three ratifications to date, there is still a

90 | Cf. European Parliament 2009.

91 | Cf. KSpG 2012.

92 | It is, however, questionable whether the opt-out clause actually does permit complete exclusion of State territory. The wording and aim of the regulation might suggest otherwise.

93 | Cf. Dieckmann 2012.

long way to go until it is legally valid. The IEA's 2005 analysis suggests possible solutions.[94]

6.1.4 Construction and Operation of CO_2 Storage Sites

The procedure for authorising a CO_2 storage site generally, but not necessarily, proceeds in two stages. The initial investigation of the underground situation for suitability for the construction of a storage site requires approval; the public must be fully involved right from the application stage for grant of an authorisation to investigate.

Planning permission is required for the construction, operation and substantial modification of a CO_2 storage site. An entitlement to grant a planning permission decision is not sufficient in itself since the planning procedure involves identifying, assessing and weighing up all relevant matters of public and private concern.[95]

One of the central requirements for authorisation of a CO_2 storage site is its long-term safety. This is defined as the state which ensures that the stored CO_2 and the stored secondary components of the CO_2 stream are permanently retained in the CO_2 storage site taking account of the necessary precautions against harm to humans and the environment. Planning permission furthermore requires the plant to cause no risks to humans and the environment. This duty to avert risks corresponds to the strict liability irrespective of fault which applies to the plant operator. This liability is made stricter by a presumption of causal connection in favour of the injured party. Refuting the presumption requires proof of proper operation and a suitable alternative cause to be provided, which means that the requirements are considerably more stringent than those under the German Environmental Liability Act.

6.1.5 Physical Planning

Planning permission for a CO_2 storage site must take account of the aims, principles and other requirements of regional planning policy. Regional planning policy is not limited to above-ground uses but also includes underground prospection and extraction of natural resources or further possible uses of underground zones. Regional planning policy bodies in the Federal States could provide a planning solution to the conflicts between competing underground uses in particular by designating priority and/or suitability zones. There are, however, natural limits set to underground physical planning by the existing geoscience data and the fact that certain resources or possible uses are tied to a specific location. Ultimately, if insufficient data are available, a site survey will be the only way of demonstrating whether a specific use or type of extraction is possible and economically viable.

Overall, KSpG has established a legal framework for CO_2 storage in Germany which, if the application deadline for storage projects is extended, will create legal certainty and security of investment while simultaneously ensuring a high level of environmental protection. The capture and transport of CO_2 are possible even without any extension of the application deadlines, which means that there are currently no legal obstacles to the further development of these parts of the process chain.

6.2 CCU and CCS as Political Themes

6.2.1 Germany

The current German government is aware of the need for action in order to achieve the aims of the Paris Climate Agreement and has not stated itself to be fundamentally opposed to CCS. If industrial emissions cannot be avoided in any other way, a possible role for CCS in this context is set to be investigated under the Climate Action Plan 2050.

The Federal Ministry of Education and Research (BMBF) AUGE project (evaluation of GEOTECHNOLOGIEN projects relating to carbon dioxide storage) is a summary and evaluation of all previous research projects into CO_2 storage as a conclusion to its completed funding programme.[96] The BMBF's CO_2 Plus funding programme into material use of CO_2 primarily takes account of CCU as a means for providing additional raw materials options.[97,98]

The COORETEC (CO_2 reduction technologies) programme under the auspices of the Federal Ministry for Economic Affairs and Energy (BMWi) has transitioned into the new "flexible energy conversion" research network. The BMWi is participating via Jülich, the project administrator, in an ERA-NET (European Research Area Network), an EU Commission Horizon 2020 joint research funding programme. ERA-NET ACT (Accelerating CCS Technologies)

94 | Cf. IEA 2011.
95 | Cf. Hellriegel 2010, Dieckmann 2012.
96 | Cf. GEOTECHNOLOGIEN 2018.
97 | Cf. BMBF 2015.
98 | Cf. DECHEMA 2016.

has so far assessed eight CCS projects in Europe as eligible for funding to a total of €41 million; a second call for applications for funding of up to €30 million was issued in June 2018.[99] The BMWi is furthermore represented on various European and national CCS fora, including the Carbon Sequestration Leadership Forum and the North Sea Basin Task Force.

6.2.2 European Union

Not one of the twelve large industrial scale CCS demonstration projects planned by the EU Commission in the first decade of this millennium has come to fruition. Two comprehensive funding programmes, the European Energy Programme for Recovery (EEPR) and funding using carbon credits from the New Entrants' Reserve ("NER 300") of the European Emissions Trading Scheme have come to nothing. The final project, the ROAD project in Rotterdam,[100] was abandoned in July 2017 after the participating companies ENGIE and Uniper Benelux withdrew their funding commitments. There are many and varied reasons for the failure to date to implement demonstration projects on a large industrial scale. The main causes may be considered to be inadequate acceptance and lack of experience with the legal framework together with technology costs combined with invariably low certificate prices. The intention is to enable funding of not only CCS projects once again but also CCU projects between 2020 and 2030 using the ETS innovation fund (NER 400).[101] Funding is also set to be extended to industry projects. In addition, the Energy Infrastructure Regulation in combination with the Connecting Europe Facility (CEF) funding scheme is offering overall funding of €5.35 billion for European energy infrastructure projects and thus also transboundary CCS projects. As a first step, four CCS infrastructure proposals which may be able to qualify for further funding, have been recognised as Projects of Common Interest (PCIs). Furthermore, all technology components of the CCU and CCS process chains play a significant role in the context of the Integrated SET Plan (Strategic Energy Technology Plan) which has set itself the goal of accelerating the development of low-carbon technologies.

6.3 Technical Standards and Risks

There are no dedicated technical standards for CCU technologies, they are covered by the existing rules for chemicals and materials of all kinds. However, in order to enable better comparability in the evaluation of the life cycle assessments for these technologies right from an early stage of research and development, voluntary guidelines are being developed in a number of initiatives both for life cycle assessments (based on the existing ISO 14040/44 standard) and for technical and economic analyses of CCU technologies.[102,103] Notwithstanding the voluntary nature of their application, these guidelines can help to establish a common approach to the evaluation and interpretability of the results.

In terms of CCS technologies, technical standards have been under development at the International Organization for Standardization (ISO) since 2011, specifically by Technical Committee ISO/TC 265 – Carbon Dioxide Capture, Transportation, and Geological Storage under Canadian leadership. ISO standards generally establish standard practice and have the nature of a voluntarily applicable recommendation unless legal documents (laws, regulations, contracts) specify their application by reference. The Federal Republic of Germany is represented in this collaborative effort by DIN – Deutsches Institut für Normung e. V..[104] At present, 29 countries are involved as active participants or observers in the development of ISO standards of relevance to CCS, with experts from Australia, China, Germany, France, Japan, Canada, Norway and the USA negotiating the crucial technical content. In addition, representatives of inter alia the International Energy Agency (IEA), the World Resources Institute (WRI) and the European Network of Excellence on the Geological Storage of CO_2 (CO_2GeoNet) are participating on an advisory basis. No comparable activity has yet been apparent in European standardisation at the European Committee for Standardisation (CEN), this being attributable in particular to the very different legal situations in the EU Member States.

99 | Cf. ACT 2018.
100 | Cf. GCCSI 2009.
101 | Cf. ETS Innovation Fund 2018.
102 | Cf. Neugebauer/Finkbeiner 2012.
103 | Cf. US EPA 2018.
104 | On the basis of the agreement between the Federal Republic of Germany and DIN – Deutsches Institut für Normung e. V. of 5 June 1975.

ISO/TC 265 is currently working on the following issues:

- capture technologies (ISO/TR 27912 and ISO 27919 series);
- CO_2 transport and stream composition (ISO 27913 and ISO 27921);
- geological storage (ISO 27914);
- quantification and verification of material streams (ISO/TR 27915);
- enhanced oil recovery (EOR; ISO 27916);
- life cycle risk management (ISO/TR 27918).

Previous estimates of the technical risks associated with transporting CO_2 by pipeline are essentially based on the lessons learnt from some 6,600 kilometres of pipeline mainly in the USA for assisting oil extraction by means of EOR. Since the CO_2 involved is from natural sources and very pure, there is no need for prior purification of the gases nor for more robust design of the pipelines to resist corrosion.

Overall, the pipeline technology to create CO_2 transport infrastructure is currently available and well understood; in other words, safe operation is technically possible. There is still a need for further research, primarily with regard to a thermodynamic description of the system, i.e. state equations for complex multiphase systems. In terms of risk analysis in relation to leaks of any kind, corrosion mechanisms within the pipeline must be better understood and incidents involving liquid CO_2 must be thoroughly modelled. In relation to monitoring transport grids, concepts are also required for admixtures of critical components in the CO_2 gas mixture and for monitoring actual mass flow rates. This is set to be the subject of a new project in ISO/TC 265.

ISO standard 27914 relating to geological storage[105] defines the requirements for the planning, site selection, modelling, risk assessment, communication, construction, CO_2 injection, operation, monitoring, verification, documentation and decommissioning of plants. Germany contributed its experience from the Ketzin pilot site (Brandenburg) to this work. The standard applies, however, only to direct CO_2 storage and does not include any CCU measures. Such measures are mentioned in relation to EOR applications[106], the standard essentially describing assisted oil extraction by means of CO_2.[107] Should the same site subsequently be used for the permanent storage of CO_2, the requirements of ISO 27914 will apply.

From a German standpoint, the quantification and verification of CO_2 streams in the overall process and in sub-processes are an essential part of both plant planning and assessing plant efficiency and potential risks. A technical report[108] outlines the various approaches.

105 | Cf. ISO 2017a.
106 | Not included under CCU in this POSITION PAPER.
107 | Cf. ISO 2017c.
108 | Cf. ISO 2017b.

CCU and CCS in a Business and Social Context

7 CCU and CCS – Common Features and Differences

Despite differing in many respects, CCU and CCS technologies are frequently considered together[109] or even confused with one another.[110] The latter is generally a matter of public perception outside the technical and scientific community and is probably due to the similarity between the terms. Considering CCU and CCS together, which is also a feature of political, business and media discourse,[111] is in part due to the common technical features with regard to CO_2 capture. Overall, however, the differences between CCU and CCS are substantial.

7.1 Drivers of the Development of CCU and CCS

The development of CCU technologies is primarily driven by the possibility of opening up a new carbon source and so broadening and securing raw materials options.[112] In this way, CCU technologies assist with moving energy systems towards renewable sources, in particular in sectors other than the energy sector, for example in manufacturing and the transport sector.[113]

CCS technologies, in contrast, have so far primarily been considered in connection with reducing CO_2 emissions, in particular in relation to large point sources such as coal-fired power stations and industrial plants.[114] CCS was therefore suggested as a way of reducing the climate-damaging side-effects of electric power generation based on fossil resources.[115] According to an IPCC estimate, some 8,000 such point sources worldwide were responsible for 40 per cent of anthropogenic CO_2 emissions in 2005.[116] Against this background, the IPCC report considers CCS to have major potential for the avoidance of emissions and so has nothing to do with the transformation of conventional energy systems.

7.2 Sources and Fate of Utilised CO_2

Numerous sources may be considered for the application of CCU since the volumes of CO_2 required are determined by the particular potential use. CO_2 sources of various sizes, which are often locally available, are thus already suitable for CCU measures. The purity of the CO_2 is usually of significance since many industrial applications require purity and upgrading the gas to a higher degree of purity may be costly. This applies in the same way to the CCS applications discussed in the present document for reducing GHG emissions from industrial processes.

CCU technologies have not so far primarily been designed for permanently binding CO_2 and generally also cannot do so. Instead, depending on the particular application, the utilised CO_2 is released back into the atmosphere. The time scale may range from a matter of days or weeks (e.g. for synthetic motor fuels) to years (e.g. for polymers), decades or centuries (e.g. cement or minerals).[117] The aim of CCS technology, in contrast, is to permanently prevent CO_2 from entering the atmosphere; permanent is here deemed to be periods in excess of 1,000 years.[118] This is a major functional difference between CCU and CCS in climate policy terms.

7.3 Sustainability Potential and Value Creation

CCU and CCS also differ in terms of the total volume of usable CO_2 they can dispose of. Given the uncertainty regarding a rapid and massive expansion of renewable energy, it may be assumed that for the time being it will only be possible to make effective use of comparatively small quantities of CO_2 for

109 | Cf. GCCSI 2013, AIChE 2016.
110 | Cf. Bruhn et al. 2016, Olfe-Kräutlein et al. 2016.
111 | Cf. McConnell 2012, Smit et al. 2014, US DOE 2015.
112 | Cf. BMBF 2013, BMBF 2015, thyssenkrupp AG 2018.
113 | Cf. Klankermayer/Leitner 2015.
114 | Cf. Haszeldine/Scott 2011, Scott et al. 2013, Scott et al. 2015.
115 | Cf. IEA 2013.
116 | Cf. IPCC 2005.
117 | Cf. Styring et al. 2011, von der Assen et al. 2013.
118 | Cf. IPCC 2005.

CCU. CCS technology, should it be used, is considered to have significant climate protection potential, as has been described above (see sections 2, 4 and 5). Irrespective of this potential, the CO_2 avoided must be individually determined for each measure on the basis of a life cycle assessment.[119] An industrial process is in principle climate-neutral if a downstream CCU measure does not give rise to more emissions than those generated by the industrial process itself. In some cases, CCU can even save more emissions than those arising from the conventional industrial process, if for example a fossil resource with a very large CO_2 footprint is partly replaced by CO_2.[120] In many technological pathways, considerable quantities of renewable energy sources have to be used in order to achieve a CO_2 saving over conventional processes.[121]

The essential sustainability potential of many CCU applications resides in the savings of fossil resources and any associated gains in efficiency. They boost independence from fossil resources and offer a possible way of reducing the environmental side-effects, perceived as critical in some circles, associated with their extraction and use.[122] From today's standpoint, it is virtually impossible to quantify the total fossil resource savings which could be made by using CCU technologies. The potential saving generated by each CCU measure has to be individually calculated (see section 4). In addition, process optimisation, which can in turn lead to indirect emission savings, can ultimately play a part which is, however, difficult to predict at the early stages of a technology.[123] Value creation is fundamentally possible in CCU by the use of alternative raw materials and efficiency gains, but this is dependent on the particular technology.[124]

The sustainability potential of CCS applications resides in placing CO_2 in secure deep underground storage and thus in the domain from which natural gas and oil are extracted. CO_2 storage is subject to strict testing and authorisation procedures by the relevant mining authorities. One crucial criterion is that the CO_2 in deep storage is permanently kept away from the atmosphere (see section 6.1.4).

7.4 Perception, Acceptance and Consequences of Inadequate Differentiation of CCU and CCS

While plans for the use of CCS technologies in Germany encountered considerable resistance from some parts of the population late in the first decade of the millennium (this resistance, together with economic factors, being considered to be behind the provisional cessation of CCS development in Germany[125]), CCU technologies have not so far been rejected. Reports on this issue in major media outlets[126] would also suggest that CCU technologies are considered to be distinctly less risky and the acceptance situation is thus less problematic than for CCS.[127] In the absence of a clear distinction being made between CCU and CCS in public discourse, there is a possibility that the earlier rejection of CCS will be directly transferred to CCU without the specific potential of CCU being taken into consideration.[128] Looking forward, this might jeopardise further political and public support for the development of CCU technologies.

In addition, CCU is frequently described as an alternative to CCS.[129] One of the consequences of such a way of looking at the issue may be that CCU technologies are primarily evaluated from the standpoint of their possible contribution to climate protection targets.[130] This disregards the fact that positive effects of CCU applications such as resource efficiency are likewise associated with climate protection.[131] In the context of the energy transition, an association between CCU and CCS may also create the impression that CCU is a strategy for extending

119 | Cf. von der Assen et al. 2013.
120 | Cf. von der Assen/Bardow 2014.
121 | Cf. Sternberg/Bardow 2015, Universität Stuttgart 2015, Bazzanella/Ausfelder 2017.
122 | Cf. von der Assen et al. 2013, BMBF 2015.
123 | Cf. Olfe-Kräutlein et al. 2016.
124 | Cf. Naims 2016.
125 | Cf. Cremer et al. 2008, Wallquist et al. 2010, Brunsting et al. 2011, Seigo et al. 2014.
126 | Cf. for example Schramm 2014, Fröndhoff 2015.
127 | Cf. Olfe-Kräutlein et al. 2016.
128 | Cf. Bruhn et al. 2016, Olfe-Kräutlein et al. 2016.
129 | Cf. Armstrong/Styring 2015.
130 | Cf. Markewitz et al. 2012, Hendriks et al. 2013, Oei et al. 2014.
131 | Cf. von der Assen et al. 2013, Bennett et al. 2014.

the service life of fossil-fired power stations.[132] Such impressions have led to CCU for example being described as a "fig leaf" for CCS.[133]

In principle, CCU technologies offer the possibility of improved resource management and recycling which are the aspirations of the vision of a circular economy.[134] CCU can therefore also be made an integral part of strategies for ensuring raw materials security, resource efficiency and a circular economy. Taken together, CCU and CCS can be considered to be two of several options in an overarching climate protection technology portfolio.

132 | Cf. ZEP 2013, Bozzuto 2015, Kenyon/Jeyakumar 2015.
133 | Cf. Lasch 2014.
134 | For example for carbon chemistry; cf. Bringezu 2014, World Economic Forum 2014.

8 Economics of CCU and CCS and Market Introduction of CCS

The efforts being made to achieve GHG neutrality as quickly as possible raise the question of whether CCS ought not to come more to the forefront for otherwise unavoidable emissions from industrial processes. Only a few countries which submitted Climate Action Plans in Paris mentioned CCS as a priority. An initial set of scenarios[135,136] reveals, however, that CCS should be a still more important component in the climate protection strategy for achieving the 1.5 degree target than for achieving the 2 degree target. Since the increase in CO_2 concentration in the atmosphere goes beyond the target concentration for each of these scenarios over the course of this century, it will be necessary to remove CO_2 from the atmosphere without recirculating it back into the atmosphere.[137] One option might be direct air capture combined with the geological storage of CO_2.[138] At present, we are not prepared for this in Germany. The significance of this issue, both now and in future, makes it vital also to consider economic aspects.

8.1 GHG-neutral Industrial Production

In the absence of financial assistance and/or reasonable CO_2 pricing, CCU and CCS will be incapable of achieving the necessary momentum. CCU is often mentioned in this connection as a possible way of making CO_2 capture economically more attractive by using CO_2 as a raw material (see section 7). The Potsdam Institute for Climate Impact Research (PIK) calculated on behalf of the Deutsches Verein des Gas- and Wasserfaches e. V. (DVGW) that the production of methane from hydrogen and infeed into the system require CO_2 prices of up to €90 per tonne. The effectiveness of CCU as a cost-effective climate protection option is, however, substantially dependent on the measurement basis. Estimates of the possible extent of the contribution made to climate protection by the production of especially long-lived products by chemical utilisation of CO_2 suggest values in the low percentage range.[139,140]

In terms of the economic significance of CCU as a climate protection measure, it is nevertheless important to compare various options with one another over the long term on the basis of their avoidance costs. Account must be taken here of what specifically is being replaced by the particular technology. If it is to be possible to include the various CCU options in appropriate models and evaluate them economically, sufficiently detailed estimates of their potentials are required. These facilitate the investigation of the hypothetical climate protection role of CCU in industry in greater detail, even if, on the basis of current knowledge, the contribution will still be small even in the medium term.[141] CO_2 avoidance costs arising from CCU and CCS measures in industry are dependent on numerous factors, for instance the type of CO_2 capture, the purity of the gaseous CO_2, the intended transport infrastructure, trends in energy costs and the manner in which the CO_2 is utilised in the case of CCU or the available storage options in the case of CCS. Cost estimates which are not based on experience from specific applications are accordingly vague.[142]

In the light of increasingly stringent climate protection targets and the associated costs, making economically viable use of CCU and CCS can prevent relocation of manufacturing sites and help to secure jobs and maintain current levels of prosperity at reasonable cost. It is furthermore conceivable that access to suitable CCU/CCS infrastructure including sufficient local availability of renewably generated electrical energy might lead to the expansion of a production site thanks to the ready availability of a solution to ensure CO_2 neutrality for energy-intensive industries.[143] Branches of industry which are part of a CCU/CCS system produce emissions-neutral products, something which is becoming increasingly important in a society with a high awareness of environmental and climate issues. This applies both to primary materials and to final products, providing manufacture is likewise GHG-neutral. Industry can in this way create a competitive edge over higher emission

135 | Cf. Rogelj et al. 2015.
136 | Cf. Luderer et al. 2013.
137 | Cf. Fuss et al. 2014.
138 | Cf. EASAC 2018.
139 | Cf. Mac Dowell et al. 2017.
140 | Cf. Bazzanella/Krämer 2017.
141 | Cf. Mac Dowell et al. 2017.
142 | Cf. Irlam 2017, McKinsey & Company 2018, EASAC 2018.
143 | Cf. Port of Rotterdam 2017.

products from other countries. The export of CO_2 capture technologies can also improve the economic viability of CCU and CCS; transport and storage companies can generate revenue from a constant supply of process emissions.

8.2 The Important Role of a Market Facilitator for CCS

Quite apart from the restrictive legal situation, inadequate levels of social, political and financial support for CCS in Germany are partly why the country has in recent years made virtually no progress in the development of CCS measures.[144] In contrast, in the USA thanks to pre-existing transport infrastructure and tax incentives for CO_2 storage, which in early 2018 were increased from US$20 to US$50 per stored tonne of CO_2,[145] a number of industrial scale CCS projects have already been developed.[146]

Suitable general conditions are essential if, in the event of a social and political consensus, it is to be possible to use CCS as a component of root-and-branch CO_2 neutrality in industry. Market facilitating institutions, market facilitators for short, can play a major role in the development and implementation of CCS infrastructure. Market facilitators are central coordination and funding agencies which also have a clearing house role. Their starting point is the many structural and financial inadequacies of the market which are currently hindering the development of a CCS system. By taking a coordinated, collective approach, market facilitators reduce risks and costs for all involved and thus eliminate critical stumbling blocks to the implementation of CCS projects. They are primarily of relevance to the formation of a CCS value chain, but can also promote the development of CCU applications.

Market facilitators should exploit the advantages of existing regional industry clusters and infrastructure hubs. Such an approach enables the largest possible number of participants to make use of suitable infrastructure. Individual manufacturing sites or branches of industry will have no need to construct their own costly infrastructure. A reduction in costs due to economies of scale will also make it easier for smaller companies to access the CCU/CCS value chain.[147] The price per avoided tonne of CO_2 will fall for all stakeholders.

8.2.1 Creating Certainty

One fundamental problem for the development of infrastructure is the existence of counterparty risks between individual links in the CCS process chains. Government or private sector investments at an early stage are therefore risky. For industry, this means that a company which captures CO_2 in its process has no guarantee that the necessary transport and storage infrastructure will be available as required. Correspondingly, companies investing in transport and storage have no guarantee that the emitters responsible for capture will supply CO_2 in the necessary purity and quantity at the intended time.

Market facilitators primarily act as a clearing house between stakeholders. They provide the necessary coordination and alignment between the plants capturing CO_2 on the one hand and the operators of the transport infrastructure and the storage sites on the other. The central task of market facilitators is to plan infrastructure projects, provide funding and assume liability and risks, so creating the necessary certainty and security for each link in the process chain.

The work of the market facilitators is also of significance to the scheduling of investment decisions, since the various links in the CCS process chains are generally governed by different time frames, and involves linking individual network components together and monitoring the requirements and deadlines for CO_2 neutrality. This kind of risk reduction attracts investors and encourages project implementation at every level.

Market facilitators also ensure that appropriate transport capacity is provided and bottlenecks are avoided and that the infrastructure can be expanded in parallel with the expansion plans of energy-intensive industries. A widely used infrastructure solution enables considerable cost savings since significant economies of scale can sometimes be achieved in the transport and supply or storage of CO_2.

8.2.2 Creation of Market Facilitator Institutions

Market facilitators require a mandate in order to carry out their tasks. National and regional governments should design the statutory provisions for market facilitators in such a manner that CO_2 network development is planned and implemented in line

144 | Cf. however section 6.3.
145 | Cf. Eames/Lowman 2018.
146 | Eleven large-scale CCS plants: cf. GCCSI 2018.
147 | A situation which may for example lead to the proposal of locally agreed supply chains for inexpensive, low-purity CO_2.

with the Paris Agreement; at the same time, key industries should be protected. Market facilitators may be both public and private sector bodies.

Essentially, a contractual framework is required which creates a basis for the allocation of market risks and liability between the public and the private sectors. To this end, CO_2 network capacities should be provided at a national and regional level which are in line with the strategic CO_2 reduction targets (see figure 12). Thus, they can be used and controlled in different ways depending on national and regional circumstances and the prevailing legal context and as a function of the conditions applied by the relevant regulatory authorities. Market facilitators may have different structures regionally, nationally and also within a project cluster, for example with regard to the government supervisory role, sources of funding or project acquisition mechanisms.

8.2.3 Funding of Market Facilitators and CCS Clusters

If CCS is used, it is to be expected that a major part of the CO_2 available for CCS projects will be stored offshore (see sections 5, 6 and 9). In general, the transport and storage of CO_2 account for a comparatively small proportion of the total cost of a CO_2 reduction measure.[148] Costs are dependent on general conditions such as the distance between CO_2 point source and storage, mode of transport used, possibility of reusing existing pipeline and well infrastructure as well as storage capacity and injection rate. Earlier estimates have established a budget for onshore storage which is in the low double digit range in Euros per tonne of CO_2 and approximately twice that for offshore storage.[149]

Market facilitators are dependent upon appropriate funding for drawing up development plans for CO_2 transport grids and storage sites. Technical studies, the development of CO_2 storage sites and the provision of transport solutions all have to be funded. Regional and national funds, contributions from industry and revenue from EU emissions trading could be used for this purpose.

At the EU level, there are already a number of funding programmes which can be considered for (co-)funding CCS projects. These programmes are, however, distributed across various EU institutions and none is designed in such a way that CCS infrastructure can be provided without an additional burden on society.[150,151] The various stakeholders (industry, civil society and unions) could work towards implementing best practice examples at a regional level in order to keep such a burden small.[152]

8.2.4 Business Models

The market facilitator approach results in two successive business model stages along the processing chain: a precommercial stage and a mature stage with established infrastructure.

The core tasks of the precommercial stage are "market procurement" and the development of a transport and storage structure. The need at this stage is primarily to fund business development costs (exploration and assessment of storage sites) together with capital and operating costs. CO_2 capture costs can vary considerably depending on the industrial process and technology involved.[153] Costs can be determined and CO_2 storage and fee levels established by calls for proposals or auctions. In most cases market facilitators which assume a high level of risk will have to be established by government, but in the medium to long term can be at least partly privatised or even wound up.

At the established market stage, day to day operation is the responsibility of private companies. Individual companies have a free hand with regard to business structure, risk allocation and the potential expansion of infrastructure. The government largely takes a back seat in order to counter possible monopoly positions and implements mechanisms which make CCS a viable business proposition. This may for example be accompanied by a guarantee of a high and stable CO_2 price, a premium for low-CO_2 power generation or low-CO_2 products or incentives for CO_2 storage.

The creation of CCU and CCS process chains by market facilitators has significant economic advantages once the appropriate infrastructure has been put in place and industry can be sure of having a purchaser for the CO_2 emissions it captures. From an environmental standpoint, reducing CO_2 emissions is the top priority.

148 | Cf. IPCC 2005.
149 | Cf. Maas 2011.
150 | Cf. Whiriskey/Helseth 2016.
151 | Cf. i24c 2017.
152 | Highly industrialised regions such as North Rhine-Westphalia might well have a great interest in infrastructure with which ambitious climate targets can be achieved without jeopardising economic power or jobs. Such regions would be the primary beneficiaries of CO_2 market facilitators.
153 | There are cost differences not only in real values, but also relative to the value of the product per tonne of CO_2.

Potential operators ...	invest in feasibility studies	... and are dependent on
of geological storage sites	relating to CO_2 storage concepts	political and public support, CO_2 supply or CO_2 purchase, low counterparty risks, economic market model
of transport infrastructure	relating to transport networks	
of industrial plants	relating to CO_2 capture plants	

Solution: Set up regional coordination centres to ensure that each link in the CCS process chain is provided in good time and in strategic manner.

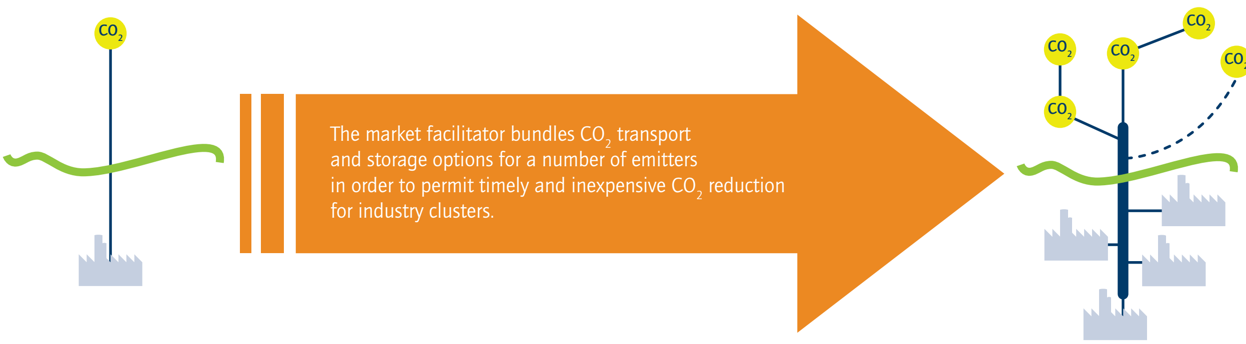


Figure 12: Model of a market facilitator institution – aims and role (source: own presentation on the basis of Whiriskey/Helseth 2016)

9 Public Perception of CCU and CCS

9.1 The Public Perspective

CCU technologies, to the extent that they are perceived at all, tend to be positively received by the public. Doubts are expressed for instance about technical feasibility and the long-term benefits for the environment.[154] Studies directed towards possible product perception likewise conclude that the overall assessment is positive and risks are in principle estimated to be low.[155] In relation to specific products, possible worrying health issues ("perceived health complaints") and disposal options are mentioned as examples of barriers to the implementation of CCU technologies.[156] A negative opinion of CCU technologies is above all apparent from discussions between social stakeholders and in media reports when a direct link is made with CCS, so modifying the context of CCU (see section 7).

In comparison with CCU processes, the perception of CCS technology[157] is distinctly less ambiguous and more differentiated. Scientists refer to wide-ranging experience in the handling of underground resources and consider CCS in principle to be a low-risk, controllable technology, while environmental stakeholders in civil society predominantly reject it. There have been essentially two reasons for this since around 2007: firstly, CO_2 storage has been stated to be accompanied by unmanageable risks which has often led to the criticism that risks and liability issues have not been sufficiently clarified. Secondly, the focus of public debate was at that time on the application of CCS to power generation from fossil energy sources, primarily by coal-fired power stations. There was a hope that it would quickly be possible to achieve GHG neutrality in electricity generation without CCS. As a result of associated path dependencies or "lock-in effects", any suggestions of introducing CCS for operational power stations will probably again trigger massive acceptance problems and protest movements. This would apply in the same way to the construction of new fossil fuel-fired power stations which involve CCS. At the present time, civil society stakeholders reject the use of CCS for fossil power stations.

9.2 Investigations into Aspects of Perception

Perceptions relating specifically to CCU technologies have to date only occasionally been scientifically investigated.[158,159] A first quantitative analysis was recently published in Great Britain.[160] According to available studies, technologies for utilising CO_2 are largely unknown and a broad public debate has not yet occurred in the absence of any perception and probably also because of the absence of any significant contact with legislative or approvals procedures. The implementation of CCU technologies, which in any event often tend to amount to changes to technical processes, would appear from today's perspective to be less dependent on a positive outcome from public debate than are other CO_2 avoidance technologies. Major perception and acceptance factors in Germany in relation to CCS have been researched in a number of studies focusing on power station technologies. Acceptance of CCS is substantially dependent on the subjective perception of the individual and social benefits of the technology, the risks attributed to it and trust in the stakeholders involved.[161] CCS technologies are perceived as risky, albeit with regional variations in the extent of hardening of opinion.[162] It is not CO_2 capture but instead the transport and storage of CO_2 which were considered critical, high-risk factors by some parts of the population. The reasons for this are for example the risks, which are considered unmanageable, associated with long-term, underground CO_2 storage. Associations with permanent storage in the nuclear energy sector are sometimes expressed. There are, however, signs that the technology is assessed more positively if the CO_2 originates from energy-intensive industrial processes or biomass power stations.[163] In the context of industrial processes, this is not least also due to the distinctly smaller volumes of CO_2 compared with the large-scale use of CCS in coal-fired power stations.

154 | Cf. Jones et al. 2015, 2016.
155 | Cf. Arning et al. 2017, van Heek et al. 2017a, 2017b.
156 | Cf. Van Heek et al. 2017b.
157 | Cf. for example Seigo et al. 2014.
158 | Cf. Jones et al. 2014, 2015.
159 | Cf. Jones et al. 2016, Olfe-Kräutlein et al. 2016, van Heek et al. 2017a, 2017b.
160 | Cf. Perdan et al. 2017.
161 | Cf. Pietzner/Schumann 2012, Scheer et al. 2014.
162 | Cf. Schumann 2014.
163 | Cf. Dütschke et al. 2016.

Against this background, it is currently uncertain whether CCS technology will find sufficient acceptance among the general public and relevant social stakeholders if it is only the source of the CO_2 which changes. It remains to be seen whether a new public debate can overcome the "old" reservations about CCS and take sufficient account of both objective facts and subjectively perceived fears and opinions. The experience gained in Germany and Europe in connection with plans for storing CO_2 from coal-fired power stations can provide important indicators regarding perception factors in society and sound them out as to their relevance to CCS applications in industry.

It is known that public perception is determined by a specific framework,[164,165] in which political events or issues are understood subjectively in a social, economic or cultural interpretive framework. An issue can here be accentuated from a specific viewpoint. Two such viewpoints can be identified in the debate around CCS in Germany[166]: firstly that CCS is being introduced as a partial solution to climate change and simultaneously as a long-term solution for the utilisation of fossil energy sources, and secondly that CCS is a risk technology for prosperous Federal States and is being used for the conventional power generation industry with the intention of delaying the necessary changeover to a GHG-neutral era. In terms of interpretive patterns, the debate thus essentially referred back to the origin of the CO_2 emissions from power stations using fossil energy sources.

By conducting a new debate, it might in principle be possible to break the close link between CO_2 storage and conventional power stations. CO_2 emissions from industrial processes are far less stigmatised than emissions from coal-fired power stations, even if the branches of industry involved (chemicals, iron and steel, cement etc.) do not exactly have the image of environmental trailblazers. If interpretive frameworks are to be influenced, the focus should accordingly be placed more on economic attributes such as competitiveness, requirements arising from globalisation, employment and income. Even if it makes no difference to the objective risk profile of transport and storage whether the CO_2 originates from fossil-fired power stations or industrial processes, the subjective perception of risk is that it does in fact make a difference.[167] When it comes to the use of CCS in industry, it is unclear whether this circumstance will lead to acceptance of this technology.

The debate around CCS and coal-fired power stations was and moreover remains marked by a perception that there are many technical alternatives for generating electricity. A number of renewable energy sources based on wind, sun and biomass are available. Such a range of suitable technical alternatives is not available to energy-intensive industries. In comparison with coal-fired power generation, the potential for mobilisation against the production of steel, cement, paper, ceramics or aluminium might therefore be much lower or even non-existent.

Furthermore, issues of equitable distribution which arose in earlier debates around CCS should also be borne in mind. There was a widespread impression that the less densely populated northern and eastern parts of Germany would have to bear the burden of CO_2 storage, while the major CO_2 emitters are primarily located in the densely populated southern and western parts (see figure 5). There was thus a clear geographic divide between benefits and perceived risks. Perceptions of equity and impact might be different if transnational or European storage structures in the North Sea were developed and used by means of shipping. In this case, sites in northern Germany might even benefit economically from the involvement of service industries. Finally, NGOs and the general population express doubts as to whether CO_2 can be permanently and safely stored in underground strata without insidious risks to humans and the environment. The occasional expression by scientists of divergent views regarding the safety and capacity of storage sites are probably partly responsible for these doubts. Despite there now being scientific evidence of twenty years of safe operation of Norway's Sleipner project[168] and despite explanations from many geoscientists as to why permanent underground storage of CO_2 is feasible and safe, most environmental interest groups and some parts of the population remain unconvinced. On the other hand, the underground CO_2 storage pilot project carried out in Ketzin (Brandenburg), which demonstrated that CCS technology was manageable, generated no opposition from the population.[169]

Another aspect of regional impact relates to the construction of CO_2 capture plants and CO_2 infrastructure. CO_2 emitters would have to construct on-site capture facilities and ensure suitable CO_2 transport arrangements. It would be important to establish here whether sufficient space is available and, if so, to what

164 | Cf. Goffmann 1974.
165 | Cf. Kahnemann/Tversky 1984.
166 | Cf. Scheer et al. 2017.
167 | Cf. Dütschke et al. 2015.
168 | Cf. IEA 2016.
169 | Cf. CGS 2018.

extent retrofitting and development of infrastructure would be involved and how much local residents would be affected by measures on and off the site.

Overall, however, the primary question remains as to whether reservations about CCS can be overcome if it is exclusively used for energy-intensive industry and other options including CCU measures have been exhausted for this sector. In this case, restricting use to industry would result in distinctly smaller volumes of CO_2 requiring geological storage in comparison with the large-scale use of CCS for coal-fired power generation. In addition, using CCS in energy-intensive industry is not contrary to the aims of the energy transition and climate protection but is instead counted among the various options and scenarios for the energy transition. Since energy-intensive industries produce components which are essential to renewable energy facilities (for instance light metals for photovoltaic systems, iron/steel products and concrete foundations for wind power systems), maintaining these industries is an important factor in safeguarding the future of a country such as Germany which has a focus on sustainability.

9.3 Impact on Acceptance

Anyone wishing to use CCU and CCS for reducing significant volumes of CO_2 must provide detailed information about the implications of both processes, engage seriously with affected stakeholders and environmental interest groups from an early stage and promote acceptance of the use of the planned technologies both by transparently examining any critical arguments which are put forward and by actively explaining the strategy used to minimise risk.[170] A perception of CCU or CCS as technologies which enable "business as usual", as a result of which the necessity for technological and social change as a response to the challenges of climate change is not apparent, undermines the acceptance of both processes. Fundamentally, those affected companies and sectors which are backing and promoting GHG neutrality strategies which make use of CCU and CCS must act convincingly with regard to climate protection

Since the production of CCU products in many cases requires the use of large volumes of electrical energy, an effective contribution to climate protection is only made if the products are predominantly or entirely produced using electricity from renewable sources. A CCU strategy must therefore be accompanied by a coordinated renewable energy expansion strategy. CCU can additionally be used in connection with recycling and extending product lifetimes or service lives in order to bind CO_2 for extended periods of time in products. The CCU pathway for producing motor fuels, which is currently the subject of much discussion, would be associated with rapid release of CO_2 into the atmosphere. While CO_2 savings can indeed be made in this way by making "double use" of carbon, achieving complete GHG neutrality would entail previously capturing this CO_2 from the air or using biomass as the carbon source. The removal of CO_2 from the air, potentially also in conjunction with CCS, will play a part in the latter half of this century in generating "negative emissions" and so offsetting unavoidable emissions for example from agriculture.[171] The use of large volumes of biomass can conflict with alternative uses (food) and nature conservation (maintenance of biodiversity).

CCS measures can only be implemented as components of a strategy for achieving GHG neutrality if there is wide support for the use of this technology from civil society, industry, politics, interest groups and science. Support and acceptance of CCS among citizens, like meeting technological, economic, geological, political and legal requirements, is also vital. Fundamental consent from citizens is the basis for creating a successful legal and economic context. In order to create a willingness to accept the use of CCS, deep underground CO_2 storage should accordingly relate to otherwise unavoidable CO_2 emissions from industry or to the direct removal of CO_2 from the atmosphere (Direct Air Capture with Carbon Sequestration, DACCS). There is still little public awareness of the necessity for reducing industrial process emissions and for the corresponding measures. Precisely when it comes to the use of CCS, it is therefore important to demonstrate that firstly the sectors concerned have definitely exhausted all potential avenues for reducing or eliminating their process emissions and secondly that it has been checked whether emissions cannot be substantially reduced by changing over to new materials and technologies. Only if this is successfully achieved will it be possible to obtain society's consent to the CCS measures which are necessary in this context.

An advisable preliminary step is to provide comprehensive information and conduct a wide-ranging public debate.[172] Many citizens may well be unaware, for example, of the strict safety and environmental conditions which have to be met to gain approval for CCS projects. Yet, it must also be borne in mind that however great a contribution they may make to

170 | Cf. Braun et al. 2017.
171 | Cf. EASAC 2018.
172 | Cf. also Grünwald 2008.

climate protection, major plants or large-scale infrastructure projects are very rarely going to be accepted with open arms. It is conducive to the acceptance of CCS measures if, firstly, the volumes of CO_2 for disposal are what remain once other potential avenues for reducing GHG have been exhausted and, secondly, the measures will, from a long-term perspective, be used for a limited time ("bridge technology"). Since reducing GHG emissions is essential for climate protection reasons it is, however, ultimately credible to count on public acceptance of CCS solutions for energy-intensive industries. CCS could in this way already make a contribution to climate protection providing that new GHG reduction methods continue to be developed and introduced onto the market.

Outlook

10 Options and Recommendations

Germany has the goal of cutting its GHG emissions by 80 to 95 per cent by 2050. Since the Paris Agreement, German climate policy has been shaped by the aim of achieving far-reaching GHG neutrality by 2050. The Federal Government has set a reduction target for industrial emissions of approximately 50 per cent by 2030 in comparison with 1990. Any further reductions in GHG emissions over and above this intermediate target are technically very challenging and require timely planning and investment: technologies will have to be brought to market maturity and necessary infrastructure will have to be constructed.

- Achieving these demanding climate protection targets means that, during the current legislative period, the strategies for decarbonising industry (with the aim of GHG neutrality) set out in the coalition agreement must be developed and ways forward identified which simultaneously maintain Germany's innovative, efficient and competitive industrial base.
- In addition to further boosting efficiency, ensuring greater electrification of industrial processes, using alternative energy sources, processes and materials, fostering innovative reduction technologies and moving towards a circular economy by implementing processes for the material (re) utilisation of CO_2 (Carbon Capture and Utilisation, CCU), a strategy for ensuring GHG neutrality of industry should also consider making use of the geological storage of otherwise unavoidable CO_2 process emissions (Carbon Capture and Storage, CCS).
- While material (re)utilisation of CO_2 can indeed contribute to GHG neutrality, overall CCU can only make a substantial contribution to climate protection if very large volumes of low-cost renewable energy are available. At present, it is difficult to estimate when this might be the case. This makes it all the more important to take action to implement other solutions before mid-century.
- If the industrial sectors concerned have definitely exhausted all potential avenues for reducing or eliminating their process emissions and it has moreover been checked whether emissions cannot be substantially reduced by changing over to new materials and technologies, the option of geological storage of CO_2 must be taken into consideration. Considerable volumes of CO_2 can be stored deep underground both onshore and offshore and if necessary re-extracted.
- Given lead times of at least ten years until CCU and CCS are in widespread use, it is necessary to examine and evaluate the possibilities of both technologies and cost-effective synergies (e.g. using common transport infrastructure) during the current legislative period. CCU and CCS will otherwise not be available to a sufficient extent in good time.
- The development of CCS infrastructure, which would also be available for CO_2 transport for CCU projects, could be coordinated and implemented by the creation of market facilitator institutions. By acting as central clearing houses, market facilitators would ensure alignment between capture, transport and storage projects and mitigate the prevailing economic risks. Implementing a cluster approach can create economies of scale.
- CCS measures can only be implemented as components of a strategy for achieving GHG neutrality if there is wide support for the use of this technology from civil society, industry, politics, interest groups and science. Fundamental support and acceptance of CCS among citizens, like meeting technological, economic, geological, political and legal requirements, is also vital.

In the light of the demanding commitments arising from the Paris Climate Agreement, there would appear to be an urgent need, during the current legislative period, to examine the opportunities, risks and limits associated with the use of CCU and CCS within the framework of a comprehensive GHG neutrality strategy and to discuss the resultant options for action in good time with all social stakeholders.

11 Summary and Outlook

The Paris Climate Agreement came about as a result of numerous scientific findings about the causes of climate change. The 2015 agreement saw the German Federal Government commit itself to a considerable reduction in GHG emissions. The starting point for this position paper is the judgement that, despite the measures which have so far been implemented and the considerable successes achieved in reducing GHG emissions, it will be extremely difficult to achieve the desired goals.

In addition to the energy sector, the largest source of GHG emissions, German industry is also responsible for releasing considerable volumes of greenhouse gases. In its Climate Action Plan 2050, the Federal Government has for the first time set a sector target for industry. Industry is thus also of great significance in terms of developing strategies for achieving GHG neutrality. On the basis of current knowledge, it is foreseeable that even a systematic reduction in energy consumption across all sectors and a changeover to renewable electrical energy wherever possible will not be sufficient to achieve the agreed goals.

Achieving further reductions in industrial emissions is technically very challenging. Any options for reducing GHG emissions must in principle be taken into consideration, these essentially being divided into:

- avoidance – by higher efficiency, greater electrification and use of alternative energy sources, processes and materials;
- (re)utilisation – by extending material use, which in the case of CO_2 means Carbon Capture and Utilisation (CCU);
- long-term geological storage of residual CO_2 volumes by Carbon Capture and Storage (CCS); stored CO_2 can if necessary be re-extracted as a raw material.

The various options should be considered in this order of priority. Consideration must be given to suitable methods and their potential while the opportunities, risks and limits of implementing them must be evaluated from both a legal and a social standpoint.

The CCU and CCS options which are examined here in greater detail are frequently mentioned in one breath and consequently considered to have comparable prospects and effects, but such is not the case. In Germany, CCU measures are one component of the energy transition, which focuses on making ever less use of carbon-containing fossil energy sources and ensuring a dominant role for wind power and photovoltaics in power generation. Major German industries do, however, remain dependent on carbon in many and varied ways. Together with biomass, CO_2 is therefore in principle an alternative carbon source, even if (re) utilising CO_2 usually involves high energy inputs. CCU technologies can thus assist with moving energy systems towards renewable sources. There has so far been very little public debate about the various applications of CCU, which ultimately differ greatly from one another. On the basis of current knowledge, it is not possible to say when the required very large volumes of low-cost renewably generated electrical energy will become available and so enable CCU to make a substantial contribution to achieving the Paris climate protection targets.[173] As one component of the energy transition, CCU technologies can be made an integral part of strategies for ensuring raw materials security, resource efficiency and a circular economy.

CCS technology has been trialled on a large scale elsewhere and in Germany in the Ketzin pilot project. CCS makes it possible to place comparatively large volumes of CO_2 into underground geological storage and so permanently remove it from the atmosphere. It is not yet making any contribution to the transformation of energy systems. In particular in the light of earlier debates around the use of CCS in coal-fired power generation, CCS is poorly accepted. It is clear that implementing CCS measures as part of a strategy for achieving GHG neutrality will only be possible if its use is broadly supported by civil society, industry, politics, interest groups and science. Such support may for example be expected for sectors which, having exhausted all other options, have no possible way of further reducing their CO_2 emissions. If CCS is to be used, it should therefore be clarified whether and, if so, for which industrial emitters this technology should be available as a priority, and answers should be provided to the questions: how long will it be available (bridge technology), who will provide the CO_2 transport and storage infrastructure, how is this to be achieved economically and environmentally while ensuring the highest safety standards, on which sites and in which regions should this preferably occur and who will bear the costs? A need for research and challenges remain above all with regard to political and social acceptance.

With their innovative products and system solutions, German companies are making a global contribution to climate protection.

173 | There is much to indicate that the expansion corridors for renewable energies defined in the 2017 Renewable Energy Act are not enough to cover future electricity demand by CCU (acatech/Leopoldina/Akademienunion 2017).

In this way they are securing and creating growth and jobs not only in engineering and plant construction but also in the electrical industry, for example with smart control engineering. Given appropriate adaptation, it should be possible to maintain existing value chains and successful industry clusters and to reconcile GHG neutrality with industrial competitiveness. Against this background, it is incumbent on the Federal and State Governments to create conditions which foster innovation and technological competition and, overall, enable cost-effective reduction of industrial emissions. Control can be effectively exercised by legal requirements and targeted use of support schemes. Early development of the necessary infrastructure can bolster belief in the survival and future success of industrial production lines and clusters and help to maintain Germany's position as a model of technological innovation.

There is an urgent need for a wide-ranging public debate about this issue. Only then will it be possible for technologies which are suitable in principle to be developed in good time and brought to market maturity and for the necessary infrastructure to be planned, approved and constructed, ideally spanning corporate and sector boundaries.[174] There is also an urgent need for answers to questions relating to business models and infrastructure funding. For selected branches of industry (chemicals, iron and steel sector, cement industry) it is appropriate to expand suitable existing development platforms or to create new ones with a ground-breaking function. Due to the know-how required, successful CCS projects outside Germany have in the past in particular been those closely related to the oil and gas industry. Overall, however, there is a need to create an understanding in society about the extent to which CCU and CCS should be major components of an overarching strategy for achieving GHG neutrality.

CCU technology offers various possible ways for permanently binding CO_2, for instance in PVC products or by CO_2 mineralisation to form aggregate for concrete. Carbon fibres could in

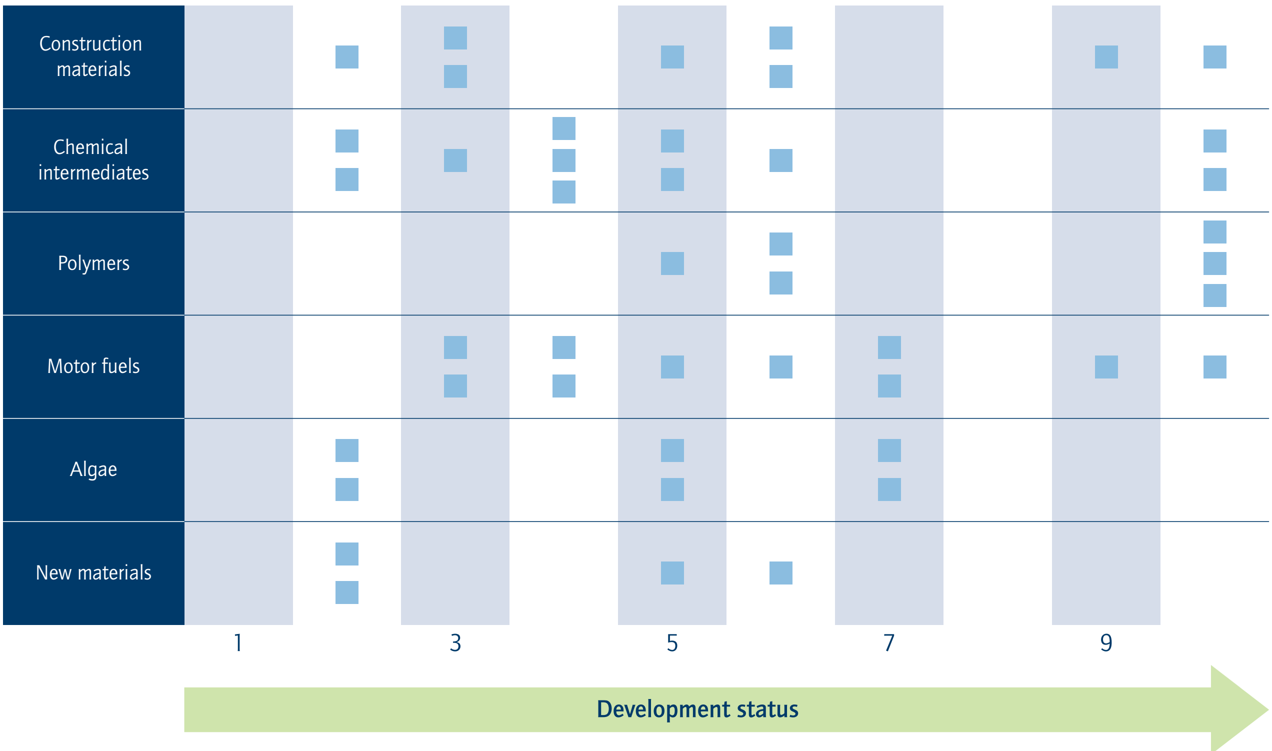


Figure 13: Technical development status of various CCU products from the product groups listed on the left; the number of symbols per table cell indicates the number of individual developments by different companies with their current status on a rising scale of technical development from 1 to 10 (source: modified after The Global CO_2 Initiative/GCI 2018).

174 | Cf. acatech/Leopoldina/Akademienunion 2017, Ausfelder et al. 2017.

future be used in composite materials as a replacement for many applications of steel, aluminium and cement.[175] If CO_2 is removed from the atmosphere, for instance using plants or algae, and the energy-intensive cracking process is performed using renewable energy, this could create a pathway into a CO_2-neutral circular economy.

Unlike CCS technology, which is already in service[176], many possible CCU applications are still at the testing or development stage (see figure 13). Reliable statements cannot at present be made about the volumes of CO_2 which can be bound and the costs involved. Power-to-Gas technology, in contrast, is already at an advanced stage of technical development. However, it cannot be used on a large scale for climate protection purposes in the short to medium term since the necessary volumes of electrical energy generated with zero emissions are not available. When Power-to-X will be able to make a substantial contribution to climate protection is thus less dependent on the technical development of the process than on the future expansion of renewable energy sources.[177]

Most scenarios for trends in GHG concentrations in the atmosphere assume that at the latest by the latter half of the century considerable efforts will have to be made to generate large volumes of negative emissions if global warming is not to exceed 2 degrees Celsius by 2100. The most recent study by the European Academies' Science Advisory Council[178] compares seven options which are often mentioned in this context: (re)forestation, land management, bioenergy CCS, enhanced weathering, direct air capture with geological storage (DACCS), ocean fertilisation with iron and CCS. The options are compared on the basis of the parameters: CO_2 reduction potential, costs, consistency between approaches, permanence of the measures, possible contrary climate effects and the probability of impact on biodiversity and major ecosystems.

Efforts to achieve a rapid reduction in GHG emissions should in principle have a high priority so that these options do not have to be used to a great extent. Against this background, there would appear to be an urgent need for debates around the use of CCU and CCS as building blocks for climate protection in industry.

175 | Cf. CleanCarbonTechnology 2018.
176 | In particular outside Europe.
177 | Cf. also SAPEA 2018.
178 | Cf. EASAC 2018.

Appendix

List of Figures

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List of Abbreviations

BDI	BDI e. V. - The Voice of German Industry
BGR	Federal Institute for Geosciences and Natural Resources
BMBF	Federal Ministry of Education and Research
BMU/BMUB	Federal Ministry for the Environment, Nature Conservation and Nuclear Safety
BMWi	Federal Ministry for Economic Affairs and Energy
BTX	Cumulative parameter for highly volatile aromatic hydrocarbons
CCS	Carbon (dioxide) Capture and Storage
CCU	Carbon (dioxide) Capture and Utilisation
CO_2	Carbon dioxide
DACCS	Direct Air Carbon (dioxide) Capture and Storage
DIN	Deutsches Institut für Normung e. V., the German Institute for Standardization
EASAC	European Academies' Science Advisory Council
ECF	European Climate Foundation
EGR	Enhanced Gas Recovery
EOR	Enhanced Oil Recovery
ERA-NET	European Research Area-Network
ESYS	Academies' Project "Energy Systems of the Future"
EU ETS	EU Emissions Trading System
EUTL	European Union Transaction Log
GFZ	Helmholtz Centre Potsdam – German Research Centre for Geosciences - GFZ
Ed.	Editor
IASS	Institute for Advanced Sustainability Studies e. V.
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISI	Fraunhofer Institute for Systems and Innovation Research
ISO	International Organization for Standardization
KIT	Karlsruhe Institute of Technology
KSpG	German Carbon Dioxide Storage Act
NGO	Non-governmental organisation
PIK	Potsdam Institute for Climate Impact Research (PIK e. V.)
PtG	Power-to-Gas
PtH	Power-to-Heat
GHG	Greenhouse gas
UBA	Federal Environment Agency
UNFCCC	United Nations Framework Convention on Climate Change

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Germany wishes to cut its greenhouse gas emissions by 80 to 95 per cent by 2050. However, despite the success to date, the measures which have already been planned and implemented are not sufficient for achieving this ambitious goal. In addition to the energy sector, the largest source of greenhouse gas emissions, German industry is also responsible for releasing considerable volumes of global warming gases. In its Climate Action Plan 2050, the Federal Government has for the first time set a sector target for industry.

The present acatech POSITION PAPER analyses the options for (re)utilising and storing CO_2 (Carbon Capture and Utilisation (CCU) and Carbon Capture and Storage (CCS)) which come into consideration for reducing greenhouse gas emissions from industrial processes. It is recommended that a wide-ranging public debate about the use of CCU and CCS be conducted in the near future. Only then will it be possible to take account of reservations about CCU and CCS, further develop suitable technology in good time and bring it to market maturity so that the necessary infrastructure can be planned, approved, funded and constructed.