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Facilitating China's Industrial Transformation with CCU/S

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Content

Executive Summary

1. CCU/S is a necessary technology for China to achieve its climate protection goals.

Different studies with estimations for Carbon Capture Utilization/Storage (CCU/S) in China show that CCU/S will be a key part of the transformation to meet China's climate targets. Some estimates have a carbon capture volume of 2.6 Gt in 2060, with CCU/S contributing 8 % of the cumulative emission reductions from now until 2060. Other estimates range from 1 Gt to 2.6 Gt CO_2 per year in 2060. Consensus exists that CCU/S will be used in the cement, lime, chemical, and steel industry, as well as in power plants, and for the generation of negative emissions through Bioenergy Carbon Capture and Storage (BECCS) and Direct Air Carbon Capture and Storage (DACCS).

Recent studies also suggest that China has a considerable potential for CO_2 storage. The estimated storage potential (onshore and near-coast offshore) ranges from 1.2 to 4.1 trillion tonnes of CO_2, which would be sufficient to cover China's storage need for centuries.

2. China is still facing significant challenges regarding the legal and regulatory framework and incentive structure for CCU/S.

One of the most significant challenges is the lack of incentive structures (e.g. sufficient carbon pricing or adequate subsidies) for the use of CCU/S, which makes it difficult to build an economic case and thus attract investment. Additionally, there is no comprehensive regulatory and standard framework for CCU/S in China, which creates uncertainty and delays the approval process for projects. This also concerns the management of possible environmental risks as well as insufficient standards for monitoring, reporting, and verification. The role of CCU/S vs. non-fossil sources of energy for the power sector is also still under debate.

Furthermore, there is a gap in some core technical knowledge, such as second-generation capture technologies, pipeline transmission technology, geological storage, and safety monitoring technology and equipment.

3. CCU/S is necessary in the long term in the following sectors in China: cement & lime industry, waste management, and negative emissions generation.

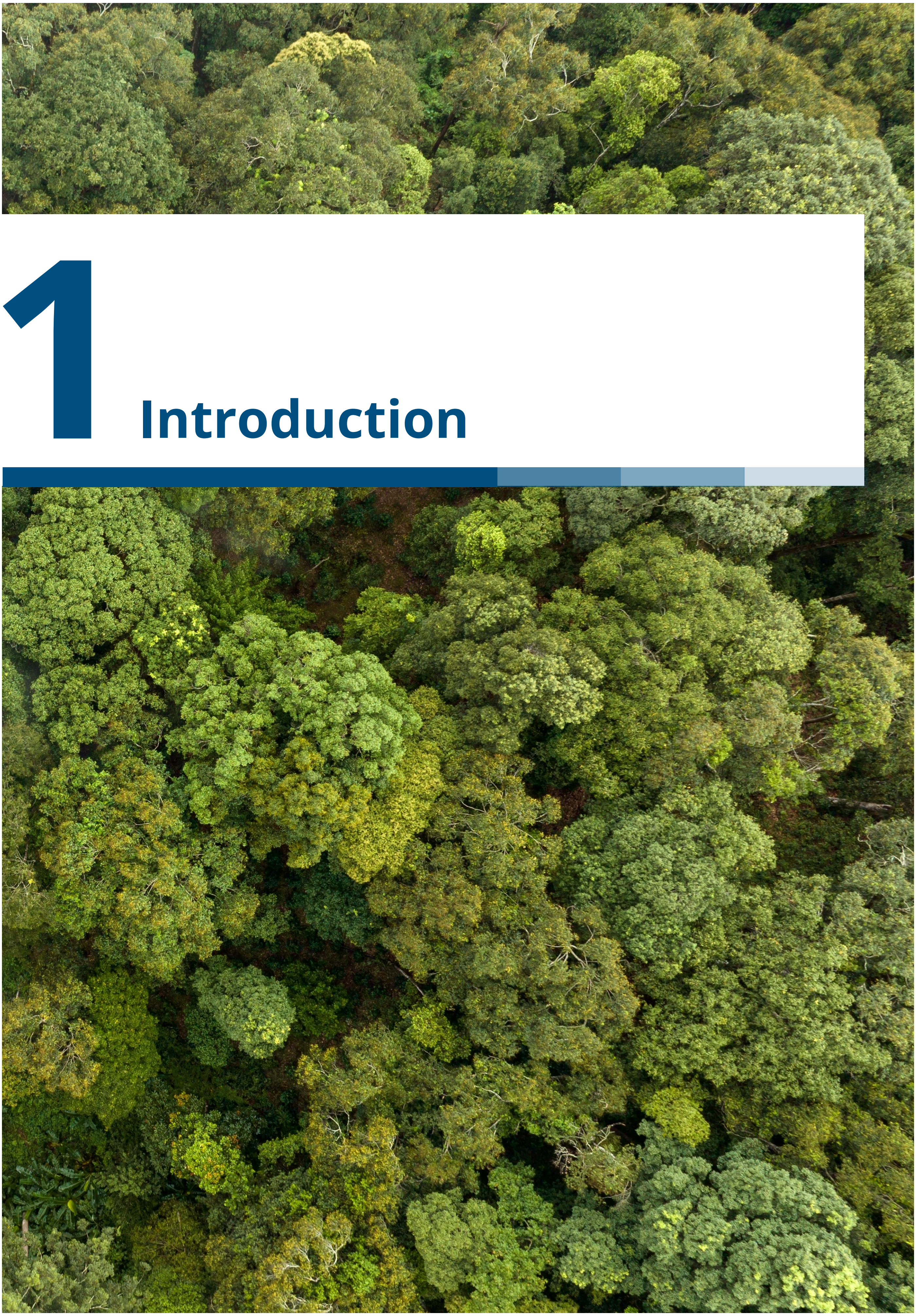
The results of our study recommend the use of CCS in the chemical industry, at coal-fired power plants (retrofit), in the steel industry (retrofit), cement and lime production, and waste management by 2030. This classification changes by 2060, when China aims to achieve carbon neutrality, as the phase out of fossil has to occur before the use of CCS. In the long term, non-fossil sources of energy are the only option compatible with a sustainable Net-Zero state. Thus, in 2060 CCS is considered an efficient climate mitigation option only for hard-to abate emissions in the cement and lime industries and waste management, as well as the generation of negative emissions (CDR) via DACCS and BECCS. In order to allocate resources and subsidies effectively, correctly size infrastructure, and avoid lock-ins, it is crucial to prioritize and define CCU/S applications.

4. The use of coal-fired power plants can be considered as a sensible option for emission reduction in the Chinese context in the short to medium term.

The technically and economically conducted analysis within the project revealed that in the long term (until 2060), the generation of electricity from renewable energy sources with adequate capacity is generally cheaper than electricity production from coal-fired power plants with carbon capture (CC) due to the availability of wind and solar power. In the short to medium term, the use of CC in coal-fired power plants will play a crucial role, especially in provinces where the availability of renewable energy is limited. Overall, based on current knowledge, the use of CC in coal-fired power plants is projected to have the highest share of captured emissions until 2060.

5. A variety of political instruments is needed to establish CCU/S with the most important being: incentives, regulatory framework for transportation, law for storage of CO_2.

A law for the storage of CO_2 is recommended, which would regulate responsibilities concerning MRV (Monitoring, Reporting, and Verification), as well as the issuance of permits, and includes concepts and regulations for dealing with potential storage failures. The establishment of a CO_2 infrastructure presents both technical and regulatory challenges, which need to be addressed early on. Considering the low ETS (Emission Trading System) price in China, additional incentives are needed to enable business models for CCU/S. Initially, investment cost incentives can be helpful, and beyond that, support schemes such as Carbon Contracts for Difference (CCfD) or flat-rate subsidies may likely be necessary at the outset.



1

Introduction

1 Introduction

Below, the most important terms in the context of Carbon Capture and Storage are defined. Subsequently, an assessment of the necessity of CCU/S is provided, along with an overview of global developments as well as in Europe, and Germany.

1.1 Definitions and terminology

CCS (Carbon Capture and Storage)

A process that involves capturing CO_2 from biogenic or fossil point sources or the atmosphere and transporting it to storage sites in order to permanently isolate it in geological formations. The climate impact of CCS depends on the CO_2 source (fossil, biogenic, atmospheric), greenhouse gas emissions throughout the process chain, and the durability of the storage, which requires appropriate monitoring.

CCU (Carbon Capture and Utilization)

A process that involves capturing and utilizing CO_2 from biogenic or fossil point sources or the atmosphere. It can either be utilized directly as CO_2 or chemically converted to new products. The climate effect of CCU depends on the CO_2 source, energy provision, product lifespan, CO_2 emissions in the process, and the replaced product.

CCU/S (Carbon Capture and Utilization / Storage)

A collective term for all CCS and CCU processes, encompassing the capture, processing, compression, transport, utilization, or permanent storage of CO_2 from the atmosphere or from point sources of biogenic or fossil CO_2 emissions.[1]

CDR (Carbon Dioxide Removal)
also referred to as “negative emissions”

Human activities that remove CO_2 from the atmosphere and bind it for climatically relevant periods in geological storage, terrestrial or oceanic carbon reservoirs (such as biomass), or durable products. A comprehensive life cycle assessment of the activity itself and potential indirect climate impact (e.g., land degradation) is crucial for evaluating the climate effectiveness of CDR.

DACCU/S (Direct Air Carbon Capture and Utilization / Storage)

CCU/S processes with CO_2 from DAC (Direct Air Capture). DACCU/S processes have the potential to achieve negative emissions under certain conditions.

BECCU/S (Bioenergy with Carbon Capture and Utilization / Storage)

CCU/S processes using biogenic sources of CO_2. BECCU/S processes have the potential to achieve negative emissions under certain conditions.

Natural Climate Solutions

Measures aimed at preserving and, where possible, enhancing the climate mitigation effect of terrestrial or marine ecosystems while also protecting biodiversity. If they remove CO_2 from the atmosphere and store it long-term, Natural Climate Solutions can achieve negative emissions (CDR).

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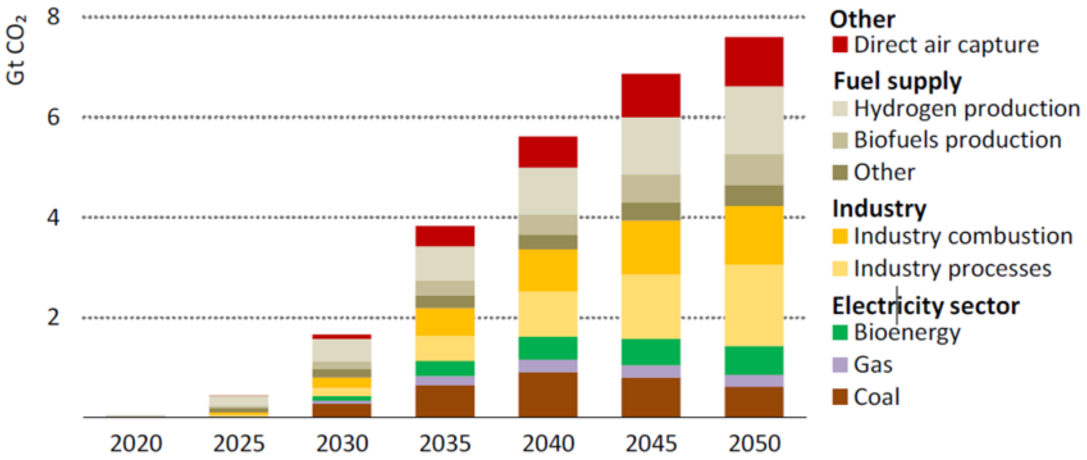
[1] The capture of CO_2 from fossil point sources is commonly abbreviated as FOCCU/S.

Figure 1: Projected development of carbon capture in Net-Zero scenario of IEA (2021). The figure is derived from IEA (2021b).



1.2 The need for CCU/S

The following is an assessment of the necessity of CCU/S based on the findings of the IEA (International Energy Agency) and IPCC (Intergovernmental Panel on Climate Change).

According to the IPCC's calculated scenarios that are compatible with the targets of the Paris agreement of limiting global warming to less than 2°C (if possible less than 1.5°C) the use of CCS and CCU is necessary, both in order to mitigate emissions from point sources (Fossil CCS) to generate negative emissions (BECCS, DACCS) and to provide carbon for feedstocks and e-fuels (CCU).

Due to the high uncertainty regarding the cost and application of CCS and CCU, the assumed CO_2 capture amounts at point sources of fossil CO_2 emissions vary from 0.1 to 1.8 Gt/a in 2050 in the sectoral scenarios (IPCC 2022).

In the IEA's "Net Zero by 2050" scenario[2], a total of 7.6 Gt of CO_2 capture is required by 2050, of which 7.1 Gt is for CCS and 0.5 Gt for CCU. The distribution of CO_2 capture can be taken from Figure 1. The IEA emphasizes the role of CCU/S for newly installed power plants (especially for coal power plants) in developing and emerging countries. As early as 2030, 50 GW of coal-fired power plants (corresponding to 4 percent of total capacity in 2030) are to be equipped with CO_2 capture according to the scenario of IEA; in addition, 30 GW of gas-fired power plants are to be fitted with CO_2 capture (corresponding to 1 percent of total capacity in 2030). By 2050, the planned capture capacity for coal-fired power plants will increase to 220 GW and for gas-fired power plants to 170 GW (IEA 2021b). Nevertheless, the amounts of CO_2 to be captured in the power sector represent only a small fraction of today's power sector emissions (about 14 Gt CO_2 in 2021 (IEA 2021b)); fossil fuels with CCU/S only account for about 2 percent of the global power mix by 2050. Most of the emissions reduction will be achieved through renewable generation, mainly photovoltaics and wind power.

DACCS and BECCS and natural climate mitigation measures are described as the main CDR technologies in the scenarios, with a greater contribution to achieving climate neutrality attributed to them than in previous IPCC reports. For scenarios likely not exceeding global warming of 2°C, the IPCC scenarios assume the following cumulative CO_2 removals by 2100 (IPCC 2022):

- BECCS: 170-650 Gt CO_2
- DACCS: 0-250 Gt CO_2
- Land sector: Agriculture, Forestry, other Land-Use (AFOLU): 10-250 Gt CO_2

These figures cover the different ranges of the scenarios and are not to be understood additively, e.g. by adding the lower or upper limits of the different technologies.

In summary CCU/S is considered essential by both the IPCC and IEA in order to effectively limit global warming to 1.5°C or below 2°C. The IEA highlights the deployment of CCU/S technologies with a specific emphasis on power plants, particularly coal power plants. This underscores the significance of CCU/S, especially in countries like China. Moreover CCS-technologies play a crucial role in removing carbon dioxide from the atmosphere via BECCS and DACCS.

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[2] A revision of the IEA's report (September 2023) anticipates a reduced need for CCS of approximately 6 Gt.

1.3 CCU/S Worldwide, EU, Germany

Below is a current overview of global developments of CCU/S with a focus on existing projects. Subsequently, the developments in the EU and Germany on this topic will be discussed.

Worldwide

The Global CCS Institute database (CO2RE) currently (as of 2023) lists 30 operational commercial CCS projects, with the majority in North America (13 in the U.S., 5 in Canada) (Global CCS Institute 2022a). There are other projects in China (3) and Norway (2), and one each in Australia, Brazil, Iceland, Qatar, Hungary, Saudi Arabia, and the United Arab Emirates. There are also 11 commercial projects under construction. The list reveals that globally CCU/S is still in its early stages, however one can infer a trend of increasing momentum and growing importance for CCU/S, which can also be observed in the political developments surrounding the topic.

Many governments are increasingly emphasizing CCS and integrating it into their Long Term Low Emissions and Development Strategies (LT-LEDS) under the Paris Agreement (IPCC, 2022). CCS was assigned a role in 15 of the 19 LT-LEDS submitted by November 2020. In parallel, the number of currently planned CCS projects worldwide for the coming years increased significantly (IEA 2022). At the end of 2020, CCS projects with a capacity of 0.075 Gt CO_2 per year were under development worldwide. This number increased by 50 percent, to 0.12 Gt CO_2 per year by 2021 and further to 0.19 Gt CO_2 per year in 2022 (Global CCS Institute 2022a, 2022b).

Despite this dynamic market development, today's worldwide CCS use does not meet the expansion path for net-zero emissions required according to the reviewed studies. In order to limit the global temperature increase to 1.5°C Celsius, the IEA considers an increase in installed CCS capacity from today's approx. 0.040 Gt CO_2 per year to almost 2 Gt CO_2 per year by 2030 and over 7.5 Gt CO_2 per year by 2050 necessary.

EU

According to scenarios analyzing the EU's transition to climate neutrality by 2050, achieving climate neutrality in the EU would require capturing 300 to 500 Mt CO_2. For this reason, there is an interest in the EU to enable and promote the deployment of CCS and CCU. The following section discusses the legal framework governing CCS in the EU. Additionally addressed is the legal classification of CCS within the EU ETS (EU Emissions Trading System). Finally, a brief overview of the current developments is presented.

EU ETS

The EU ETS has been the EU's central climate protection instrument since its implementation in 2005. It covers emissions from over 10.000 plants in the energy sector, inner-European air-travel, and most industry sectors – thereby pricing 36 percent of GHG emissions in Europe. The EU ETS operates on the principle of cap and trade. A cap determines an annual CO_2 limit that may not be exceeded by installations subject to emissions trading. Certificates are tradable on markets and the annual reduction of certificates is in line with European climate targets. In its July 2021 "Fit for 55" package, the European Commission proposed a further tightening of the annual cap reduction from the current 2.2 % to 4.2 % per year, plus a one-time reduction of a yet undetermined amount (likely to be implemented in 2024). In Germany, a CO_2 price applies to sectors not covered by the EU ETS, mainly heating and transport. The Fuel Emissions Trading Act (BEHG), promulgated in 2019, determines steady price rises within a predefined framework since 2021. From 2026, pricing will take place on market based principles. There is currently no link between the price and the emission reduction targets of Germany.

No ETS allowances are required for CO_2 captured and permanently stored under the CCS Directive. The transport of captured CO_2 is covered by the corresponding monitoring regulation.

In Europe, the situation regarding CCU has not yet been sufficiently coordinated and clarified. For CCU processes, according to Art. 49 Par. 1 of the EU Monitoring Regulation, only the production of precipitated calcium carbonate has so far been fully eligible for emissions reporting. As part of "Fit For 55", the EU ETS Directive is currently being amended. According to the current state of negotiations, the use of CO_2 will now also be eligible for inclusion in the ETS if CO_2 is permanently chemically bound in a product so that it is not released into the atmosphere during its intended use and disposal. The Commission will define the conditions by means of delegated acts.

Legal situation

The EU CCS Directive, which has been in place since 2009, regulates the geological storage of CO_2 and certain aspects of pipeline transport at the European level. The regulation includes requirements for dealing with leakages and monitoring storage sites, the process for developing storage sites including storage licensing, and regulations for operators during operation and after "closure" of the storage facilities.

Projects of Common Interest (PCI)

PCIs are cross-border key projects for energy infrastructures in the EU that connect the energy systems of member states. To be designated as a PCI, projects must have a significant impact on energy markets and contribute to European energy security and the achievement of climate protection goals. Projects that are designated as PCIs benefit from accelerated planning and permit granting processes. Additional advantages include the responsibility of a national authority for permit granting, improved regulatory conditions, enhanced public participation, and increased visibility for investors.

In December 2021, the European Commission released a communication plan called “Sustainable Carbon Cycles”, which is one of the regulatory tools implemented by the EU to facilitate meeting its decarbonisation goals. It sets out an action plan on how to develop sustainable solutions to increase carbon removals. The proposal sets the following goals (European Commission 2023b):

1) Monitoring: By 2028, every tonne of CO_2 captured, transported, used, and stored in the industry should be reported, and its origin determined.
2) Quota requirement: By 2030, at least 20 % of the carbon used in the chemical and plastic industry should come from sustainable non-fossil sources.
3) Capture requirement: By 2030, through technical solutions (frontrunner projects), 5 million tonnes of CO_2 should be captured from the atmosphere annually and permanently stored.

In this context, the EU Commission also announced a legal framework for the certification of carbon removals. The framework will help ensure the transparent identification of carbon farming and industrial solutions that unambiguously remove carbon from the atmosphere (European Commission 2023b).

Current policies and developments in the EU

Within the EU, the Netherlands and Denmark are currently leading the way in the field of CCU/S. Both countries have operational or upcoming projects for offshore CO_2 storage. Furthermore, various infrastructure projects are planned to connect storage sites with carbon capture facilities. These major projects are supported within the EU through the PCI status. Research and demonstration projects are funded through the EU Innovation Fund. The focus of these projects is primarily on industries such as cement, lime, and thermal waste treatment. The current climate protection plans of European countries provide the following information:

The EU requires member states to define mid- to long-term climate protection targets, strategies and measures, such as the “National Energy and Climate Plans” (NECP) which cover the period from 2021 to 2030. The NECPs of 20 out of the 27 EU member states mention CCS or CCU/S as a possible option to decarbonize industrial production and/or power generation or to achieve negative emissions (European Commission 2022b). The specific role of CCU/S and policy measures vary widely across countries. They range from supporting (further) research activities, considering CCU/S in scenarios for future GHG emission reductions, preparing feasibility studies, continuing work to investigate national storage potentials, to implementing large-scale CCS projects.

In summary, the necessary legal framework for the deployment of CCS already exists in the EU. Work is currently underway to establish the legal framework for CCU. In recent years, particularly with the introduction of the Net-Zero Industrial Act, CCU/S was recognized as an essential technology to achieve climate protection goals and is promoted accordingly (European Commission 2023a). However, apart from demonstration projects, there are currently no commercial large-scale projects in Europe capturing CO_2 from industrial sites. In terms of storage, experience can be drawn from Snohvit and Sleipner in Norway, two storage sites which have been in operation for over 25 years.

Germany

In Germany, the Carbon Dioxide Storage Law (Kohlendioxid-SpeicherungsGesetz - KSpG) provides the legal framework for the pipeline-based transport and storage of CO_2. The KSpG came into force in Germany in 2012 (Acatech 2018).

The Law regulates exploration and planning approval of potential carbon dioxide storage facilities, which is subject to strict environmental law requirements (Deutscher Bundestag 2018). The KSpG also regulates planning approval for CO_2 pipelines as well as the requirements for the connection and access of third parties to CO_2 storage facilities and pipelines (Cf. § 4 and 33 KSpG, respectively).

The law allows the federal states to exclude areas under their jurisdiction from CO_2 storage (Acatech 2018). Currently, no state has approved CO_2 storage.

Hence, apart from two exploration projects, CCS has never been used in Germany.

Germany, following the passing of the first climate protection act stipulating a net-zero target for 2050 in 2019, is considering CCU/S as a climate protection technology. The evaluation of the law in 2022 concluded that both CCU and CCS are needed for the decarbonization of various industries (such as cement, lime, and waste management) and are thus a necessary requirement for Germany to reach its net-zero target (Bundestag 2022). Currently, the German government is developing a Carbon Management Strategy (CMS) which will set strategic guidelines and goals for CCU/S, with a focus on the industry and waste management sectors. Initial results are expected to be published in the fourth quarter of 2023.

2

CCU/S in China

2 CCU/S in China

The following section discusses the current status of CCU/S in China, with a focus on existing and planned projects. Next, the current Chinese political strategy regarding CCU/S is explored. Lastly, the future role of CCU/S in China will be presented based on selected studies, leading to a concluding assessment of the challenges involved.

2.1 Current State of CCU/S in China

China has made significant commitments to address climate change and reduce greenhouse gas emissions. These commitments include a contribution to global efforts to address climate change by achieving carbon neutrality before 2060, with a target to reach peak CO_2 emissions before 2030. Additionally, the country has pledged to decrease its CO_2 emissions per unit of gross domestic product by over 65 % until 2030 from 2005 levels (Asian Development Bank 2022).

China plans to increase the share of nonfossil fuels in primary energy consumption to around 25 % in order to support climate goals. The country also aims to increase its forest stock by approximately 6.0 billion m^3 above 2005 levels. Moreover, China has set a goal of installing 1.2 TW capacity of wind and solar power (Asian Development Bank 2022).

Figure 2: Overview of current CCU/S demonstration projects in China. Figure is derived from Zhang et al. (2023).

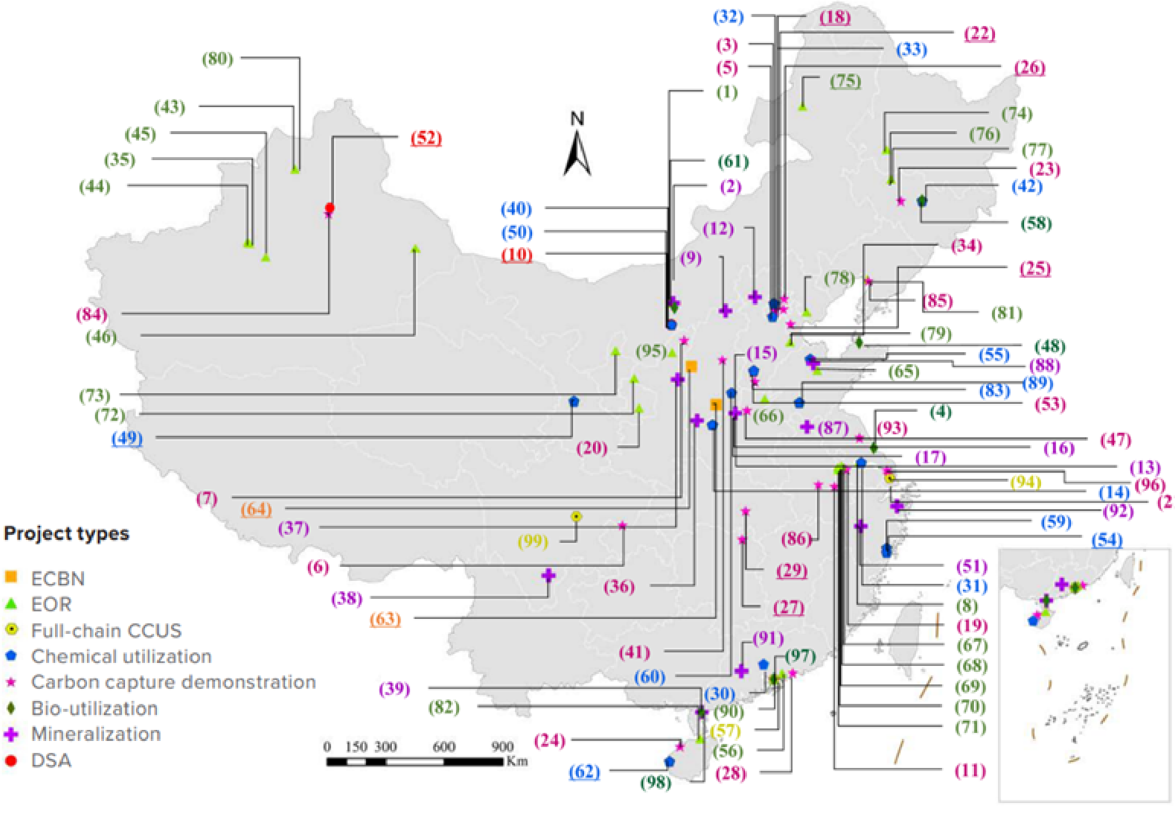
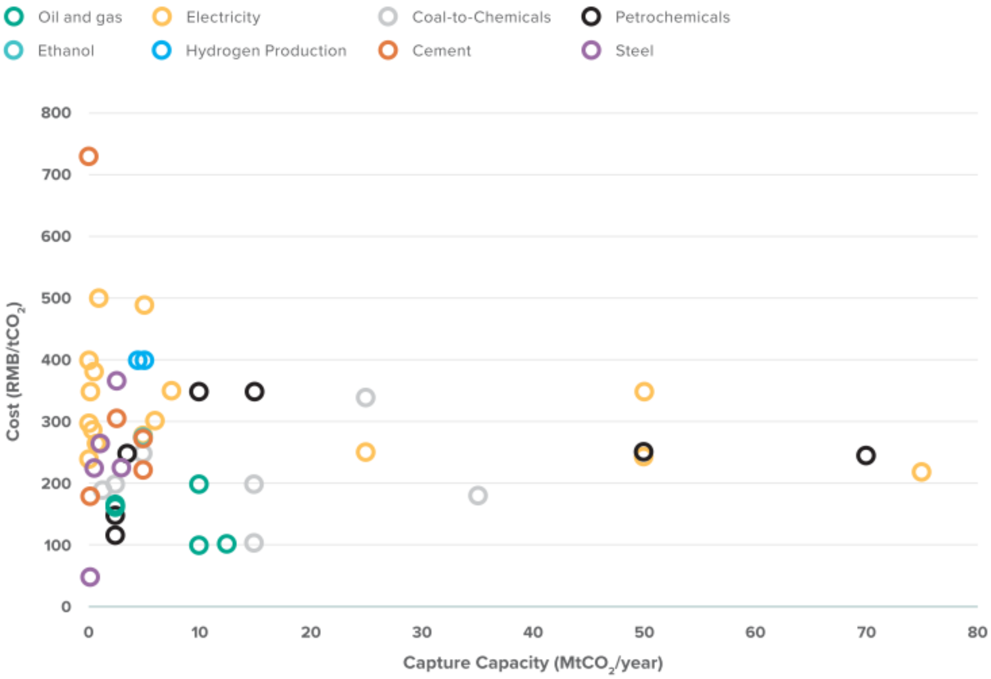


Figure 3: Overview of costs for different projects realized in China. The figure shows that most projects have abatement costs of around 200 to 400 RMB/t CO_2. The lowest costs are achieved in the chemical industry and oil & gas industries.



Source: authors

2.1.2 Overview of projects

As of November 2022, there were around 100 CCU/S demonstration projects in China as shown in Figure 3. Nearly half of the projects have already been put into operation, with a CO_2 capture capacity of more than 4 Mt per year and a CO_2 injection capacity of more than 2 Mt per year. This is an increase of about 33 % and 65 % compared to 2021 (Zhang et al. 2023).

CCU/S technology projects in China span across nineteen provinces, encompassing a diverse range of industries and utilization/storage methods. Thirteen pure capture demonstration projects involve power plants and cement plants, with a total CO_2 capture scale of around 850 kt per year. Additionally, eleven geological utilization/storage projects have reached a total scale of 1.8 Mt CO_2 per year, including approximately 1.5 Mt CO_2 per year utilized through the EOR (Enhanced Oil Recovery) method alone.

China's CO_2 capture projects include:

- pre-combustion capture, post-combustion capture, and oxyfuel combustion from coal-fired power plants
- post-combustion capture from gas-fired power plants
- CO_2 capture from the coal chemical industry
- and tail gas capture from cement kilns.

CO_2 storage and utilization entail various methods such as saline aquifer storage, Enhanced Oil Recovery (EOR), enhanced coal bed methane recovery (ECBM), CO_2 mineralization utilization, synthesis of degradable polymers using CO_2, reforming to produce synthesis gas, and microalgae fixation.[3]

Full-scale operational projects

The Ordos CCS demonstration project has successfully shown a full-process operation at a scale of 100 kt CO_2 per year. The EOR project, at the Jilin Oilfield represents the largest EOR project in Asia, having already injected over 2.5 Mt CO_2 cumulatively. Moreover, the full-process demonstration project at Guohua Jinjie Power Plant aims at post-combustion capture and storage, with an annual capacity of 150 kt. In August 2022, China successfully completed and operationalized its inaugural one-million-tonne-level CCUS project—Sinopec Qilu Petrochemical-Shengli Oilfield—coinciding with the launch of the first domestic one-million-tonne-level CO_2 pipeline engineering project.

China's state-owned oil and gas producer CNOOC completed the country's first offshore CCS project in 2022. This will capture and geologically store about 0.3 Mt CO_2 per year produced by oil production in the Pearl River Delta in Guangdong under the seabed (Xin 2022).

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[3] Expert Interview

Current project development in China

(1) Huaneng's 1.5 Mt CO_2 per year carbon capture project. Certain technical difficulties persist for the existing absorption tower and compressor.[4]

(2) Huadian Group's carbon capture project in Xinjiang, with a capacity of 200 kt at a power plant, is set to be completed. Its design specifies a renewable energy consumption of 750 kWh/t CO_2, and the captured CO_2 is destined for EOR.[4]

(3) The 500 kt thermal power carbon capture project from Sinopec faces considerable challenges in regards to the 100-km-level pipelines. These issues include phase changes caused by pressure variations under supercritical conditions and potential pipeline leakage risks. Currently, transportation standards for the petrochemical industries are applied.[4]

(4) PetroChina's Carbon Capture Project involves 21 units and aims for a group capacity of 3 Mt CO_2 per year. The hurdles include:

1. A target wellhead price of 200 RMB/t CO_2 is challenging due to high steam capture costs;
2. Inconsistencies in calculating renewable energy consumption;
3. Full-load operation could lead to exceeding NO_x emission standards and less than 100 % capture rates;
4. Extended demonstration time and the difficulties in synchronizing sources and sinks pose CO_2 disposal issues.[4]

(5) Jidong Cement's under-construction project, with a capacity of capturing 100 kt of CO_2, employs a chemical absorption method for carbon capture.[4]

(6) Baosteel's under-construction project aims for a capture capacity of 500 kt in a lime kiln. Storage challenges remain. Concerning carbon finance, while Voluntary Carbon Standard (VCS) has been purchased, CCS has yet to be accepted by major international voluntary carbon markets (VCM).[4]

(7) Icelandic company Carbfix is set to build a CO_2 storage project in basalt formation in China, which is expected to be completed and commissioned in 2023 (Zhang et al. 2023).

(8) In October 2022, China National Building Material Group (CNBM) completed the world's first CO_2 capture in glassmaking process, with an annual capacity of 50,000 t CO_2 (Zhang et al. 2023).

The "Karamay Dunhua Oil Technology CCUS EOR" project, with an annual capacity of about 0.1 Mt CO_2, has been in operation since 2015 as the oldest commercial CCS project in China. Here, the CO_2 is captured at a methanol plant and transported by tanker trucks for injection to increase oil production (Global CCS Institute 2022a).

Project development and challenges

The box on the left provides an overview of the different projects currently in development and the challenges they are facing.

In summary, the projects are advancing in accordance with the disclosed timelines and plans. Significant challenges remain due to corrosion. The absence of supportive policies such as tax credits or a strong carbon pricing scheme do not enable large-scale commercial models.

There has been considerable progress in CO_2 transportation the current year. For instance, the pipeline construction for Sinopec Qilu Petrochemical-Shengli Oilfield's million-ton CCUS demonstration project was completed as planned, marking its transition to a trial operation phase. The pipeline stretches 109 km from Zibo Qilu Petrochemical Station to Gaoqingmo Station and boasts a maximum designed capacity of 1.7 Mt CO_2 per year—thus representing China's first hundred-kilometre-level pipeline.[4]

Despite the progress made in CCUS development, high costs, high energy consumption, and a lack of extensive large-scale demonstration project experiences remain significant bottlenecks in the adoption of CCUS technologies (Liu et al. 2022a). Second-generation CCUS technologies are expected to be widely applied in 2035, which could reduce energy consumption costs by more than 30 % compared to first-generation technologies (Liu et al. 2022a).

Most of the existing CCU/S pilot projects in China are relatively small in scale and most of them use trucks for transport. CO_2 ship transport is mainly for liquefied gases.

There is still little experience of large-scale full-chain demonstration projects in China, especially in pipeline and hub development, which only reached the pilot stage (Zhang et al. 2023).

In summary, China has made significant progress in pilot and demonstration projects for CCU/S in recent years. At the same time, there are only a small number of commercial projects. The projects examined are still affected by technical challenges, however we assume that these issues can be overcome through further experience. Similar assessments also emerge from Europe and the U.S..

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[4] Expert Interview

2.2 Political strategy

As of October 2022, China has issued about 70 CCU/S-related policies at the national level. This includes plans, standards, roadmaps, and technology catalogues related to technical standards. Investment and financing are also increasing, such as the Climate Investment and Financing Pilot Work Plan, the Green Bond Endorsed Projects Catalogue (2021 Edition), China's National Standardization Development Outline, and the Implementation Plan for Science and Technology Support for Carbon Dioxide Peaking and Carbon Neutrality (2022-2030) (Zhang et al. 2023).

Previously CCU/S was only mentioned in the power sector and oil & gas industries, however; recently CCU/S was added to more hard-to-abate sectoral policy guidelines, including the Guidelines on the Transformation and Upgrading of Energy Intensive Industries and Key Areas for Energy Conservation and Carbon Reduction (2022 Edition) and the Carbon Peaking Implementation Plan for the Industrial Sector (Zhang et al. 2023).

China also set ambitious targets in its 13th Five-Year Plan for CCU/S technologies. The plan included selecting and implementing 5-10 large CCU/S demonstration projects in the coal chemical industry and 1-3 large-scale CCU/S demonstration projects in coal-fired power plants to overcome technical barriers and reduce costs. The plan also planned CCS projects for new coal-fired power plants in Shaanxi, Ningxia, Inner Mongolia, Xinjiang, and other regions, as well as to build CCS-ready power plants (Asian Development Bank 2022).

During the 13th Five-Year Plan period, China made some progress in implementing CCU/S technologies and achieving its targets. However, according to Asian Development Bank (2022) there were gaps compared to other advanced economies in CO_2 capture from coal-fired power plants (Asian Development Bank 2022).

Obstacles in policy framework

There are several major obstacles that hinder the development and implementation of CCU/S technologies in China. One of the most significant challenges is the lack of incentives for the use of CCU/S ("no economical case") which makes it difficult to achieve cost competitiveness and to attract investment. Additionally, there is no comprehensive regulatory and standard framework for CCU/S in China, which creates uncertainty and delays the approval process for projects (Asian Development Bank 2022).

Another obstacle is the concern about environmental risk, as the geological complexity of CCU/S seriously restricts the government and public's understanding and acceptance of this technology. The lack of public awareness and understanding of CCU/S further complicates the process of developing and implementing these technologies (Asian Development Bank 2022).

Furthermore, there is a gap in some core technical knowledge, such as second-generation technology, pipeline transmission technology, geological storage, and safety monitoring technology and equipment. The different speed of development of the existing carbon capture, utilization, and storage technology chain is also a challenge (Asian Development Bank 2022).

Missing legal and regulatory frameworks

Due to the absence of clear regulatory authority, the instituion initiating the project is responsible for the regulation of storage/demonstration projects. As geological storage is predicated on mining, the respective mining institution is likely responsible for regulation. However, there are currently no specific regulations for geological CO_2 storage, leading to a regulatory vacuum in this area.[5]

The authority responsible for the stored CO_2 remains ambiguous due to the lack of standard regulations. As the concept of CO_2 sealing remains novel, no department has been explicitly responsible for supervision. There is no agreement on which authority should oversee underground sealed resources and saline aquifer resources.[6]

Currently, the only standard concerning monitoring comes from a group guideline issued by the Chinese Society for Environmental Sciences, which addresses the risk assessment of CO_2 geological utilization and storage project leakage. There is no national standard in place and relevant monitoring responsibilities have been assigned to the project party without specific requirements.[7]

Summary

The naming of CCU/S as a key technology on the path to CO_2 neutrality in the five-year plans shows its high political relevance in China. The current CCU/S governance does not yet meet these goals, as it lacks a clear and sufficiently detailed framework legislation specifically for CCU/S, market incentives, and an ambitious financing program (Jiang et al. 2019). Nevertheless, the IEA forecasts China to have the world's largest capacity growth in carbon capture by 2070 (IEA 2020).

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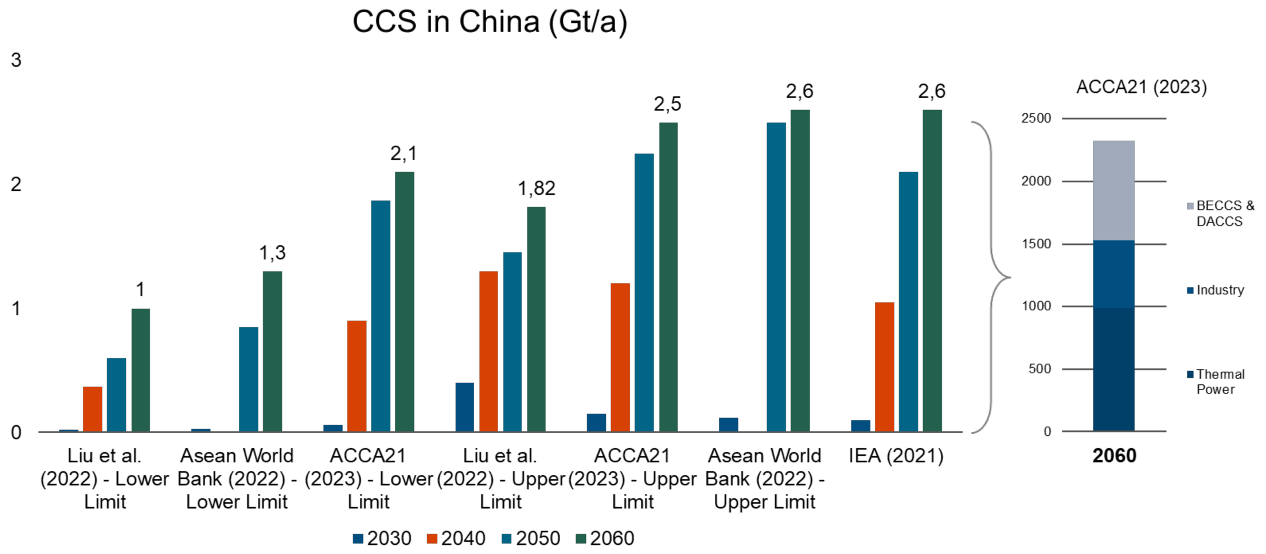
[5] Expert Interview

[6] Expert Interview

[7] Expert Interview

2.3 Envisioned role for CCU/S as mitigation option

Figure 4: Overview of studies estimating the development of CCU/S in China. Figure is based on IEA (2021b), Liu et al. (2022), Asian World Bank (2022) & Zhang et al. (2023) – called ACCA21 (2023) in the graphic.



There are different studies that estimate the potential for CCU/S in China for different sectors (see Figure 4). For example, IEA (2021) estimates a carbon capture volume of 2.6 Gt by 2060. CCUS contributes to 8 % of the cumulative reduction in China's CO_2 emissions from now to 2060 (IEA 2020, 2021a).

Liu et al. (2022) show that CCU/S can contribute to emission reduction:

- 2030: 20 to 408 Mt,
- 2050 600 Mt to 1.45 Gt,
- 2060: 1 to 1.82 Gt

The potential contribution varies in 2060 from 1 to 2.6 Gt CO_2 per year. Overall both studies show that CCU/S will be a key part of the transformation.

When looking at the different industrial sectors, IEA's study shows that by 2060 heavy industry accounts for over 820 Mt; almost 32 % of all CO_2 captured. In Zhang et al. (2023) it is estimated, that CCU/S should be ready for industrial applications by 2030.

Cement Industry

Liu et al. (2022) see a demand for CCU/S in the cement industry by 2030 of around 10 to 152 Mt CO_2 per year and 190 to 210 million tonnes by 2060, which would account for about 60 % of the total emissions in the cement industry. Asian World Bank (2022) estimate that by 2030, 5 to 10 Mt will be captured annually and 150 – 200 Mt CO_2 per year by 2060.

Steel Industry

For the steel industry Liu et al. (2022) estimate a carbon capture volume of 2 - 5 Mt CO_2 per year until 2030, 90 to 110 Mt CO_2 per year until 2060. Asian World Bank (2022) sees a similar potential with 2 to 10 Mt CO_2 reduction by 2030 and 90 to 290 Mt CO_2 per year in the long term (2030 – 2060).

Power sector

There are widely different estimates for the role of CCU/S in the power sector in China.

By 2060 the power sector accounts for around 1.3 Gt CO_2 per year, or half of all the CO_2 captured in the IEA scenario.

The carbon capture volume of coal power plants peaks in 2040 with 200 to 500 Mt CO_2 per year and remain unchanged going forward in the estimation of Liu et al. (2022). Gas fired power plants will be gradually phased out and will remain unchanged after reaching a peak in 2035, with a reduced rate of 20 – 100 Mt CO_2 per year. Asian World Bank (2022) estimates that by 2030 the cumulative CO_2 emission reduction capacity of the thermal power industry will reach about 10 – 50 Mt CO_2 per year. It is predicted that the annual CO_2 capture capacity will be 600 Mt CO_2 per year in 2060, and all operational coal and gas fired power plants will be equipped with CO_2 capture devices.

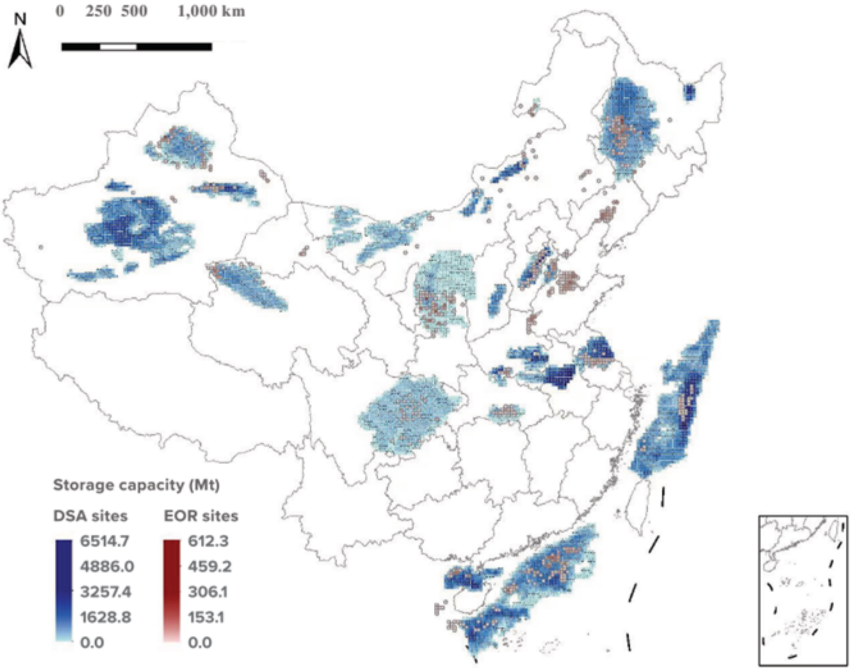
Chemical Industry

For the chemical industry IEA (2021) estimates that the CO_2 capture from chemical reduction will rise to 200 Mt per year in 2060. Asian World Bank (2022) see a capture volume of around 200 Mt CO_2 per year in 2050. Production of low-carbon hydrogen will reach 15 Mt around 2030 and 57 Mt in 2050.

Infrastucture demand

IEA (2021) argues that a cross-country CO_2 trunkline network in excess of 15.000 km of CO_2 pipeline could be required to connect industrial clusters to storage resources by 2060 in the APS. The roadmap of ACCA21 targets the construction of two onshore pipelines with a capacity of 1 Mt per year by 2025, expanding to a total transport capacity of 1 Gt CO_2 per year and more than 20,000 km of pipeline by 2050.

Figure 5: CO_2 storage potential in China derived from Zhang et al. (2023).



Storage potential

Recent studies have estimated that China has a considerable potential for CO_2 storage. The estimated storage potential ranges from 1.2 to 4.1 Tt of CO_2, which suggests that China has significant capacity to store CO_2 underground (Liu et al. 2022a). Of this, deep saline formations are particularly promising, with an estimated storage capacity of approximately 2.2 Tt of CO_2 (Liu et al. 2022a) (see Figure 5).

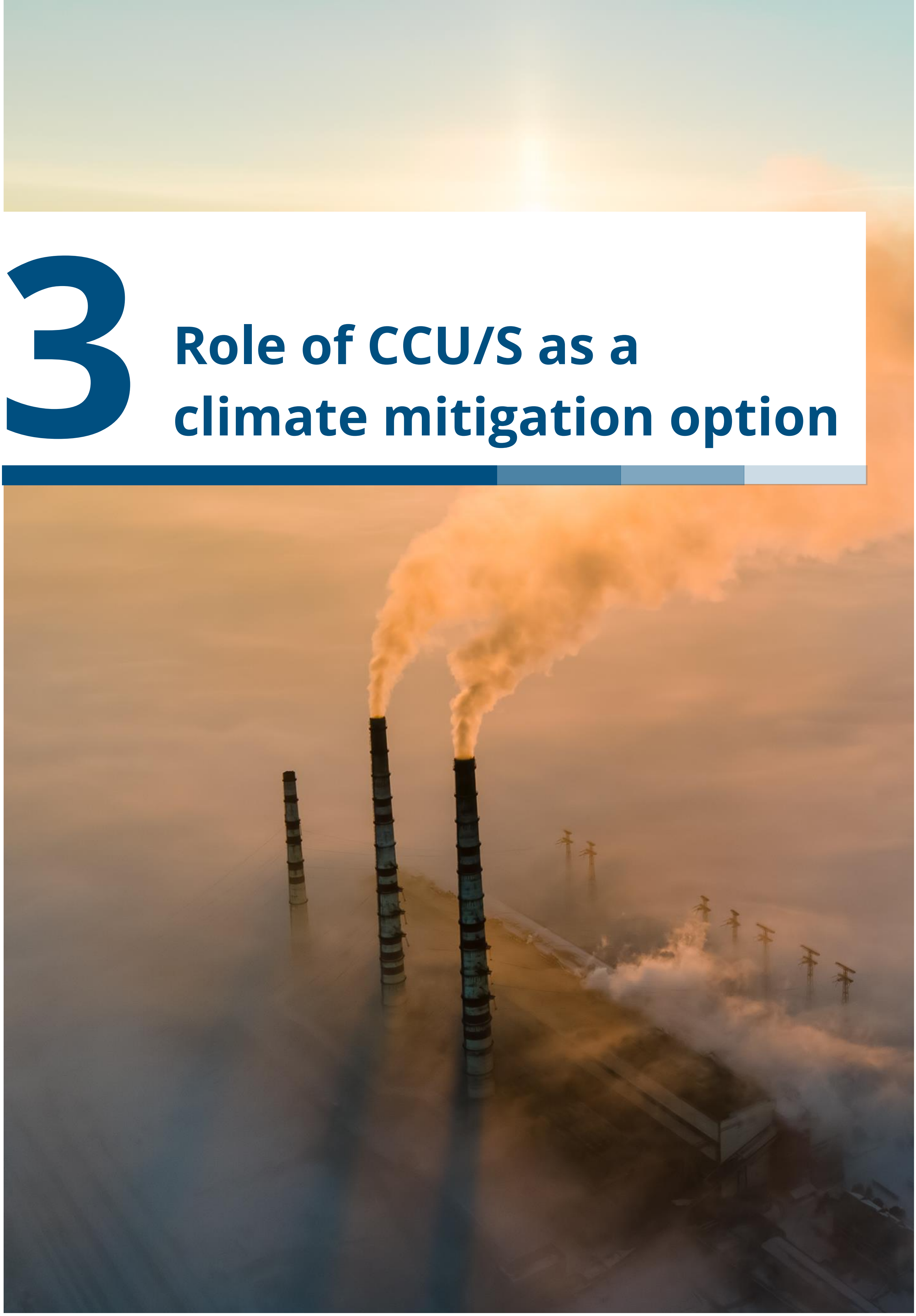
Technical Negative emissions (CDR)

Technical negative emissions (BECCS/DACCS) have a major role in 2060 according to the IEA scenario. Around 260 Mt CO_2 are removed via BECCS and DAC with CO_2 storage in 2060.

Summary

This brief analysis of the studies shows that CCU/S plays a crucial role in achieving the climate protection goals in China. The amount of CCU/S required by 2060 is around 1 - 3 Gt per year, whereas 2.5 Gt per year can be regarded as the best estimate (see Zhang et al. (2023)). Carbon capture at power plants with about half of the CO_2 is identified as an essential driver besides the industrial sectors cement, steel, and chemicals as well as BECCS/DACCS.

Such a rapid scale-up is accompanied by significant challenges. Therefore, the next chapters will take a closer look at the individual sectors and the development of CO_2 capture. The aim of this review is to determine an initial prioritization.



3

Role of CCU/S as a climate mitigation option

3 Role of CCU/S as a climate mitigation option

This chapter will examine the role of CCU/S in various industrial sectors, power plants, and thermal waste treatment in achieving greenhouse gas neutrality.

3.1 Need for comparison with other climate mitigation options

A detailed analysis of other climate mitigation options is important as the use of CCU/S may have various drawbacks, including residual emissions, lock-ins to fossil fuels, and the possibility of inefficient funding allocation.

Furthermore, there has been very little large-scale deployment of CCU/S so far, posing a risk to resilient achievement of climate targets when relying too much on CCU/S, as it might scale less well than expected. Lastly, there are other measures/technologies that could possibly achieve nearly complete emissions reduction in specific sectors. The economic viability of these alternatives compared to CCU/S needs to be considered to assess the future role and scale of CCU/S.

Studies such as those conducted by dena (2021) and Prognos et al. (2021) examined how the industrial transformation towards greenhouse gas neutrality can be achieved in Germany (Deutsche Energie-Agentur GmbH 2021; Prognos et al. 2021). The processes in China are similar, as can be inferred from studies on the development in various sectors.

The deployment of CCU/S is especially relevant for process emissions, which cannot be avoided by transitioning to renewable energy sources alone. The most significant sectors are cement and lime, steel, chemicals, glass and ceramics, aluminum, as well as waste management.

In this study, the glass and ceramics industries are also not considered because they have very low amount of process emissions, and can be mostly avoided by replacing carbonates with hydroxides and increasing recycling rates. Research is ongoing to reduce emissions in glass production by replacing carbonates with hydroxides and increasing recycling rates. The same applies to the ceramics industry, where emissions could also be reduced by using carbonate-free clays. The issues of plant size and profitability also exist in these industry, which is why they are not examined in this study (Geres et al. 2021; Bundesverband Glas 2022). In the case of the aluminum industry, these emissions can be completely avoided by switching to inert anodes.

As a result, the following industries are investigated in this study: cement and lime industry, steel industry, chemical industry, hydrogen production, and thermal waste treatment. Additionally, technical negative emissions (CDR) and carbon capture at power plants are examined, with a focus on coal-fired power plants due to its role in the Chinese energy system.

Regarding technical negative emissions, BECCS and DACCS are considered. Within BECCS, various industries are described in which the use of biomass in the future is considered likely and where CO_2 capture is feasible.

For the power sector, existing renewable energy technologies allow achieving greenhouse gas neutrality without CCS. Therefore, in Germany there is currently no ongoing discussion on CO_2 capture at power plants and it is not likely to come up again. However, the situation in China is different, as new coal-fired power plants are still being built and the net-zero date is later, by 2060. Therefore, the use of CCU/S as a transition technology is already being discussed and politically supported, as described in the previous chapter.

Within this report, insights on CCU/S (Carbon Capture, Utilization, and Storage) in Europe and Germany are used to discuss its applicability for China. The aforementioned difference in climate protection goals has a significant impact on the evaluation of CCU/S as a climate protection measure. Furthermore, there are differences arising from the economic development that need to be considered. China's economy continues to grow, with a crucial role of the construction industry. Consequently, the production quantities of steel and concrete are high: China produced nearly 60 % of the world’s cement, crude steel, and aluminum, and 30 % the primary chemicals used to make plastics and fertilisers (IEA 2021a).

As depicted in Figure 6, it can be assumed that these quantities will decrease. Factors contributing to this trend include demographic developments and the transformation towards a service-oriented society. Unlike Germany and Europe, where the transition to greenhouse gas-neutral technologies is already planned for the next investment cycle, China may still rely on transitional technologies. These factors must be taken into account when assessing the necessity and role of CCU/S in the respective regions.

3.2 Cement

3.2.1 Cement industry

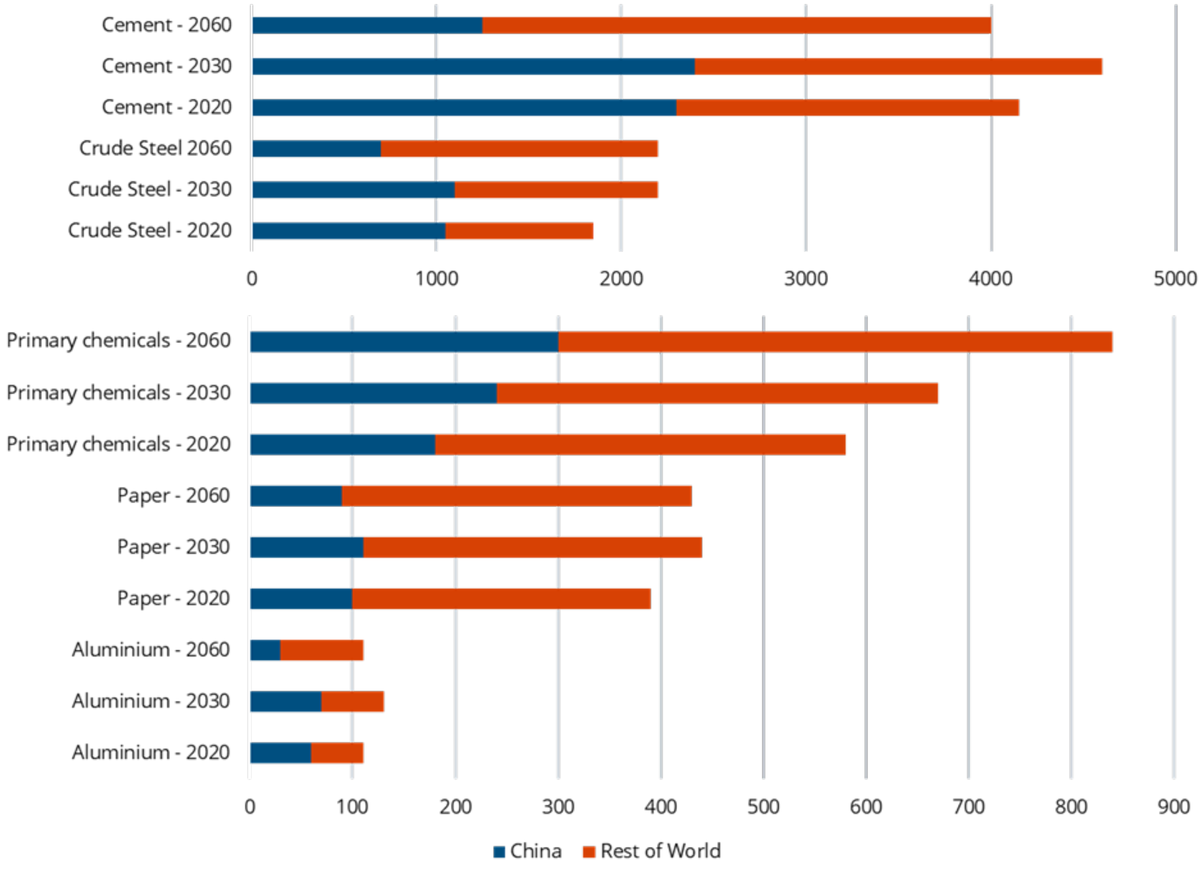
The production of cement is an energy-intensive process, and the use of fossil fuels for heating the kiln releases a significant amount of CO_2. The basic raw materials used in the production of cement are limestone, clay, and gypsum.

The process of cement production can be categorized broadly into three phases: the preparation of raw materials, calcination of clinker, and cement grinding. The calcination stage accounts for over 95 % of total carbon emissions, primarily attributed to the combustion of fossil fuels and the CO_2 released during the breakdown of carbonate raw materials (process emissions). A universally applicable alternative to limestone, whether in the form of a raw material, production process, or binder material, remains elusive. Thus, these process emissions stand as the foremost obstacle in the path of the cement industry's transformation to carbon neutrality (VDZ Hrsg. 2020; BV Kalk 2020, 2023).

Lime industry

Similarly to the cement industriy, about 2/3 of emissions in the lime industry are process emissions from the decomposition of limestone (BV Kalk 2020). Key applications for lime include the steel industry, flue gas cleaning, the chemical industry, and the construction sector (BV Kalk 2023). It is expected that the switch to H_2-DRI in the steel industry will reduce the demand for lime. Achieving a complete emissions avoidance, however, will require Carbon Capture (BV Kalk 2020).

Figure 6: Comparison of the production volume of China and the rest of the world in energy intensive industries (IEA 2021b).



3.2.2 Cement industry in China

In 2020, the cement industry's emissions in China were estimated to be around 1.3 Gt CO_2, constituting 13 % of the nation's total carbon emissions. Coal accounts for about 75 % of the energy inputs used in the cement industry in China, which contributes to the industry's high level of greenhouse gas emissions (IEA 2021a).

The cement industry in China has experienced an unprecedented expansion over the past two decades, with production quadrupling from approximately 600 Mt in 2000 to approximately 2.4 Gt in 2015. Despite a modest increase of 2 % in 2020, cement production in China remains relatively flat and is projected to peak in 2025 before entering a progressive decline due to the maturation of the country's infrastructure and building stocks. In terms of clinker-cement ratios, China's ratio is 0.66, which is lower than the global average of 0.72 (RMI and China Cement Association 2022; IEA 2021a).[8]

Projected development of Chinese cement industry

China is the world's largest producer and consumer of cement, accounting for 57 % of global production, with an output of 2.4 Bt in 2021. The projection for medium- to long-term cement and clinker demand hinges upon a suite of macroeconomic indicators encompassing GDP, fixed asset investment, population size, and the rate of urbanization. China's cement consumption stems mostly from the construction of infrastructure such as residential buildings, dams, highways, and railways. However, it is anticipated that a gradual downturn in housing construction will emerge in the medium- to long-term, spurred by demographic trends and saturation of the urbanization rate. Consequently, cement demand is forecasted to diminish from 2.4 Bt in 2021 to between 600 Mt and 800 Mt by 2050, leading to a similar reduction in clinker demand (IEA 2021a; RMI and China Cement Association 2022).

3.2.3 Energy efficiency

One initial measure to reduce CO_2 emissions in the cement and lime industry is to increase energy efficiency to the state of the art. Potential efficiency measures include replacing mills and grinders, as well as improving and retrofitting rotary kilns (VDZ Hrsg. 2020).

In the German cement industry, energy efficiency measures are already widely applied, such as utilizing waste heat for preheating combustion air, drying, and preheating fuels and raw materials. Both VDZ (2020) and ICF & Fraunhofer ISI (2019) estimate a hypothetical energy reduction potential of around 10 % for Germany. Therefore, improving energy efficiency alone will only result in a moderate reduction.

Chinese context

There is substantial potential for carbon emission reduction via energy efficiency improvements at the calcination stage. Approximately 75 % of China's clinker production lines conform to the “third-level standard”, characterised by a unit clinker energy consumption rate of 944 $kWh/t_{Clinker}$. An upgrade of all production lines from level three to level one (806 $kWh/t_{Clinker}$) could lead to a reduction of around 14 % in both energy consumption and energy-related emissions.

3.2.4 Alternative fuels

The energy supply for the necessary process heat is currently provided by coal, natural gas, biomass and alternative fuels, and the co-incineration of waste.

Definition of alternative fuels

These include, for example: used tires, used oil, organic waste, processed fractions from commercial and municipal waste (refuse derived fuels - RDF), and sewage sludge. Avoidance of up to 0.7 t CO_2 per ton of alternative fuel used compared with hard coal.

The use of sustainably grown biomass and green hydrogen as fuels offers the possibility to completely reduce emissions from combustion (1/3 of total emissions). Regarding the use of hydrogen in clinker production, further research is needed.

Another option could be the electrification of the rotary kiln. This technology is still in the research phase and is indicated by Nurdiawati & Urban (2021) to have a Technology Readiness Level (TRL[9]) of 2-4 (Nurdiawati and Urban 2021). VDZ (2020) does not expect this technology to play a significant role in the cement industry.

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[8] Cement to Clinker ratio: The cement clinker distribution refers to the clinker content in the cement product. The production of clinker is associated with process emissions. A lower clinker content therefore leads to a reduction in process emissions.

[9] "Scale for the systematic assessment of the development stage of new technologies. The value range extends from 1 'Observation and description of the functional principle' to 9 'Qualified system with evidence of successful deployment.
TRL 1: Observation and description of the functional principle
TRL 2: Description of the application of a technology
TRL 3: Proof of the functionality of a technology
TRL 4: Laboratory experiment setup
TRL 5: Experiment setup in operational environment
TRL 6: Prototype in operational environment
TRL 7: Prototype in operation (1-5 years)
TRL 8: Qualified system with evidence of functionality in the operational domain
TRL 9: Qualified system with evidence of successful deployment" (ESA 2022; Tzinis 2015)

Chinese context

China has recently demonstrated some progress in the deployment of alternative fuels. Predominantly, this involves the application of co-disposal technology in cement kilns, which represents an initial phase of solid waste utilization.

Currently, the most extensively implemented method within the cement industry is the co-disposal of waste materials, thus reducing the consumption of coal. This method currently serves merely as a supplementary heating measure within China's cement industry. For it to fully capitalize on its role as a fuel substitute, there is a need for a paradigm shift towards more refined management practices. As of the end of 2020, approximately 17 % of Chinese cement production lines possessed co-disposal capabilities.

3.2.5 Clinker-efficient cements and binders

Clinker is both the most important and the most CO_2-intensive component of cement. The clinker content can vary depending on the type of cement. A reduced clinker content leads to a reduction in process-related emissions.

The clinker content in cement affects the performance of the concrete. Potential substitutes for clinker can include limestone, blast furnace slag, and, to a lesser extent, pulverized coal fly ash and calcined oil shale. According to VDZ (2020), the clinker-to-cement ratio has decreased to 71 % in recent decades in Germany. In China, the clinker content in cement is already lower with 66 %.

Due to construction requirements, standardization of these cements is necessary before their application is possible. Current examples include CEM II/C and CEM VI cements. In CEM II/C cements, the clinker content can be reduced to as low as 50 %. For this type of cement, the maximum content of blast furnace slag is 30 % and non-fired limestone is 20 %. In CEM VI cements, a reduction in clinker content to 35-50 % is possible. Initially, the application of CEM VI cements will be limited to specific areas compared to CEM II/C cements (VDZ Hrsg. 2020).

New binders

There is worldwide research and work on alternative clinker and binder systems with the lowest possible specific CO_2 emissions and comparable performance and availability to Portland cement clinker.

From the perspective of VDZ (2020) and ICF & Fraunhofer ISI (2019), the following alternative clinker/binder systems are considered viable in the medium term for Germany: Calcium Sulfoaluminate Cements (CSA cements), Calcium Hydrosilicate (CHS), and the carbonation of Calcium Silicate (hydrates). The limitation arises from the assessment of the following factors: regional availability of materials, technical performance, and associated application possibilities in structures.

3.2.6 Concrete Resource Efficiency and Recarbonatization

Another lever for emissions reduction is material efficiency, which involves achieving the same performance with less (primary) material. There are various strategies for this, such as extending the lifespan of existing buildings or infrastructure, increasing their utilization, or constructing them with the minimum amount of material necessary to fulfill the required structural function. Innovative business models, consumer preferences, and policy instruments can also significantly reduce the production of large quantities of energy-intensive materials.

Reduction of cement usage and overdesign in construction

Many construction and infrastructure projects currently use more cement than necessary to meet the performance requirements according to technical standards. Established standards are usually adhered to as a precautionary measure, even though they are not mandatory and concrete with lower cement content would be suitable. Safety margins often correspond to +20 % of material consumption (Pameter and Myers 2021). The high strengths specified by the standards are only needed for certain applications.

Examples of approaches that already enable a reduction in concrete usage in buildings include the use of prefabricated steel-concrete elements in lightweight construction or geometrically optimized structural elements (Favier et al. 2018). While precast concrete elements are already widely used in many construction projects, other approaches, such as geometrically optimized structural elements, are not yet widespread. Prestressed concrete precast ceilings require up to 50 % less concrete and up to 75 % less steel compared to conventional concrete ceiling systems, while meeting comparable static requirements (Bundesverband Spannbeton-Fertigdecken e.V. 2020).

Carbon fiber-reinforced concrete

Carbon fiber-reinforced concrete, a composite material made of carbon fibers and fine concrete, offers a potential option for optimizing resource usage. Since carbon does not rust, a thin concrete cover of a few millimeters is sufficient instead of several centimeters as required for steel. As a result, carbon fiber-reinforced concrete is significantly lighter than steel-reinforced concrete and about six times stronger. It also enables the reinforcement and repair of existing structures, thereby significantly extending their lifespan. Research projects and studies have shown that energy demand and CO2 emissions in the production and maintenance of buildings can be reduced by 50-75 % (Kortmann et al. 2021).

Currently, carbon fiber-reinforced concrete is still more expensive than steel-reinforced concrete.

Recarbonation

Some of the CO_2 captured during cement production can be injected into the concrete to accelerate the curing process and sequester CO_2 in the final product. Studies suggest that with current low-carbon cement technologies, up to 5 % of the CO_2 can be bound, with a potential of 30 %. It is estimated that by 2050, globally, carbon-containing concrete could store 60 Mt CO_2 per year (McKinsey & Company 2020).

Recarbonation can be considered as an emissions reduction measure, but it is not a measure for decarbonizing the cement sector itself. Furthermore, there are still significant uncertainties in research regarding the actual uptake and time horizon of recarbonation (Dayaram 2010).

3.2.7 Reduction in demand for cement and concrete

The demand for cement and concrete can also be reduced through changes in behavior. In China, there are other factors to consider. The RMI & China Cement Association (2022) indicate that it is expected that the demand for cement will halve by 2050 (RMI and China Cement Association 2022). This is due to the saturation of the market, a slower population growth, and the growth of the construction sector in recent years, which is not projected to continue at the same pace for the next years/decades.

However, behavior changes are not directly influenced by the cement and lime industry and, therefore, despite their positive effects on emissions reduction, they are not a focal point of the report.

Extension of the lifespan

The utilization phase of a building offers significant potential for emission reduction by extending its lifespan and avoiding new construction. While buildings in Europe typically have a technical lifespan of about 60 to 100 years, the actual lifespan of many building types often falls short. Both commercial as well as residential buildings are often demolished before the end of their technical lifespan, often after only 15 to 40 years (Bahr and Lennerts 2010). Extending the lifespan of buildings through renovation can lead to a reduced demand for cement. In a study, Watari et al. (2022) estimated the mitigation effect to be around 4 % of the total emissions of the cement industry.

Substitution of building materials

In some cases, concrete in building construction can be replaced by less emission-intensive materials such as bricks or wood. Particularly, timber construction is suitable not only for low-rise residential buildings but also for projects such as high-rise buildings (examples in Vienna or Norway). However, its potential is limited by structural reasons in construction and by the potential of sustainable biomass and the simultaneous effort to expand the natural carbon sink of forests.

3.2.8 Conclusion

In comparison to Germany, China has a greater potential for emission reduction through the use of alternative fuels and energy efficiency. Furthermore, the demand for cement in China is expected to decrease significantly according to current forecasts. Similar to Germany, in China, a combination of additional measures alone will not enable the cement and lime industry to achieve GHG neutrality without the capture of CO_2 (Klepper and Thrän 2019).

3.3 Power Sector

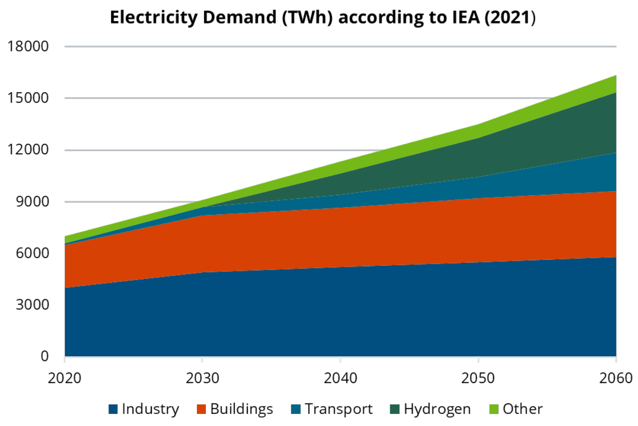
3.3.1 Power sector in China

China currently relies heavily on coal as a source of energy for power generation. In 2020, around 4,900 TWh of electricity was generated from coal, which corresponds to 64 % of China's electricity generation. Electricity and heat generation from coal accounted for 5.2 Gt CO_2 in 2020 (IEA 2021a).

3.3.2 Renewable Energy

Various renewable energy sources are available for the generation of greenhouse gas-neutral electricity. Among them, photovoltaic (PV) systems and wind turbines have the highest potential. According to the IEA (2021a), it is estimated that between 2030 and 2060, 220 GW of PV capacity and 57 GW of wind power capacity will be added annually. Due to the fluctuations in PV and wind

Figure 7: Project development of electricity demand in IEA (2021b).



generation, backup capacity is needed to provide electricity in case of supply shortages. Possible options for this include flexibilization of electricity demand, power plants, batteries, and other storage solutions. In a completely decarbonized electricity system, power plants will still be necessary. In the IEA (2021a), a backup capacity of nearly 2,800 GW is assumed for 2060. Overall, China's electricity demand will significantly increase due to the electrification of transportation, buildings, and the industrial sector. The assumed development in the IEA (2021a) can be seen in Figure 7. Due to the substantial increase in electricity demand, power plants will continue to be built in China (IEA 2021a).

3.3.3 Role of CCU/S

In China, new coal-fired power plants are still being constructed. One reason for this may be the increasing electricity demand, which cannot be met solely through the expansion of renewable energy sources. The economic competitiveness of providing energy through renewable energy with appropriate flexibility options in 2050/2060 is examined in chapter 0. Nevertheless using CCS in power plants can contribute to emission reduction, as underscored by (2021). Therefore, the use of CCS in coal-fired power plants, taking into account the circumstances of the Chinese energy system, remains an effective option for reducing greenhouse gas emissions, even though renewables are the more sustainable option in the long term.

Power plants that have been decommissioned but retrofitted with CCS technology can enhance their operational lifespan, while newly constructed units equipped with CCS could serve as Back-Up capacity. Power plants within a range of 300 to 600 MW capacity would be sufficient due to peak shaving requirements. Large-scale units are not cost-effective for peak shaving and contribute to increased carbon emissions.[10]

3.4 Steel

3.4.1 Steel sector

In the blast furnace route, iron ores (Fe_2O_3 or Fe_3O_4) are reduced to metallic iron at temperatures of up to 2,200°C. Today, the reduction process relies almost exclusively on fossil fuels, mainly coke, leading to high levels of emissions. Further process emissions are generated in the converter by burning out the carbon residues of the coke in the pig iron. For these reasons, a change of the energy source alone is not sufficient to achieve climate neutrality. Transformative technologies are needed alongside efficiency measures that lead to far-reaching changes. CO_2 capture can therefore play a role in the steel industry to reduce process-related emissions.

Secondary steelmaking is carried out in the electric arc furnace with electrical energy and can lead to complete decarbonization via the use of greenhouse gas-neutral electricity.

3.4.2 Steel sector in China

Over the past two decades, China's steel demand has increased, especially in the construction and manufacturing sectors due to surging infrastructure needs. Despite the COVID-19 pandemic, steel production in China rose by 7 % to a record 1.1 Gt in 2020 and has continued to rise in 2021. In 2020, Hebei province alone produced around 250 Mt (around 13 % of global steel production). In 2020, China's CO_2 emissions from steel production were approximately 1.5 Gt (IEA 2021a).

Only 10 % of the country's crude steel involves electric furnaces, which presents a major hurdle to decarbonizing China's steel sector. The relatively low age of existing production capacity, with an average of 15 years compared to 35 years in the US and 40 years in Europe, is also a challenge (IEA 2021a), as existing coal-based assets are expected to keep operating for decades.

The carbon intensity of steel production can greatly differ depending on the employed production process. In China, roughly 90 % of crude steel is manufactured through the traditional Blast Furnace-Basic Oxygen Furnace (BF-BOF) process, which emits about 1859 kg/t CO_2 crude steel.

Development of the Chinese steel industry

The carbon emissions from China's steel industry account for more than 15 % of the total emissions, making it the highest among manufacturing sectors. Most future emission projections for the steel industry concur that China's steel industry is likely to see its carbon peak early in the "14th Five-Year Plan" (2021-2025) period. Both coal consumption and carbon emissions in the steel industry are forecasted to continually decline as measures to control coal consumption and to reduce carbon emissions through energy-efficient technologies are implemented. As such, the estimated volume of CO_2 emitted by this sector is predicted to be in the ranges of 0.9-1.5 Gt in 2030, 0.6-0.8 Gt in 2040, 0.3-0.7 Gt in 2050, and 50-200 Mt in 2060.[11]

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[10] Expert Interview

[11] Expert Interview

3.4.3 Direct reduction with Hydrogen (H_2 – DRI) / Natural Gas / Gasified Coal

During the direct iron reduction (DRI) process, solid, pelletized iron ore is reduced to sponge iron using a gaseous reducing agent, which can then be melted into raw steel in an electric arc furnace or shaft furnace. Currently, about 5 % of global raw steel production is carried out using DRI, primarily with natural gas or gasified coal (Midrex 2021).

While the conventional blast furnace process relies on coke, it can be avoided in direct reduction using green or low carbon hydrogen, resulting in a significant reduction in CO_2 emissions (85-91 % compared to the blast furnace process - (Patisson et al. 2021)). However, a residual amount of emissions is generated due to the provision of a carbon carrier for slag foaming. These emissions can be avoided by using sustainable biomass or by carbon capture (Norgate et al. 2012).

Commercial hydrogen direct reduction plants are currently in the planning phase. Due to the limited short-term availability of green hydrogen, the planned DRI plants in Germany intend to use blast furnace gases and natural gas as reducing agents along with hydrogen while gradually increassing the proportion of hydrogen (Agora Energiewende 2021). By using natural gas, a CO_2 reduction of 66 % compared to the conventional blast furnace route can be achieved. Natural gas can be gradually and completely replaced by hydrogen. In the subsequent process step of iron production through direct reduction, an electric arc furnace is used, which is also employed in secondary steel production.

Costs of the process

The transition to the direct reduction process, according to current studies, is associated with investment costs ranging from 414 to approximately 600 €/t_{CS} (Conde et al. (2021), Vogl et al. (2018), Bhaskar et al. (2022), and Lopez et al. (2023)). In contrast, the VDI estimates investment costs at approximately 1 billion € per Mt crude steel capacity (1000 €/t_{CS}). For comparison, literature suggests that the construction of blast furnaces costs 442 €/t_{CS} steel (Vogl et al. 2018). OPEX costs are particularly dependent on electricity and hydrogen prices. The costs for DRI mainly depend on the electricity price for the production for green hydrogen and therefore vary between 350 and 900 €/t_{CS}.[12]

TRL

The TRL of H_2 direct reduction will reach 9 for newly constructed facilities by 2026, according to German steel companies. This means that the technology will be ready for deployment in the coming years. Salzgitter, ThyssenKrupp, and ArcelorMittal have already announced their plans to fully transition their primary steel production to the direct reduction process by the 2030s.

Chinese context

The demand for DRI in China is substantial, exceeding 15 Mt in 2020. The domestic DRI technology due to the uneven distribution of natural gas as a reducing gas, is in its initial stages of development.

China has constructed seven production lines that employ a coal-based rotary kiln for DRI production, yielding an annual capacity of approximately 650 kt.[13]

As for gas-based vertical furnace DRI technology, Liaoning Huaxin Iron & Steel Group initiated a demonstration project in 2018, boasting an annual output of 100,000 tonnes of high-quality steel, utilizing a coal-to-gas-rich hydrogen vertical furnace-electric short process flow. In 2019, the Inner Mongolia Mingtuo Group adopted Midrex gas-based vertical furnaces with an annual capacity to undertake a project reducing 1.1 Mt per year using synthetic methane as the reducing gas.

In May 2021, HBIS commenced construction on the Energiron DRI Project in Zhangjiakou city, with an annual output capacity of 600 kt, while planning to build an additional 3 Mt annually across Tangshan, Handan, and Xuanhua. Furthermore, in the third quarter of 2021, Baowu Steel is scheduled to construct 2 Mt hydrogen-based vertical furnace DRI demonstration projects at Zhanjiang Steel. These projects will utilize varying proportions of coke oven gas, natural gas, hydrogen, and electrolytic water-produced hydrogen as reducing gases.[14]

3.4.4 HIsarna® – process in combination with CCS

The HIsarna® process in combination with CCS continues to use coal as an energy source and reducing agent. A special reactor is used instead of a blast furnace. The iron ore is injected directly into the reactor, where it reacts with pure oxygen instead of air and coal. The product is a CO_2-rich off-gas, which is more suitable for separation. The process can achieve a capture rate of 86 % when combined with CCU/S (Agora Energiewende 2021). If the process is used without CCU/S, a reduction of emissions by about 30 % is possible (Nurdiawati and Urban 2021).

TRL

The technology is expected to be ready for the market between 2030 and 2035. For Germany, the technology has

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[12] Own calculation

[13] As iron concentrate production by mining companies became more profitable than DRI production, all seven rotary kilns used for DRI production in steelmaking were forced to cease operation due to economic losses.

[14] Expert Interview

no relevance. At present, China has not adopted this technology.[15]

3.4.5 CCU/S blast furnace route

An overarching challenge in the integrated carbon capture in existing blast furnace plants is the presence of multiple emission point sources. These include the blast furnace, the sinter plant, the converter, and the coke oven (Perpiñán et al. 2023; Birat 2010). Therefore, the consolidation of individual flue gas streams is necessary to capture a significant portion of the total emissions.

If the exhaust streams from the major CO_2 emission sources are combined and subjected to amine scrubbing, the emission reduction potential is reported to be 50-75 % (Leeson et al. 2017).

Another option is the capture of CO or CO_2 from blast furnace flue gas to produce chemical substances. Retrofitting of the technology to blast furnaces is possible and can be used from 2025 at the earliest. Due to the high electricity demand, emissions savings potential needs to be considered over the entire life cycle, including energy supply. The potential emission reduction is between 50 and 63 % (Agora Energiewende 2021).

Costs

It is essential to consider whether all process emissions can be integrated and not just the furnace gas from the blast furnaces can be captured. The investment costs for CH_4-DRI and BF BOF with CCS are between 500 and 900 €/t_{CS}[16] in Germany.

Agora Energiewende and Wuppertal Institute (2021) calculated CO_2 abatement costs for CCU at blast furnaces of 231 - 439 €/t CO_2 in 2030 for the German context, resulting in specific additional costs of 63 - 119 % for the capture of CO_2 from metallurgical gases and production of chemicals.

TRL

The capture of CO_2 of metallgurical gases is considered as a transitional technology and thus has low relevance for the achievement of the German climate protection goals, since the ramp-up of direct reduction with hydrogen has to be started early (2025 - 2030) (Mobarakeh and Kienberger 2022; Nurdiawati and Urban 2021).

In the "Carbon2Chem" project, processes for converting carbon compounds (mainly CO and CO_2) from metallurgical gases from steel production into basic chemicals were developed. In a second project phase, the processes developed will be scaled up and validated for large-scale implementation (BMBF 2023).

3.4.6 Secondary steel (Recycling)

An alternative mitigation option in steel production is the reduction of the share of currently emission-intensive primary steel through secondary steel production (recycling). Steel recycling is carried out exclusively through the electric arc furnace, where scrap metal is melted. There is also the option to use sponge iron from the DRI process in the electric arc furnace and to vary the amount of scrap used. When renewable electricity is used, the process is largely GHG neutral.[17]

The potential of steel recycling is limited by the availability of steel scrap and impurities in the scrap, especially copper, which leads to reduced quality of the new steel (downcycling). Achieving higher purity requires not only further research but also organizational changes, such as the separate collection of specific types of scrap or the use of smaller recycling plants or batch sizes, which also presents a challenge (Agora Industry 2022).

3.4.7 Role of CCU/S

Emission reduction measures such as process enhancements, efficiency improvement, and the substitution of energy and raw materials can reduce the steel industry's emissions by about two thirds. Even with large-scale implementation of hydrogen DRI will have residual carbon emissions of about a tenth of current emissions.

Scope 3 emissions

Figure 8 schematically illustrates the distribution of Scope 1, 2, and 3 emissions for basic chemicals in Germany. The chemical industry faces the challenge of reducing both Scope 1 and 2 emissions through a transition to new technologies and energy sources, as well as Scope 3 emissions by using non-fossil raw materials. The chemical industry presents a particular challenge in terms of decarbonization because it needs to replace both the energy supply and raw material demand with non-fossil energy sources to achieve the goal of climate neutrality by 2045. Ensuring the sustainable supply of carbon as a raw material in the chemical industry is especially challenging.

In the context of CCU/S, the chemical industry is involved in the discussion of both CO_2 capture and CO_2 utilization. This involves considering different technologies. In this section, the focus is on CO_2 capture for emissions directly occurring during production.

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[15] Expert Interview

[16] Own calculation

[17] The dena-Leitstudie Aufbruch Klimaneutralität assumes an increase in the share of recycled steel in Germany to 35 percent by 2045. According to Agora Industry (2022), it is possible that by 2050, 80-90 % of the EU's steel demand could be met by secondary steel, provided that there is a separation of steel scrap based on impurities.

Therefore, additional strategies are necessary to make the steel industry carbon neutral.[18]

At present, hydrogen-based direct reduction in combination with a biogenic or synthetic carbon source is the only available option to completely eliminate CO_2 emissions from the steel industry.

In China the cost of low-carbon hydrogen is significantly higher than that of fossil fuels such as coke and natural gas. Consequently, hydrogen prices are a significant constraint on the low-carbon development of the steel industry. Until hydrogen is available in sufficient quantities and production routes are converted to DRI, there is a substantial opportunity for the use of Carbon Capture in blast furnaces. This period is estimated to persist until 2040. By 2060, the use could also extend to DRI plants due to the limited availability of hydrogen, as these plants can transition to hydrogen without the need for new construction, thereby reducing the lock-in risk. In the long term, the use of green hydrogen is envisioned as the production route that enables greenhouse gas-neutral steel production. Possible residual emissions from carbon addition and the utilization of carbon anodes can be avoided through implementation with a synthetic carbon carrier or biomass.[19]

Even then, there may still be a need to capture residual emissions e.g. from rolling mills or from necessary carbon inputs. Therefore, CCU/S could potentially play a role in the steel industry in the long term.

3.5 Chemical industry

Figure 8: Life cycle emissions for the production of 1 ton of plastic via the process of naphtha cracking. The figure is based on Agora Energiewende and Wuppertal Institute (2021). Source: dena.

3.5.1 Main processes in chemical industry

The chemical industry has a special role, as carbon is necessary as a raw material for production. In the context of CCU/S, the chemical industry is to be discussed for both CO_2 capture and CO_2 utilization, requiring different technologies. In this part, the focus is on CO_2 capture and the emissions that are directly generated during production.

The non-energy use of fossil fuels is complex, since chemical production sites are highly interconnected in terms of infrastructure, consisting of different production paths between which substances and energy are reciprocally transported. Due to the large number of different products and plant complexes, only the most important chemicals are described. Energy-related CO_2 emissions are not discussed in detail, as the same considerations apply as for power plant processes.

Given China's resource endowment, characterised by low oil and gas reserves and abundant coal, the predominant approaches to ethylene production in the country are as follows:

Steam cracking (Ethylene / Ethen production)

In steam cracking, saturated hydrocarbons are thermally split at approximately 850°C. The resulting unsaturated and reactive components form a significant portion of the basic chemicals used in further processing in the chemical industry. Ethylene production capacity in Europe is approximately 25 Mt per year.

The primary feedstock for steam crackers in Germany and Europe is naphtha, although other options include using ethane or propane. Compared to the thermal cracking of ethane or propane, naphtha crackers produce a larger quantity of other high-value chemicals (HVC), such

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[18] Expert Interview

[19] Expert Interview

as propylene, butadiene, benzene, etc., which are of considerable importance in subsequent chemical processes.

In the steam cracking process, an inevitable byproduct is an off-gas consisting mainly of methane with lower amounts of hydrogen, which is internally used for heat generation in the cracking furnaces, thus leading to CO_2 emissions. Figure 8 provides a basic mass balance for a naphtha-based steam cracker.

Coal-to-Ethylene process

The coal-to-ethylene process uses coal (in the form of methanol) as a raw material. The efficient production of low-carbon olefins such as ethylene and propylene from coal through synthesis gas has the potential to supplant the long-standing Fischer-Tropsch (FT) synthesis technology utilized in coal conversion processes. This method not only obviates the energy and water resource-intensive water-gas shift reaction route but also reduces the reaction temperature, shortens the process flow, and expands the sources of olefin raw materials.

However, producing ethylene from coal inherently necessitates adjusting the hydrogen-to-carbon atomic ratios. In this case, hydrogen can solely be derived from steam reforming, a process that culminates in substantial carbon dioxide emissions (11 t CO_2/t H_2).

Fischer Tropsch with Coal

The technology for converting coal to oil can be broadly segmented into direct and indirect liquefaction processes. The former entails transforming coal into an oil slurry that undergoes catalytic hydrogenation at a temperature of 450℃ under a pressure range of 10 to 30 MPa, resulting in a liquid fuel that is further processed into diesel, gasoline, or petrochemical products.

On the other hand, indirect liquefaction entails gasifying purified coal into synthetic gas, which undergoes Fischer-Tropsch synthesis at a reaction pressure between 2.0 and 3.0 MPa and a temperature below 350℃. This method utilises catalysts to yield synthetic oils and petrochemical products. Both energy consumption and carbon emissions are significantly higher in the coal chemical industry than in oil and gas pathways.[20]

Coal gasification

The process of coal gasification involves several stages and chemical reactions, including drying, pyrolysis, and gasification, aided by gasifying agents under high-temperature conditions. The resulting gases are then separated from the residual ash and further processed within the system.

In terms of energy consumption, the principal inefficiency in the coal gasification process predominantly lies in CO_2 emissions. In the energy obtained through coal gasification, the molar ratio of CO to H_2 is typically within the confines of 2. Through a chemical reaction, CO can be transformed into water gas, which can subsequently be converted to CO_2. The synthesis gas necessitates the discharge of a considerable volume of CO_2. This process represents the primary source of waste gas generation and energy wastage in the coal gasification process.[21]

Refinery Processes

In the refinery, the basic processes are carried out to produce high-quality products from the basic raw materials. The basic process is crude oil distillation in which crude oil is separated into different fractions. According to Fischedick et al. (2015), CO_2 process emissions do not play a role in refinery processes (Fischedick et al. 2015).

Another process is the cracking process in which sometimes very high temperatures are necessary (800 - 850 °C). In the process, naphtha is converted into products such as ethene for further processing. The process is one of the most important processes in the chemical industry.

Another important process is synthesis gas production. Synthesis gas is an intermediate product for various other products in the chemical industry, especially for the production of hydrogen. During the production process-related CO_2 emissions occur in addition to the energy-related CO_2 emissions. The by-product CO_2 is present in pure form and offers the possibility of recycling into the process or further use in other processes.

3.5.2 Current state of chemical industry in China

As of 2020, China's ethylene production capacity has surged to 35.2 Mt per year, with projections indicating a rise to 73.5 Mt by the conclusion of the "14th Five-Year Plan" period. Notably, in 2019, 24 coal (methanol) to olefin units were operational, possessing an aggregate capacity of 13.6 Mt per year.

Challenges for Chinese chemical industry

In China, a significant portion of the chemical industry relies on the conversion of coal into carbon-based products. These processes result in considerably higher CO_2 emissions compared to the petroleum and natural gas-based chemical industry (see chapter 3.6). Transitioning entirely to petroleum and natural gas to reduce emissions is not feasible due to limited availability. Consequently, the early adoption of CO_2 capture will play a crucial role in mitigating CO_2 emissions.

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[20] Expert Interview

[21] Expert Interview

In the future, green hydrogen will be essential for the chemical industry in China to enable greenhouse gas-neutral production. Notably, the northwestern region of China, endowed with abundant coal, solar power, and wind power resources, provides an ideal environment for combining the coal-based chemical industry with the green hydrogen chemical industry.[22]

3.5.3 Mitigation of Scope 1 and 2 emissions

Power-to-Heat

The chemical industry has process heat requirements ranging from 100 to over 1000°C, which leads to different technologies being applied. For this reason, various power-to-heat processes are considered for decarbonization. In the low temperature range (up to 200°C), the use of-high temperature heat pumps is possible (Agora Energiewende 2021). The use of such high-temperature heat pumps is expected to reach industrial scale by 2025.

Electrode boilers reach temperatures of up to 500°C. They are already market-ready and available and lead to a complete reduction of emissions when using climate-neutral electricity (Mobarakeh and Kienberger 2022).

The further high temperature heat demand can be covered by hydrogen as well as biomass. Another option to provide heat can be the retrofitting of existing CHP plants with CO_2 capture.

Decarbonisation of steam crackers

In some processes in the chemical industry, electrification can also take place at temperatures exceeding 500°C. Steam crackers are the most important technology in this regard. The possibilities for decarbonization are presented in more detail below.

The off-gas used for heat generation is generated regardless of the plant configuration. To reduce energy-related emissions from its combustion, hydrogen can be used, or the process can be electrified. The use of CCU/S is also discussed in detail in chapter 3.6.

Transition to Hydrogen

Switching to hydrogen does not change the core reaction process. However, using hydrogen as a heating gas comes with challenges such as:

- The higher flame temperature leads to increased nitrogen oxide (NO_x) formation
- Burners for 100 % hydrogen are currently limited due to hydrogen's higher flame speed and lower flue gas volumes compared to methane/natural gas

Electrification

As an alternative to conventional crackers, the use of electric crackers is also conceivable, which could completely eliminate energy-related emissions. In electrification, the core reaction process remains the same. A typical cracking furnace today consists of two zones: the radiation zone (where the reaction occurs) and the convection zone for preheating the feedstock. In an electric cracking furnace, the convection zone is eliminated, so preheating the feedstock to about 600°C must occur in separate preheaters. Electric cracking furnaces produce less steam overall, so parts of the compressors need to be electrified as well. It is currently assumed that large-scale plants will be available between 2030 and 2040.

There are currently various developments in the areas of hydrogen-based combustion, electrification of the cracking process, or carbon capture processes from flue gases. It is expected that promising approaches will reach technical maturity in the coming years.

Conclusion

In the short and medium term, coal chemical processes are poised to continue playing a significant role in China. The high concentration of CO_2 in waste gas streams during coal gasification, coal to ethylene as well as in the FT synthesis with coal, significantly reduces the cost of CCU/S.[23]

In processes with temperatures below 500°C, electrification is expected to prevail in the medium to long term, as it enables greenhouse gas-neutral production. The defossilization of steam crackers is more complex because electrification is still in the research phase, and a solution for dealing with the unavoidable off-gases needs to be found. In the long term, it is expected that electrification will also become established in this context. The use of CCU/S could also occur in the long term, depending on how Scope 3 emissions are managed and what purpose is found for the off-gases.

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[22] Expert Interview

[23] Expert Interview

3.5.5 Mitigation of Scope 3 emissions

As previously described, in the chemical industry, hydrocarbons are required for products that result in emissions during their production, conversion, and end-of-life stages. These Scope 3 emissions require different approaches to achieve zero greenhouse gas emissions. The main challenge is to replace fossil feedstocks with renewable alternatives such as recycling, biomass, or CCU.

There are already various processes in which CO_2 is utilized (CCU), including the production of urea or soda as well as the food industry. However, the current uses of CO_2 are significantly lower in demand compared to the future demand. In Germany, for example, 2 Mt CO_2 per year are used annually, while VCI and VDI (2023) estimate that 44 to 52 Mt CO_2 per year will be needed by 2045 for the production of key basic chemicals.

CCU

Through CCU, basic chemicals such as methanol and the aromatics benzene, toluene, and xylene (BTX) can be directly produced. Additionally, it is possible to produce higher hydrocarbons and olefins using the Fischer-Tropsch or Methanol-to-Olefins/Aromatics (MTO/A) processes (VCI and VDI 2023). Possible sources for GHG-neutral production are either DAC or biogenic CO_2.

Recycling of plastics

Another possibility to meet the carbon demand is the recycling of plastics. Below, various methods for recycling plastics are presented, along with potential limiting factors. Finally, an assessment of the potential is made based on the information presented earlier.

Mechanical Recycling

Mechanical recycling can reduce the amount of waste by keeping plastics in the loop for a longer time, thus replacing primary production. During mechanical recycling, plastics are crushed, sorted, and divided into granules that can be re-used. However, the material properties of plastics can be slightly altered during processing, necessitating the use of additives to restore the desired characteristics. For these reasons, two to three recycling cycles are considered possible in mechanical recycling (Arena and Ardolino 2022).

The quality of recycled plastics can be significantly affected by impurities in polymer waste, including trace elements like small degradation products and additives. Multilayer materials that cannot be separated pose another challenge. Additionally, plastics that are temperature-sensitive and do not become liquid at high temperatures can limit the recycling process. However, there are some types of plastics, especially from the packaging sector such as PET, polyethylene, and PP, which are typically treated and recovered through mechanical recycling processes (Arena and Ardolino 2022).

Chemical Recycling

There are different processes for chemical recycling, the main processes gasification and pyrolysis are described below.

Gasification - Gasification converts solid waste into a mixture of hydrocarbons and syngas. This process occurs at temperatures ranging from 700 to 1200 °C, depending on the process and feedstock. Plastic waste can be transformed into syngas (H_2 + CO) in the gasification process. Subsequently, conversion into basic chemicals, fuels, energy, and other products can be achieved through various additional processes. Autothermal gasification utilizes approximately 28 % of the energy from the carbon in the feedstock to obtain the remaining 72 % of gas (Porshnov 2022). Gas cleaning is crucial to achieve higher efficiency and lower costs. The use of catalysts for FT and methanol synthesis is hindered by their sensitivity to impurities like oxygen, bromine, chlorine, and sulfur (Porshnov 2022) (Mamani-Soliz et al. 2020).

Pyrolysis - Pyrolysis is a chemical recycling process in which e.g. plastic waste is thermally cracked at temperatures between 300 and 700 °C, in the absence of oxygen. The products of this process are gas, charcoal, and liquid oil, with pyrolytic oil being the desired product in most cases. However, pyrolysis is not suitable for treating mixed waste because pyrolysis oils are contaminated with heteroatomic elements such as O, N, Cl, F, and Br. These impurities result in acidic, unstable oils that are immiscible with oil and, therefore, cannot be used as fuel without further reforming processes (Porshnov 2022) (Solis and Silveira 2020).

Conclusion

An increasing share of recycling and the role of mechanical and chemical recycling are significant future treatment paths for plastic waste. As not all plastics can be recycled various additional measures are necessary to complement recycling efforts. Waste reduction measures, such as avoidance, reuse, and recycling, usually come with the lowest avoidance costs.

It should be noted that progress in reducing plastic consumption and improving recycling processes as energetically preferred options with low avoidance costs reduces the necessity for material biomass utilization and CCU processes.

Biomass as feedstock

Biomass consists of complex carbon-containing molecules. These molecules contain many C-C bonds, which makes further processing more energetically favorable compared to processing CO_2. The carbon present in biomass is of biogenic origin, which means the use of biomass could potentially be accounted for as GHG-neutral. The choice of feedstock used for biomass processing is particularly relevant.

Feedstock is commonly categorized into different generations.

First generation biomass - First-generation feedstock includes carbohydrate-rich biomass, which is easy to process but conflicts with its use as food or feed.

Second-generation biomass - comprises biomass that is unsuitable for use as food or feed, such as lignocellulose, which is more challenging to process than carbohydrates.

Third-generation biomass - refers to biomass from algae, which is complicated to process due to high water consumption, water content, and technical and geographical obstacles (Klepper and Thrän 2019)

Drop Ins

The concept of "drop-ins" refers to identical counterparts of fossil-based plastics that are currently in use, but are instead sourced from renewable materials. These "drop-ins" possess the exact same chemical and physical properties as their fossil-based counterparts.

New materials

Certain new materials, such as polylactic acid (PLA) and polyhydroxyalkanoates (PHA), have different chemical and physical properties compared to conventional fossil-based plastics. However, they can still be utilized in a wide range of packaging applications. However, it may have limitations in terms of mechanical strength and heat resistance compared to some fossil-based plastics (Brizga et al. 2020).

Fermentation processes can play a key role in providing drop-in biochemicals for existing production pathways. For instance, sugars present in biomass can be fermented into ethanol, which can then be easily converted into bioethylene, identical to fossil-based ethylene. Fermentation can also be utilized for producing alternative bio-based chemicals.

For the production of drop-ins, technologies such as biomass pyrolysis and gasification will be required. A description of these technologies can be found above.

3.5.6 Role of CCU/S

CCS

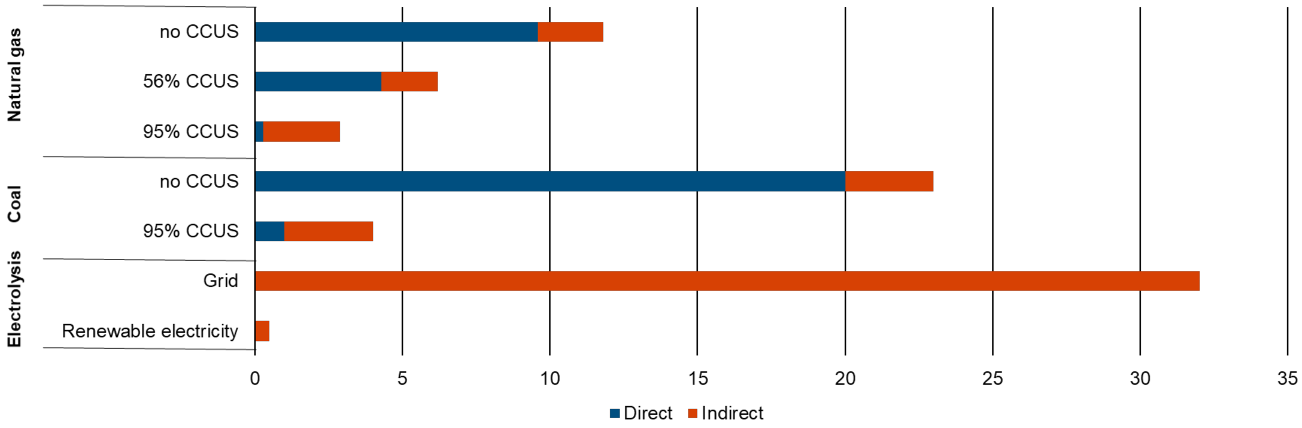
To achieve carbon neutrality, the use of CCS is not essential in the chemical industry. However, employing CCS as a transitional technology is advisable to mitigate emissions from steam crackers, coal gasification, and other processes with high CO_2 concentrations. It is anticipated that the application of CCS to steam crackers will remain relevant for an extended period due to the lack of alternatives and the potential for retrofitting existing crackers.

CCU

CCU is necessary for the defossilization of the chemical industry and thus for achieving greenhouse gas neutrality. The proportion of CCU will strongly depend on the biomass potential and the feasibility of recycling. In the short term the availability of low carbon hydrogen will be the main restriction for the production of chemicals via CCU technologies.

3.6 Hydrogen production

Figure 9: GHG emissions of different hydrogen production pathways by IEA (2021b).



3.6.1 Hydrogen sector

Hydrogen plays a crucial role in the chemical industry. It is primarily used for the synthesis of ammonia and methanol (Fischedick et al. 2015).

When producing methanol or hydrogen, the hydrogen content must be enhanced through the water-gas shift reaction. This process results in the production of one mole of CO_2 for every mole of CO in the product gas:

$$CO + H_2O \longrightarrow CO_2 + H_2$$

The carbon present in the resulting CO_2 originates from the hydrocarbon used in steam reforming. This process, along with subsequent water-gas shift reaction, contributes to process emissions during hydrogen production. However, the generated CO_2 byproduct is separated and obtained in its pure form. The CO_2 can be reintroduced into the process for the reforming of hydrocarbons using the following reaction equation:

$$-CH_2 - + CO_2 \longrightarrow 2\,CO + H_2$$

This enables adjustment of the H_2/CO ratio. Alternatively, the CO_2 can be utilized in other processes (Fischedick et al. 2015).

3.6.2 Hydrogen sector in China

China has been the world’s largest producer and consumer of hydrogen since 2010, owing to growing demand from its industry sector and the availability of low-cost resources. Since 2010, according to data sources in China, national hydrogen consumption has increased by 30 % reaching around 33 Mt in 2020, and accounting for around 30 % of the global production.[24] Dedicated hydrogen and by-product hydrogen production amount to around 26 Mt (IEA and ACCA21 2022).

3.6.3 Hydrogen with CCU/S

Hydrogen production offers a cost-effective measure to scale up renewable energy sources in regions rich in resources. Furthermore, the utilization of captured CO_2 and hydrogen to produce transport fuels presents a promising avenue for decarbonization. With an average chemical plant lifespan of 30 years, these plants can play a significant role in the transition to hydrogen technologies as this highlights the potential for retrofitting and repurposing these facilities to produce hydrogen.

There are also plans to develop a large CCUS hub in North-West China to capture and store CO_2 from refineries’ hydrogen production units. This project would involve gradual CCUS deployment, starting with a capture volume of 1.5 Mt CO_2 per year during 2020-2023 and growing to 10 Mt CO_2 per year during 2030-2040 (Zhang et al. 2021).

The definition of "low carbon hydrogen" in China

In China, the definition of low-carbon hydrogen is based on a lifecycle carbon emissions threshold of 14.5 kg CO_2/kg H_2. This threshold indicates the maximum allowable carbon emissions throughout the entire production process. Hydrogen produced from coal gasification has been assessed to emit 29.0 kg CO_2/kg H_2, exceeding the low-carbon threshold. On the other hand, "clean" hydrogen, which is subject to a stricter threshold, has a maximum carbon emission limit of 4.9 kg CO_2/kg H_2.

Coal gasification

Globally, there are approximately 130 coal gasification plants in operation, with the majority located in China. Coal gasifiers produce high-CO_2-concentration gas streams, typically around 80 %, after removing impurities such as sulphur and nitrogen. This high concentration makes it relatively easy to capture CO_2, with capture rates reaching 90-95 %. Coal without carbon capture has an emission intensity of 17.8 to 21.6 kg CO_2/kg H_2 (Fischedick et al. 2015; IEA and ACCA21 2022) (see Figure 9).

Hydrogen from natural gas

Typically, 30-40 % of the natural gas is combusted to fuel the process, giving rise to a “diluted” CO_2 stream, while the rest of it is split into hydrogen and a more highly concentrated CO_2 stream. Autothermal reforming (ATR) is an alternative technique in which the required heat is produced in the reformer itself, meaning that all the CO_2 is in the shifted syngas. Other technologies include gas-heated reformers and partial oxidation of natural gas (IEA and ACCA21 2022).

Different hydrogen production technologies have varying lifecycle GHG emissions. When natural gas is used without carbon capture, the direct process CO_2 emissions range from 8.9 to 9.8 kg CO_2/kg H_2. However, the application of CCUS can significantly reduce process CO_2 emissions. For coal with 90-95 % capture, the estimated emissions are 1.0 to 2.2 kg CO_2/kg H_2, while for natural gas with partial CO_2 capture (56 %), the emissions range from 4.3 to 5.4 kg CO_2/kg H_2. Natural gas with full CO_2 capture (95 %) has the lowest emissions, estimated at 0.5 to 0.6 kg CO_2/kg H_2 (IEA and ACCA21 2022).

To minimize residual emissions from fossil fuel CCUS hydrogen production routes, it is crucial to achieve high capture rates (>90 %) and reduce upstream emissions.

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[24] This includes hydrogen used for onsite co-generation of heat and power in industrial processes, such as coal-coking in steelmaking and chlor-alkali electrolysis in chlorine and caustic soda production.

Costs

In the medium term, coal gasification with CCUS continues to be a cost-effective option, with an estimated cost range of approximately 1.4 to 3.1 \$/kg H_2, for producing low-emission hydrogen. This is particularly relevant in regions where coal and CO_2 storage resources are abundant and renewable energy sources are less readily available. While cost reductions are expected for CCUS-based production routes through economies of scale and technological advancements, they are likely to be more limited compared to electrolysis, a process that uses renewable energy to produce hydrogen.

3.6.4 Green Hydrogen

During electrolysis, water is split into oxygen and hydrogen using electrical energy.

$$2\,H_2O \longrightarrow 2H_2 + O_2$$

When electricity demand is met through renewable energy sources, hydrogen can be produced in a greenhouse gas-neutral manner (green hydrogen) (Fischedick et al. 2015).

3.6.5 Role of CCU/S

Based on projections by China Hydrogen Alliance, annual hydrogen production is expected to reach 130 Mt by 2060, with green hydrogen constituting up to 80 %. Technologically, China must persist in making substantial breakthroughs across several dimensions including hydrogen production, storage, transport, and establishing a technology-led hydrogen energy network.

Currently, grey hydrogen remains the market's principal component, whereas blue and green hydrogen constitute a minimal portion. However, the trajectory is leaning towards a green hydrogen future, especially by 2060.[25]

Accordingly, CO_2 capture in both coal gasification and steam methane reforming processes can contribute to reduction since fossil-based hydrogen will continue to be used during a transitional period. Particularly, the capture of pure CO_2 stream during synthesis gas production represents a cost-effective option that results in a significant reduction in emissions.

In the target state, it is expected that only green hydrogen will be used and CCU/S will likely play no role. Overall, it can be concluded that CCU/S is not necessary in a GHG-neutral target state.

3.7 Waste to energy

3.7.1 Waste sector

Thermal waste treatment primarily serves the purpose of waste inertization, with energy recovery being a secondary objective. For this reason, waste incineration cannot be compared to conventional power plant processes, as the emissions from waste incineration cannot be substituted by renewable energy sources. According to the European Waste Hierarchy implemented in Germany through the Circular Economy Act, waste incineration occupies the fourth position, following waste prevention, reuse, and recycling, and serves as the final option before resorting to landfilling.

In Germany, various types of facilities are available depending on the nature of the waste. The majority of thermal waste treatment is carried out in municipal waste incineration plants and waste-to-energy (WtE) plants. Additionally, there are specialized waste incineration plants, facilities dedicated to the mono-incineration of sewage sludge, and biomass heating power plants that utilize old wood for thermal energy production. Apart from facilities specifically designed for waste incineration, industrial plants also engage in the co-incineration of processed waste known as substitute fuels.

Despite potential waste reduction measures through the implementation of circular economy practices, thermal waste treatment facilities will continue to be necessary in Europe even in 2050 (as indicated by (System IQ 2022)). These facilities have a critical function in eliminating pollutants derived from the processing of secondary raw materials within the framework of a circular economy.

China

The annual production volume of solid waste in China will approach nearly 12 Gt, with a growth rate of between 5 - 7 %. Since 2003, industrial solid waste generation in China has risen annually. However, the comprehensive utilization rate has remained at approximately 60 %, and after peaking at 68 % in 2009, declined and sustained at a relatively low level.[26]

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[25] Expert Interview

[26] Expert Interview

The prevalence of incineration has notably increased, rising from 5 % in 2003 to 40 % by 2017, almost a tenfold growth within 15 years. Consequently, incineration technology is steadily supplanting sanitary landfill as the principal technical strategy for domestic waste treatment in China.[27]

The projected installed capacity for power generation from waste incineration is anticipated to reach 22 GW, with annual power generation predicted to hit 130 TWh (CACE 2023). The continuous growth in Municipal Solid Wastes (MSW) and policy promotion have contributed to a steady increase in China's MSW incineration capacity. It is anticipated that the overall installed capacity will continue to expand rapidly as the demand for downstream electricity increases (Sohu 2021).

By the end of 2035, it is expected that the annual clearing volume will be around 550 Mt nationally, with incineration-based energy recovery accounting for approximately 75 % of all cleared wastes.

3.7.2 Role of Carbon Capture

Germany

Two studies have examined the future development of waste generation in Germany. The study "Perspectives of Thermal Waste Treatment - Roadmap 2040" conducted a conservative assessment of relevant waste types and the available capacities for thermal waste treatment in the year 2040. According to the study, there is projected to be a minimal decrease in waste quantities from 34.5 Mt to 33.4 Mt in 2040. This is attributed to the fact that while recycling reduces the amount of waste, demographic and economic developments, as well as new waste streams resulting from changing requirements for waste management, will also contribute to an increase in waste quantities. Therefore, the study expects a near-stagnation in waste generation (Hoffmeister et al. 2020).

The study conducted by the Öko-Institut, titled "Capacities of Energy Recovery from Waste in Germany and Their Future Development in a Circular Economy," also examined various scenarios. These scenarios project a more significant reduction in waste quantities while recognizing the continued necessity of waste incineration. In the most ambitious scenario, the waste quantity decreases from approximately 26 Mt to 17 Mt per year (Dehoust and Alwast 2019).

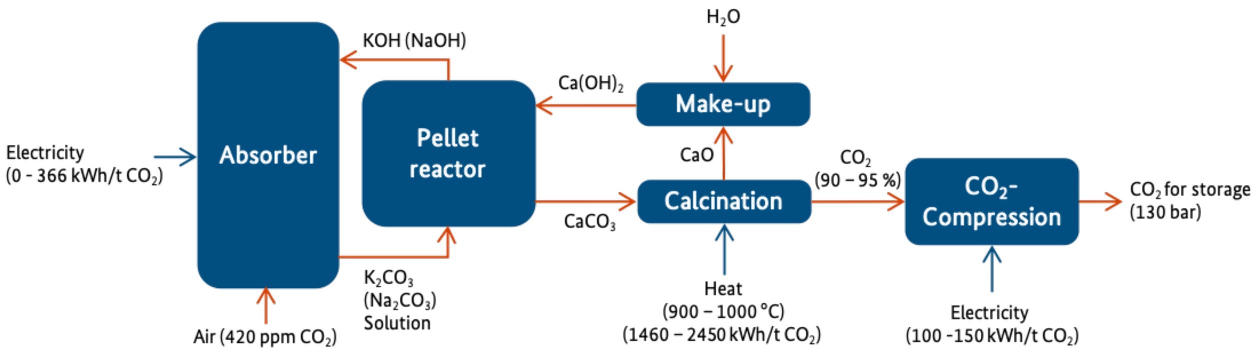
China

The evolution of carbon capture facilities for waste-toenergy plants is predicted to advance in parallel with the overall growth trajectory of CCU/S in China. The inception of such facilities will likely coincide with the maturity of the business model for carbon capture in coal-fired power plants.[28]

Conclusion

Based on the developments in China, the transition from landfilling to waste incineration, the establishment of significant capacities, and the information from Germany regarding the development of thermal waste treatment, it can be assumed that waste incineration will continue in China even in 2060. The implementation of carbon capture technology is suitable for these facilities, as it allows for the separation of fossil emissions to reduce overall emissions, as well as the capture of the biogenic component that can lead to negative emissions.

Figure 10: Process scheme of high temperature direct air capture (absorption-based). Source: dena.



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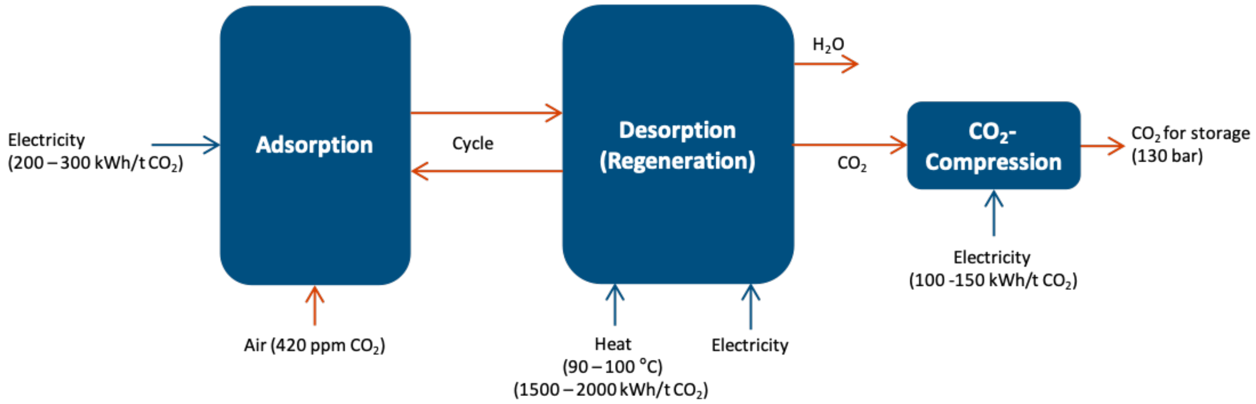
[27] Expert Interview

[28] Presently, only the flue gas carbon capture project at the Pinghu Waste-to-Energy Plant in Zhejiang has undergone a 168-hour assessment and successfully commenced operations in July 2022, serving as a pathfinder project.

3.8 Negative emissions

3.8.1 The need for technical negative emissions

Figure 11: Process scheme of low temperature direct air capture (adsorption-based). Source: dena.



The CCS technology of (technical) capture, transport, and storage is not only an option for reducing hard-to-avoid fossil emissions at stationary point sources but also serves as the foundation for BECCS and DACCS as CCS-based methods for CO_2 removal. A detailed analysis of DACCS and BECCS, along with a comparison with alternative CDR methods, will not be conducted here but is necessary in the future to estimate their potential.

3.8.2 DACCU/S

DACCU/S encompasses technologies that directly capture CO_2 from the surrounding air and enable its storage (DACCS) or utilization (DACCU).

These methods can complement the capture of CO_2 from fixed emission sources, as DAC facilities can be deployed anywhere and remain operational even after phasing out most fossil fuel emissions.

Ideally, DAC facilities are situated near renewable energy sources and CO_2 storage sites to meet their energy requirements and minimize transportation distances (Erans et al. 2022).

In its scenarios, the IPCC includes DACCS as one of the two technological approaches, alongside BECCS, for achieving negative emissions (Shukla et al. 2022). Furthermore, DAC is expected to play a crucial role in providing renewable CO_2 for e-fuels (E4tech 2021).

In DAC processes, CO_2 capture occurs by passing ambient air through fans towards an absorbent substance, known as a sorbent. The sorbent captures CO_2 from the air and, with the application of thermal energy, releases it in a concentrated form (Prognos 2021; Erans et al. 2022). The current methods employed in DAC can be categorized into two main approaches, which differ based on the type of sorbent used (liquid or solid), the temperature requirements for capturing CO_2, and the regeneration method of the sorbent (Prognos 2021).

Absorption-based high-temperature approach

One type of DAC process is the absorption-based high-temperature approach shown in Figure 10. It utilizes an aqueous absorption medium and typically employs a hydroxide-based sorbent with a strong affinity for CO_2, such as sodium hydroxide (NaOH), potassium hydroxide (KOH), or calcium hydroxide ($Ca(OH)_2$).

For example, Carbon Engineering utilizes KOH as the sorbent for CO_2 absorption. In a pellet reactor, in the process potassium carbonate (K_2CO_3) is converted into KOH) and calcium carbonate ($CaCO_3$) by adding $Ca(OH)_2$. Thermal energy is then employed in a calciner to separate calcium carbonate into calcium oxide (CaO) and CO_2. The resulting CO_2 is compressed into a pure stream suitable for utilization or storage, while the calcium oxide is transformed back into calcium hydroxide through slaking with water and returned to the pellet reactor.

It's worth noting that the calcination process requires high temperatures ranging from 900 to 1000°C (Prognos 2021). Carbon Engineering achieves these temperatures by burning natural gas, which fossil CO_2 emissions also need to be captured and stored. The potential use of hydrogen produced from renewable energy sources would reduce the CO_2 emissions generated during the process, but it would significantly increase the overall cost (Keith et al. 2018).

Adsorption-based low-temperature

Adsorption-based low-temperature DAC plants capture CO_2 using a solid sorbent shown in Figure 11. The process involves repetitive cycles of adsorption and regeneration: the sorbent initially captures CO_2 from the surrounding air. Once it becomes saturated with CO_2, the airflow is stopped. In the subsequent step, the sorbent releases the CO_2 and undergoes regeneration for future use. To release the adsorbed CO_2, the sorbent is heated to temperatures of 85 to 100°C.

ClimeWorks, for instance, employs a cellulose fiber filter infused with solid amines that bind CO_2 with ambient humidity. The sorbent releases CO_2 at a temperature of 100°C, and a complete cycle of the ClimeWorks system takes 4-6 h (climeworks 2022).

Conversely, Global Thermostat utilizes an amine polymer adsorbent that releases CO_2 within a temperature range of 85-95°C. Their system operates with shorter cycles lasting only 30 minutes, achieved by using saturated steam under vacuum as both a direct heat transfer fluid and a purging gas (Fasihi et al. 2019).

Current state of development

The DAC technology is still in its early stages of development, with less than 20 facilities globally and a combined capture capacity of around 10 kt CO_2 per year. The largest DAC plant, operated by ClimeWorks, removes 4,000 t CO_2 per year in Iceland, and they are currently constructing a facility with a capture capacity of 36,000 t CO_2 per year (climeworks 2023).

Plans for constructing large-scale DAC plants with a capacity of 0.5-1 Mt of CO_2 exist in countries like the United Kingdom (Dreamcatcher project) and the United States.

Cost estimates for DAC vary widely depending on factors like technology, energy sources, legal frameworks, and reference years. The existing literature provides a range of 100 to 1,000 €/t CO_2 for low-temperature processes and 85 to 465 €/t CO_2 for high-temperature processes. These estimates do not include transportation and CO_2 storage costs (Fasihi et al. 2019).

According to the recent IPCC report, DAC costs range from 92 to 277 €/t CO_2. It is expected that capture costs will decrease and reach below 200 €/t CO_2 in the medium term.[29]

In a net-zero scenario projected by the IEA, it would be necessary to build eight DAC plants per year with a capture capacity of 1 Mt CO_2 per year by 2030, followed by increased plant construction in the subsequent decades. Scaling DAC to this extent would require substantial water and energy resources.

It is expected that DAC plant construction is economically viable in regions with low energy and capital expenditure costs, such as the Middle East, according to the IEA.

Conclusion for Chinese context

According to IEA (2021) and Liu et al. (2022), the deployment of DAC is also necessary in China to offset residual emissions and achieve the goal of carbon neutrality by 2060. This is attributed to remaining emissions from the industrial, transportation, building, and energy supply sectors, as well as emissions that will persist in the LULUCF sector in China. A more precise estimation is not available based on current knowledge.

Drawing from insights in Germany, it is evident that offsetting these emissions cannot be achieved solely through natural negative emissions, and the implementation of technical negative emissions is required.

3.8.3 BECCS

Problems with biomass

When using biomass, it is crucial to ensure that the biomass is sustainably cultivated. Often, the cultivation of biomass for energy purposes competes with its use for food production or leads to the depletion of existing ecosystems, resulting in far-reaching consequences for local ecosystems, biodiversity, and significant CO_2 emissions. For this reason, biomass is categorized into generations (as outlined in chapter 3.5.4).

Lastly, residues and waste products should be mentioned, which can also be classified as sustainable as long as efforts are made to minimize them during production.

At the same time, there is also competition in the utilization of biomass among different sectors, as cultivated biomass, such as wood, can be used for various applications. It is essential to ensure that biomass is utilized in a cascade manner to unlock the highest climate protection potential. Such a cascade is depicted in Figure 12.

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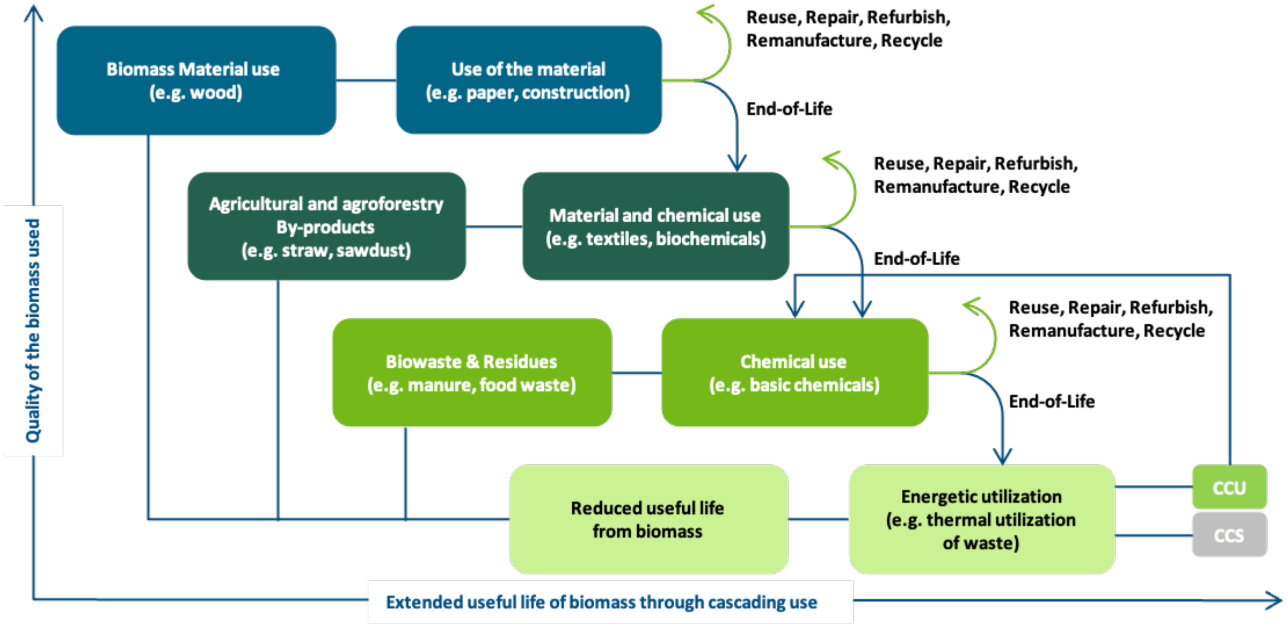
[29] Adsorption-based low-temperature DAC processes have the advantage of utilizing renewable and waste heat sources for the required temperatures. The use of waste heat reduces energy costs, and when heat pumps are employed, external heat sources are not necessary, allowing facilities to be fully powered by electricity. Low-temperature DAC plants also do not require a water connection, providing flexibility in their location. These plants can be integrated into future renewable energy-based energy systems.

Figure 12: Biomass cascade. Based on Agora Industry & Carbon Minds 2023.



Potential use of CCU/S for biomass

CCU/S can also be applied to processes using biomass. Some of these processes utilize first-generation biomass and, therefore, should be considered unsustainable, but they are still presented for completeness. As mentioned above, energy utilization should only be considered as a last resort. Consequently, it is reasonable to capture CO_2 in such facilities.

Biogas / Biomethanation

The utilization of moist biomass as a preferred substrate in the fermentation process is a common practice. This process allows for the conversion of various types of residues and waste materials, including manure, the biogenic fraction of household waste, products from paludiculture, and macroalgae biomass (seaweed).

Typically, the obtained biogas consists of approximately 50-60 % methane, with the remaining portion primarily composed of carbon dioxide (Fischedick et al. 2015). Such biogas represents a valuable energy resource that can be harnessed for energy purposes. Biogas can be subjected to upgrading to produce biomethane, which involves the separation of CO_2 to attain methane concentrations of approximately 95 %. This process enables the efficient capture of CO_2 with comparatively minimal effort (Klepper and Thrän 2019).

Bioethanol

The process of fermentation offers the potential for the conversion of diverse input materials, including carbohydrates, fats, proteins, cellulose, or hemicellulose (lignin) into valuable products. Through anaerobic fermentation, biogas can be generated, while alcoholic fermentation yields bioethanol/butanol.

It is important to note that during biomass fermentation, CO_2 is produced as a byproduct, and further emissions of CO_2 occur when the fermentation products are combusted. However, it is worth emphasizing that in all cases, there exists the possibility of capturing and separating the CO_2 produced (Klepper and Thrän 2019).

Syngas

The gasification of biomass provides the opportunity to produce synthesis gas from which CO_2 can be separated. The advantage of this process is that woody biomass (2nd generation) can be utilized (Klepper and Thrän 2019).

Various products can be generated: the synthesis gas can be used as a fuel or utilized for the production of liquid fuels or chemical feedstocks. Gasification is a well-established technology for obtaining synthesis gas from fossil fuels and waste materials (Borchers et al. 2022).

Pyrolysis

Lignocellulosic biomass can be introduced into pyrolysis facilities. The process of pyrolysis is decribed in chapter 3.5.4. The objective of fast pyrolysis is the production of pyrolysis gas and oil. The resultant CO_2 could be captured. In contrast, biochar derived, especially from slow pyrolysis, can serve as both a raw material in the industrial sector and a long-term carbon reservoir, concurrently enhancing soil fertility (Borchers et al. 2022).

Pyrolysis constitutes an established and extensively investigated technology pertinent to both biogenic and fossil fuels. A diverse array of providers already offers small and medium-scale technologies (Borchers et al. 2022).

Paper- and Pulp industry

In fiber and paper production, waste with a high biogenic content is generated, particularly black liquor.[30] Currently, this waste is already incinerated in the facilities of fiber and paper production to provide process heat.

Biogenic part of waste-to-energy

In waste incineration plants, the waste consists of a mixture of biogenic and fossil waste. During combustion, both fossil and biogenic emissions are generated. Therefore, the capture of biogenic emissions is a potential source for BECCS or BECCU.

Combustion of biomass for energy generation

During the combustion of biomass for the generation of electricity or heat, CO_2 is also produced, which can be captured and considered for storage or utilization.

Discussion

Various processes can be considered for the energetic utilization of biomass. Accordingly, a prioritization can also be made, depending on the intended use of the biomass. If material utilization is given priority, biomass should be subjected to gasification or pyrolysis. In this context, the question arises whether CO_2 or solid carbon should be produced. The carbon generated during pyrolysis can be used for negative emissions, as can the resulting CO_2. Furthermore, it is open for debate whether the biogenic CO_2 should be primarily used for the production of products (BECCU) or for generating negative emissions through storage (BECCS). As a result, there are conflicts in usage regarding end-of-life utilization and the use of biogenic CO_2.

Conclusion for Chinese context

China has limited potential for sustainable biomass, which is why a cascade utilization approach is recommended. Until a strategic determination for biomass utilization is established, making specific recommendations beyond the discussed aspects is not recommended. Certain sectors, such as the cement and steel industries, are likely to use biomass for decarbonization. However, a recommendation cannot be derived solely from this aspect; all necessary areas must be considered. Overall, it can be concluded that BECCU/S will play a role in China, as it is required for the defossilization of the chemical industry (BECCU) and for negative emissions (BECCS) to achieve climate protection goals.

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[30] Black liquor is generated during the paper production process by dissolving fibers from lignin. Black liquor is thus a byproduct that is currently primarily burned in boilers to produce energy.

4

CCU/S Technologies

4 CCU/S Technologies

Below, the essential information on CCU/S technologies is presented. The insights are based on existing analyses.

4.1 CO_2-Capture

The following section presents findings from Europe and Germany, offering insights into the development status and costs of ongoing carbon capture projects. These insights are then contextualized for their relevance to China. The technologies are divided into Pre-Combustion, Oxyfuel, and Post-Combustion methods. An analysis of the overall costs, including transport and storage, can be found at the end of this chapter. This chapter serves primarily to qualitatively assess the respective technologies.

4.1.1 Pre-Combustion

Pre-combustion processes are characterized by the fact that the CO_2 is already separated before the actual process (see Figure 14). Preliminary physical processes are used for this purpose due to the increased pressure. Separation rates of up to 95 % can be achieved with these processes.

The advantages of physical scrubbing at higher pressure compared to chemical absorption are the lower power or heat consumption required for regeneration, since no chemical compounds are broken. Physical solvents are non-toxic and only slightly hazardous to the environment.

Areas of application can be synthesis gas production, in the conversion of biomass in the context of BECCS as well as in chemical processes. A possible application option with an already existing commercial plant is the use in IGCC power plants.

Steam cracker

The pre-combustion and post-combustion methods offer the possibility of future greenhouse gas-neutral production of olefins and aromatics in steam crackers (see Figure 13 & Figure 15), provided that GHG-neutral feedstocks are used in the future; otherwise, the fossil Scope 3 emissions of the products will remain.

Overview of capture processes

Adsorption process

Molecules adhere to the surface of a substance due to physical forces (Van der Waals forces). A chemical bond is not formed in this process.

Absorption process - Chemical

Absorption is the dissolving of gases and vapors in a liquid or solid. Chemical absorption requires additional third components in the detergent. These components form a chemical bond with the substances to be absorbed.

Absorption process - Physical

The binding of the substance to be absorbed takes place via intermolecular forces, usually Van-der-Waals forces. Compared to chemical absorption, no chemical reactions occur.

Gas-solid reactions

Solid alkaline earth oxides are often used in the processes and are converted into carbonates in a chemical reaction with CO_2. The process takes place in two process stages.

Cryogenic process

In cryogenic processes, the CO_2 is physically separated from the flue gas by sublimation, condensation or distillation. The basic requirement for the process is that the sublimation and condensation temperature is higher than that of the other gas components, otherwise impurities will occur.

Membrane

The membrane process uses the fact that atoms and molecules can be retained or allowed to pass through the pores of the membrane. This depends on the selected membrane material. The separation is purely physical. One advantage of the process is that hardly any thermal energy is required.

Figure 13: Steam Cracker with Post-Combustion carbon capture. Source: dena.

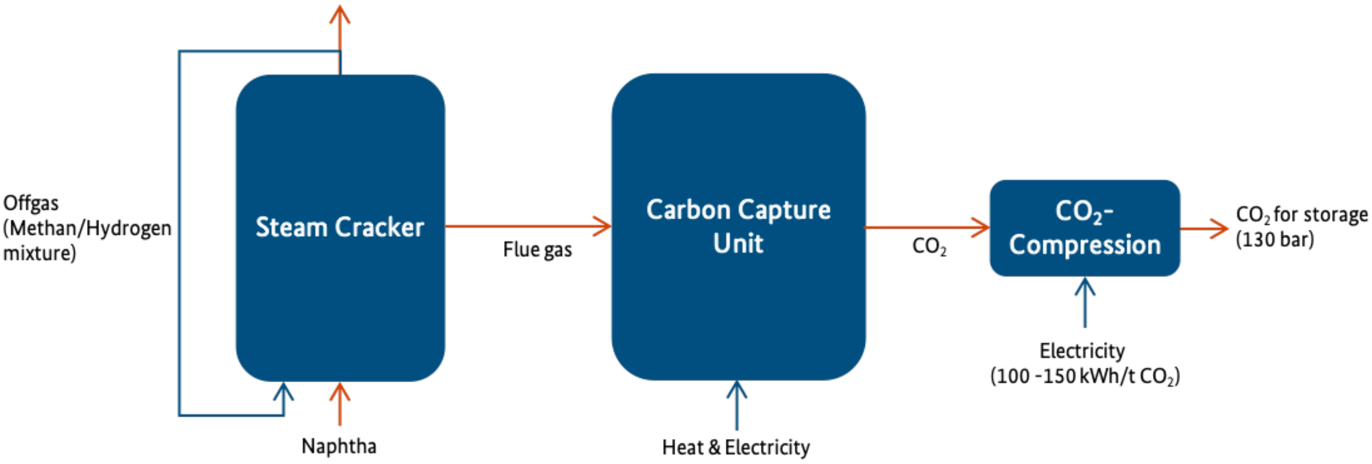
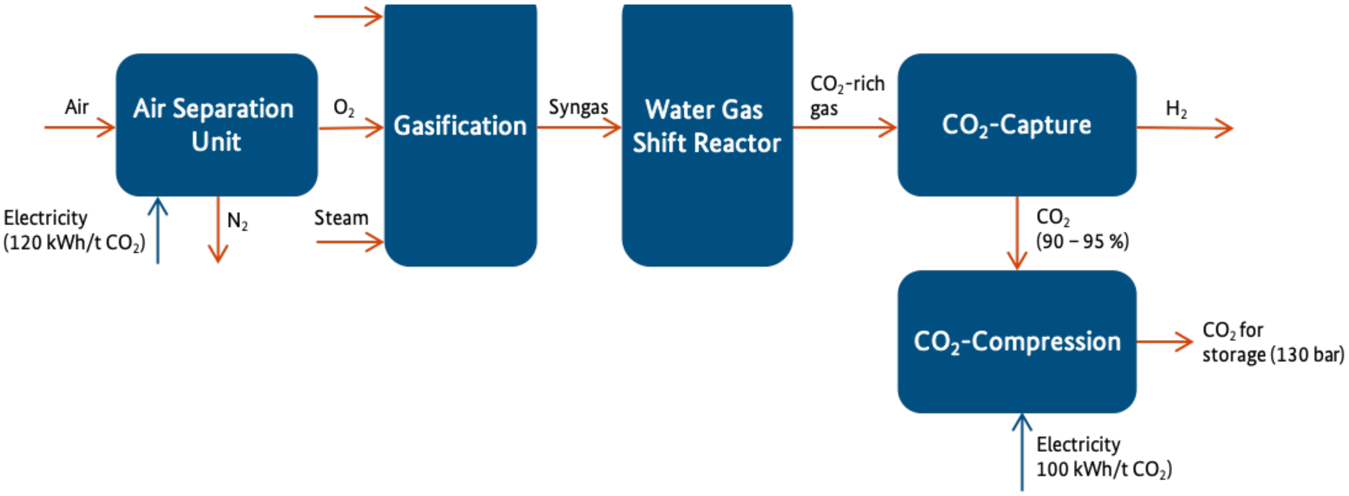


Figure 14: Process scheme Pre-Combustion. Source: dena.



As described in chapter 4, steam crackers produce products like ethylene and others, as well as off-gas. The off-gas can be converted with pure oxygen through partial oxidation or autothermal reforming (POX/ATR), producing a mixture consisting mainly of H_2 and CO_2. The CO_2 is separated and the H_2 can be used to provide energy for the process. As mentioned above, the pre-combustion method may require some modifications to the crackers (indicated by the red boxes).

In electrification, the off-gas continues to be produced, making the described conversion in POX/ATR with subsequent CO_2 capture a viable option to reduce emissions. If the feedstock is biogenic (sustainable), there is an option to generate negative emissions through the process.

In the post-combustion method, the challenge lies in finding a technically efficient way to separate CO_2 from the flue gas. The flue gas contains not only oxygen but also nitrogen oxides. Both components have a negative impact on amines used for CO_2 absorption and lead to amine degradation. There are various developments investigating solvents without amines for separation.

Due to the high CO_2 content in the exhaust gas, Global CCS Institute (2023) estimates low CO_2 capture costs for the pre-combustion method, ranging from 20 to 50 €/tCO_2 (Global CCS Institute 2023). On the other hand, operators estimate capture costs of up to 140 €/t CO_2 for both pre-combustion and post-combustion methods. According to current knowledge, retrofitting costs are approximately 500 million to 1 billion € for a cracker emitting 1 Mt CO_2 per year.[31] Operational costs can vary significantly, requiring a holistic assessment based on site-specific conditions.

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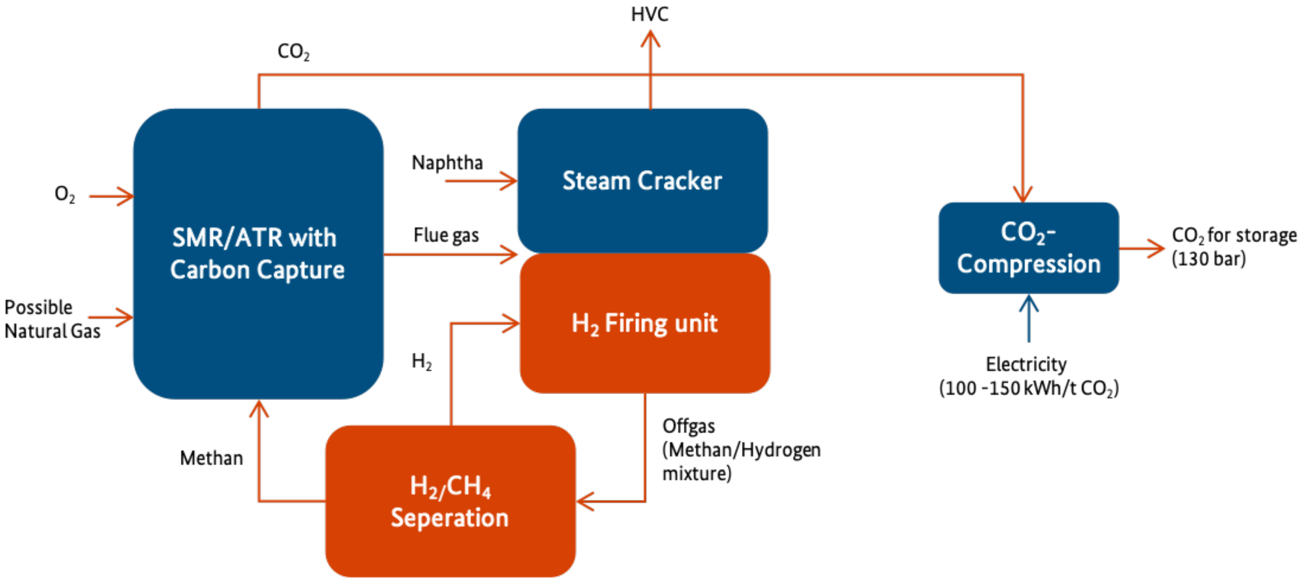
[31] Expert Interview

Figure 15: Steam Cracker with Pre-Combustion carbon capture. Red boxes show the processes which are modified for the process. Source: dena.



The choice of a method should be made based on overall efficiency considerations and depends on site-specific conditions.

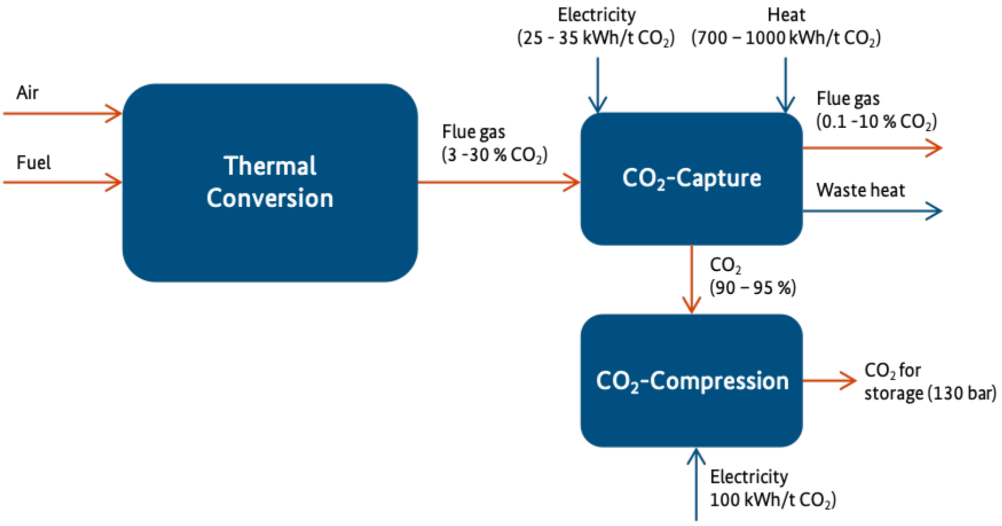
Summary with focus on Chinese perspective

Within the petroleum and chemical industries, the range of carbon dioxide concentrations emitted varies considerably (10 %-55 %).

For the primary sources of carbon dioxide emissions in the chemical industry, frequently used mainstream carbon capture technologies include Pre-Combustion processes such as physical solvent absorption. From a cost perspective, low-temperature methanol washing has emerged as a preferred choice with costs ranging from 72-74 RMB/t CO_2.[32]

Considering the high concentration of CO_2 (surpasses 80 %) captured by coal-to-hydrogen plants, the related cost of carbon capture is relatively low. Based on current rates of equipment, raw materials, energy, and labor costs in China, the CCS project cost for coal-to-hydrogen is 292 RMB/t CO_2. The costs for capture, transportation (assuming a distance of 200 km), and storage amount to 194 RMB/t CO_2, 65 RMB/t CO_2, and 33 RMB/t CO_2, respectively.[33]

Figure 16: Process scheme Oxyfuel carbon capture. Source: dena.



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[32] Expert Interview

[33] Expert Interview

4.1.2 Oxyfuel

The basic process step in the oxyfuel process is the reaction of the fuel with pure oxygen (see Figure 16). The reaction with pure oxygen results in a purely relative homogeneous exhaust gas consisting of CO_2 and H_2O. The water content can then be condensed out with low (energetic & process) effort via a compression and purification unit. Combustion with pure oxygen results in special requirements for the respective industrial and power plant processes. On the one hand, the use of oxygen results in significantly higher temperatures, which are accompanied by demands on the materials. This is due to the elimination of heat absorption by nitrogen. To reduce the temperatures, exhaust gas can be recirculated. In this process, 60-70 % of the cooled flue gas is recirculated (Danish Energy Agency 2021). For this reason, it is necessary to consider the plant location in order to decide to what extent retrofitting and new construction with integrated oxyfuel technology is possible (CEMCAP 2019; Prognos 2021).

The most important component of the technology is the air separation unit (ASU), which provides almost pure oxygen. Air separation is an energy-intensive process and determines the efficiency of the method (Danish Energy Agency 2021; Prognos 2021).[34] The oxyfuel process differs significantly in its changes on the process for power plant processes as well as for the cement industry.

Oxyfuel in different industries

In cement plants, the use of the oxyfuel process is possible, but leads to in-process adjustments due to the much more integrated process (calcination, clinker burning, clinker cooling, etc.). The conditions during combustion change and a large part of the flue gas is reused. This leads to a change in the cement kiln process. The gas atmosphere in the clinker cooler, the rotary kiln, the calciner and the preheater is changed. However, this does not preclude a retrofit of the process.

The oxyfuel process requires additional energy compared to a plant without separation, mainly for the ASU and the compression purification unit (CPU). Part of this energy requirement can be used to recover the waste heat (Danish Energy Agency 2021).[35]

TRL + projects

Project K6 (France) - The K6 project in Northern France is a CCS project utilizing the oxyfuel process in a cement plant (production capacity of 0.8 Mt per year) operated by EQIOM. The facility is expected to start operating in 2028. Separation rates of 95 – 98 % are anticipated (European Commission 2022a).

Project Everest (Germany) - At the largest lime plant in Europe, the company Lhoist plans to capture up to 1.6 Mt of CO_2 in the Everest project. The first 0.4 Mt are scheduled to be captured by 2028. The site will feature the first oxy-combustion lime plant (Air Liquide), constructed alongside a new Maerz kiln. The project aims to raise the oxyfuel process for lime plants to TRL 9.

Project Catch4Climate and Westküste 100 (Germany) - The Catch4Climate project aims to demonstrate an advanced oxyfuel process, the so-called polyisus® pure oxyfuel process. A key feature is the elimination of a CO_2 recirculation line.

The Westküste 100 project is an interdisciplinary initiative aiming to produce hydrogen through electrolysis, which will be combined with CO_2 from a cement plant to produce methanol. The methanol will then be processed into gas, gasoline, and kerosene (Westküste100 2023).

The CO_2 capture as part of the Westküste 100 project will be the first full-scale project capturing CO_2 from a cement plant using the oxyfuel process. After commissioning, the TRL will be 8. The plant is expected to start operating in 2027.

Costs

The capture costs are estimated at approximately 45 - 62 €/t CO_2. Other cost estimates range from 60 - 100 €/t CO_2 for greenfield plants. The cost estimate includes transportation and storage costs of 45 €/t CO_2. Due to different site conditions and the associated differences in operating costs, relatively large variations of +/- 25 €/t CO_2 are possible.

For brownfield plants (retrofitting), estimating costs for the oxyfuel process is very difficult due to the high diversity of technical options. This assessment is shared by various experts who consider retrofit measures to be particularly CAPEX-intensive. In these cases, new construction may be more beneficial.

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[34] The oxyfuel process can have synergies with the production of hydrogen via electrolysis, as pure oxygen is produced within the process

[35] The waste heat can be used to generate electricity via an Organic Rankine Cycle (ORC) or, if possible, fed into a district heating network.

Summary with focus on Chinese perspective

The use of oxyfuel technology is particularly relevant for new constructions. It is predicted that cement demand in China will significantly decrease in the future. Therefore, it is questionable how the number of new cement plants will develop; a lower expansion is to be expected as the age structure, similar to the steel industry, is still relatively young (25 years). Consequently, the oxyfuel process is likely to be initially implemented in a limited number of projects.

In theory, oxyfuel technology holds significant potential in China, but its practical application is currently immature. The implementation of oxyfuel technology necessitates the construction of new units, yet few such units are being constructed at present. Furthermore, oxyfuel technology is not considered during the design phase of these new units, leading to a missed "window period" for its implementation.

4.1.3 Post-Combustion

Post-combustion processes are end-of-pipe technologies and can be retrofitted to power plants and industrial facilities. The advantages of retrofitting are shorter periods of time, the elimination of investment costs for a new construction of the entire plant. Furthermore, the proportion of existing plants is significantly higher than that of planned new plants (see Figure 17).

Chemical absorption (amine scrubbing)

In the amine scrubbing process, CO_2 is absorbed using an aqueous solution of amines, such as monoethanolamine (MEA). Other substances that can be used include ammonia, alkali carbonates, amino acid salts, and ionic liquids. The saturated amine solution is then heated in a separate part of the plant at temperatures of about 120 – 150°C, releasing the CO_2 (Fischedick et al. 2015). On a dry basis, the CO_2 purity is typically at least 99.9 % by volume (Danish Energy Agency 2021). A reduction of over 90 % of CO_2 emissions at a point source is achievable using amine scrubbing (Danish Energy Agency 2021).

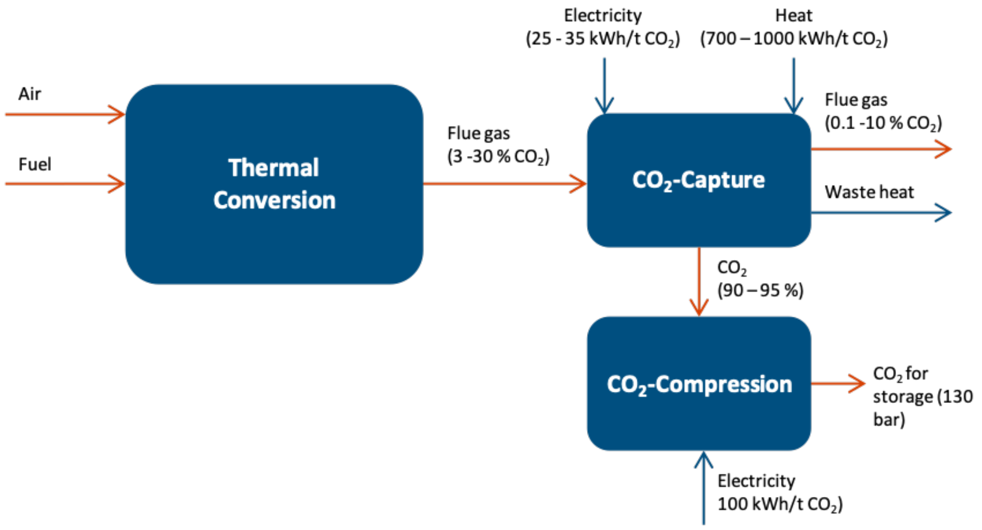
The use of amine scrubbing is possible for all major industries. Possible limitations may arise from a detailed analysis of site conditions and process conditions. Amine scrubbing is flexible regarding the flue gas source (waste, biomass, etc.) and the composition of the flue gas (CO_2 content typically ranging from 3 to 30 %). Therefore, the process is well-suited for retrofitting existing plants.

Technical requirements

The amine washing process is an energy-intensive process. The largest energy demand is for steam generation. The heat demand for the separation is between 700 - 1000 $kWh_{th}/t\ CO_2$, and the electricity demand is between 25 - 35 $kWh_{el}/t\ CO_2$ according to the Danish Energy Agency (2021). In the literature, a commonly cited value for the heat demand of approximately 1000 $kWh_{th}/t\ CO_2$ is often used for amine washing with MEA (Jakobsen et al. 2017; Markewitz et al. 2019; Beiron et al. 2022; Nina Svinhufvud 2022).

According to experts, this value can vary depending on the solvent used and internal heat optimization, ranging from approximately 600 to 1200 $kWh_{el}/t\ CO_2$. The electricity demand for the process can vary depending on the solvent between about 50-800 $kWh_{th}/t\ CO_2$. Additionally, for conditioning/preparation, approximately 150 $kWh_{el}/t\ CO_2$ on average is required for compression. Further 100 $kWh_{el}/t\ CO_2$ is needed for liquefaction.

Figure 17: Process scheme Post-Combustion carbon capture. Energy demands refer to amine scrubbing. Source: dena.



Efficiency Potentials

Heat optimization holds significant potential for increasing the efficiency of amine washing. This includes utilizing waste heat from a pre-treatment process (e.g., thermal energy from exhaust gas, integration of steam from a thermal waste treatment plant) (Danish Energy Agency 2021).

Furthermore, there are various other options for reducing the thermal energy demand of the process, including mechanical steam compression, intermediate cooling in the absorber, or internal heat integration (Danish Energy Agency 2021; Eliasson et al. 2022).

Projects in Germany/EU + TRL

The process is already being used on an industrial scale, for example, for carbon capture at power plants. Long-term experience comes from its use in the food industry, gas purification processes, and the chemical industry. The TRL is 9 (Danish Energy Agency 2021).

Brevik - The demonstration project at the Brevik (Norcem) cement plant in Norway plans to use amine scrubbing to capture about 400 kt CO_2 per year (half of the emissions). (Danish Energy Agency 2021).

Twence Waste Incineration Plant, Hengelo - As part of a CCU demonstration project in the Netherlands, the amine-based separation plant at the waste incineration plant in Hengelo with a CO_2 capture capacity of 100 kt CO_2 per year, has been operational since 2019 (Carbon Capture Journal 2021).

AVR Duiven - In Duiven, a plant has been in operation since 2019. The facility is a thermal waste treatment plant, capturing 100 kt per year through amine washing with MEA as the sorbent.

CAP2U Project Lengfurt - In Lengfurt, at the cement plant of Heidelberg Materials, a separation plant using the OASE® blue process from Linde is planned and currently under construction. The capture capacity of the plant is designed for 70,000 t CO_2 per year. The plant is expected to be operational by 2025. Within the project, the waste heat from the exhaust gas is utilized for the separation process, eliminating the need for additional thermal energy for the capture.

In conclusion amine scrubbing is commercially available, but research is still ongoing. Process plant providers are also starting to develop optimized plants. The potential for reducing CAPEX is considered significant, as these investigations have not been conducted due to market uncertainties (Danish Energy Agency 2021).

Costs

The costs for amine washing (WtE and cement) according to experts vary depending on energy demand and other factors such as plant size, CO_2 concentration in the exhaust gas, and purification quality, ranging from 70 to 130 €/t CO_2. Additionally, there are costs for storage and transportation.

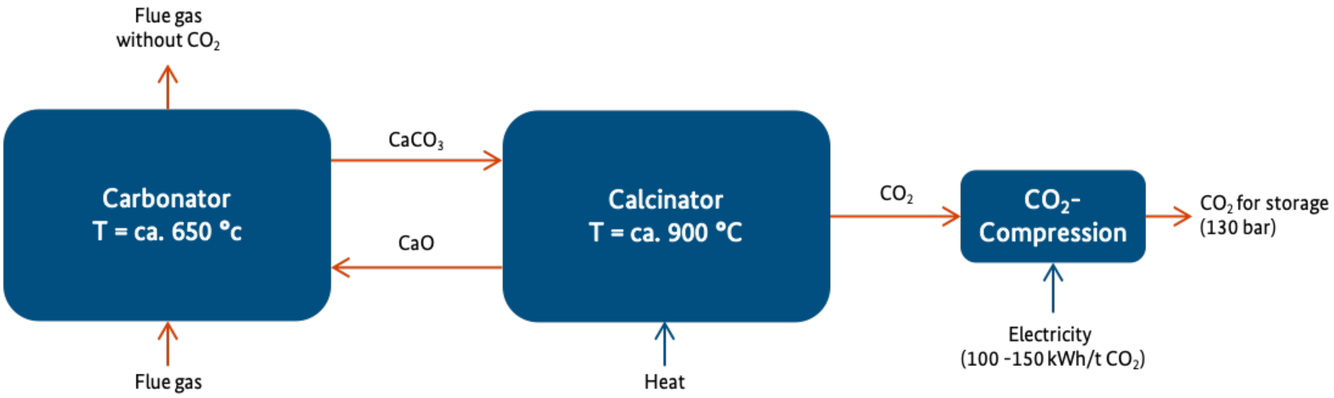
Summary with focus on Chinese perspective

In China, amine scrubbing is already utilized in various demonstration projects. Since amine scrubbing represents the separation technology with the highest TRL and the most practical experience, it can be assumed that this technology will be employed both in the short and long term. Particularly, improvements in the energy requirements of amines as well as further efficiency gains could lead to a significant reduction in the costs of amine scrubbing.

Carbonate Looping (CaL)

In Figure 18 a simplified process scheme is shown. CO_2 reacts with CaO in a reactor to form $CaCO_3$. The $CaCO_3$ then flows into another reactor where it is thermally separated back into CaO and CO_2. The CO_2 is then directed for compression. The necessary temperatures for the process can be found in the figure. The resulting CaO can be recycled back into the first reactor. The process allows for separation rates of 90 %.

Figure 18: Process scheme Carbonate Looping. Source: dena.



Technical Requirements

The process requires a high temperature level (650 - 900 °C). The flue gas temperature at the entrance to the carbonator can vary, for example, it can range from 20-200°C (typical temperature ranges of various industrial processes), making the process retrofitable to all production plants or power plants. The temperature at the carbonator entrance can be even lower or higher, and the process would still function. The optimal carbonator operating temperature of 650°C is determined by the exothermic reactions of CaO with CO_2 to form $CaCO_3$.

Feastibility for different industries

The process can be used in various plants, with the high temperatures enabling synergies in power plants and industrial facilities that already have high temperatures. In the cement industry, there is the option to employ the process in two different configurations. The process can be used as both end-of-pipe technology and integrated technology, where, simplistically, the calciner for CO_2 capture is combined with the precalciner of the cement plant. Furthermore, using the process in cement plants offers synergies since CaO is already present. Its application in waste incineration plants is also possible, but the CO_2 stream would need to be cleaned of chlorine.

TRL

The process is being tested in pilot plants that consider industrial conditions (1 MW). Further investigations are underway on an industrial scale (>100 MW). The process has been studied for cement plants as part of the CLEANKER project. The TRL is classified as 6-7.

When constructing a large-scale plant, a construction period of 3 years is expected until the plant becomes operational. This is partly because existing components such as fluidized bed reactors are used, which are already employed on a large scale in other applications.

Costs

Within the SCARLET project, avoidance costs and capture costs for the application of the Carbonate Looping process at cement plants have been calculated. The capture costs amount to 15.8 €/t CO_2, and the avoidance costs amount to 27.6 €/t CO_2 (Ströhle et al. 2017). Compared to amine scrubbing (MEA), the costs are initially higher due to higher CAPEX.

As part of the SCARLET project, the costs for CO_2 capture at a 600 MW coal-fired power plant have also been examined. The capture costs amount to 15.4 €/t CO_2, and the avoidance costs amount to 20.2 €/t CO_2. The efficiency reduction at full capacity is 3.5 %, and if compression is included, it is 7 %. At lower capacity, these values decrease to 4.9 % / 8.6 %.

The higher investment costs are partly due to the installation of a waste heat steam power plant that utilizes the waste heat for electricity production. When Carbonate Looping is retrofitted to a 100 MWel power plant, an additional 50 - 80 MWel can be generated. Through the sale of the extra generated electricity, a cost advantage over amine scrubbing is expected to be achieved within a few years. Another advantage of the process is that limestone (CaO) is available in large quantities and at favorable prices on the global market.

Summary with focus on Chinese perspective

The retrofit capability and significantly lower avoidance costs due to electricity generation compared to amine washing make the process a very attractive alternative for CO_2 capture at coal-fired power plants. The application has so far only been studied at 20 MW plants; therefore, a demonstration project would be necessary to confirm its commercial viability.

Membrane-assisted liquefaction (MAL) process

The basic principle behind the use of membranes has already been introduced in Chapter 4.1. It can be divided into gas separation membranes (gas/gas membranes) and gas absorption membranes (gas/liquid membranes). The separation rate is between 60-80 %.

Technical Requirements

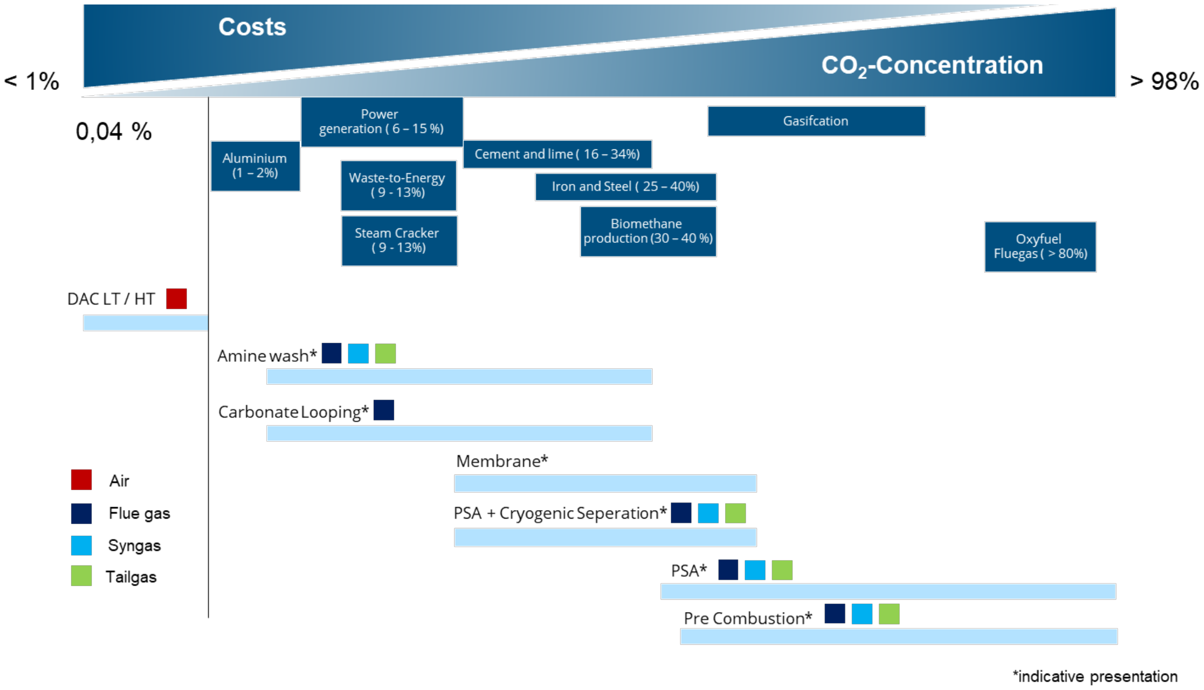
The biggest challenge in membrane technology is the low CO_2 partial pressure in the flue gas. This makes it challenging to generate a driving force (CO_2 pressure gradient) for CO_2 transport through the membrane. This is resolved by compressing the flue gas and/or maintaining a high vacuum on the permeate side (CO_2 side) of the membrane. Both methods result in significant power consumption (Danish Energy Agency 2021).

A separate process is considered for the cement industry, where CO_2 liquefaction is combined with polymer membrane technology - membrane-assisted CO_2 liquefaction. Polymer membranes are used for CO_2 separation, resulting in moderate product purity. This CO_2-rich product is then fed into the liquefaction process. By liquefying the CO_2, the more volatile impurity components can be removed, resulting in a highly pure CO_2 product (CEMCAP 2019).

TRL

The CO_2 separation with membranes has a low TRL for flue gas and is better suited for gas separation under high pressure (Danish Energy Agency 2021). According to ECRA's assessment, the TRL is 4-5.

Figure 19: Overview of suitable carbon capture processes for certain CO_2-concentrations. Figure is based on Global CCS Institute (2023).



Projects

Holcim/Helmholtz-Hereon at Höver Cement Plant - The capture process is based on Hereon's PolyActive membrane technology. An initial test phase of the capture plant began in early 2022. In beginning of 2024, a second test phase will commence, aiming to evaluate the long-term operation over a year. The plan is to expand the plant in two further phases and capture 170 kt per year from 2024 and 1.3 Mt per year from 2026. In the final phase, over 90 % of the carbon dioxide emissions should be captured (Global Cement 2021).

Costs

The avoidance costs range from 45 to 50 €/t CO_2. If the technology is further developed, costs of 25 €/t CO_2 or less are expected.

Summary with focus on Chinese perspective

The deployment of the technology is still associated with high uncertainties due to its low TRL. Further research is needed. Accordingly, for the first installations in China, it should be considered of lower relevance.

Cryogenic Capture and Pressure Swing Adsorption

In this process, the exhaust gas is first cooled and compressed before being directed into a Pressure Swing Adsorption (PSA) unit. The separation effect of the method is based on the different adsorption constants of the components, with the pressure swing being the driving force. The higher the partial pressure difference, the better the process works. The process allows for capture rates of 99 %. Purity levels of 99.9 % and higher are possible. This process is a commercially available carbon capture technology offered by Air Liquide (Cryocap™) and Linde (HISORP® CC) (Global CCS Institute 2022c).

Technical Requirements

The process requires only electrical power, making it particularly attractive when combined with electricity from renewable sources. The costs decrease disproportionately with an increase in the CO_2 flue gas concentration in a range of 16 - 25 % CO_2 per percentage point increase in the exhaust gas CO_2 content. The process has an approximately 2 to 2.5 times higher power demand than the specified energy requirement for the Oxyfuel process (200 - 220 $kWh_{el}/t\ CO_2$).

TRL of the technology

Currently, processes with adsorptive CO_2 separation and cryogenic purification are in commercial operation.

Costs

The costs (CAPEX + OPEX) for the CryocapTM FG process are estimated by Air Liquide to be in the range of 40 - 80 €/t CO_2 (Global CCS Institute 2022). The HISORP® CC process by Linde falls within a similar range.[36]

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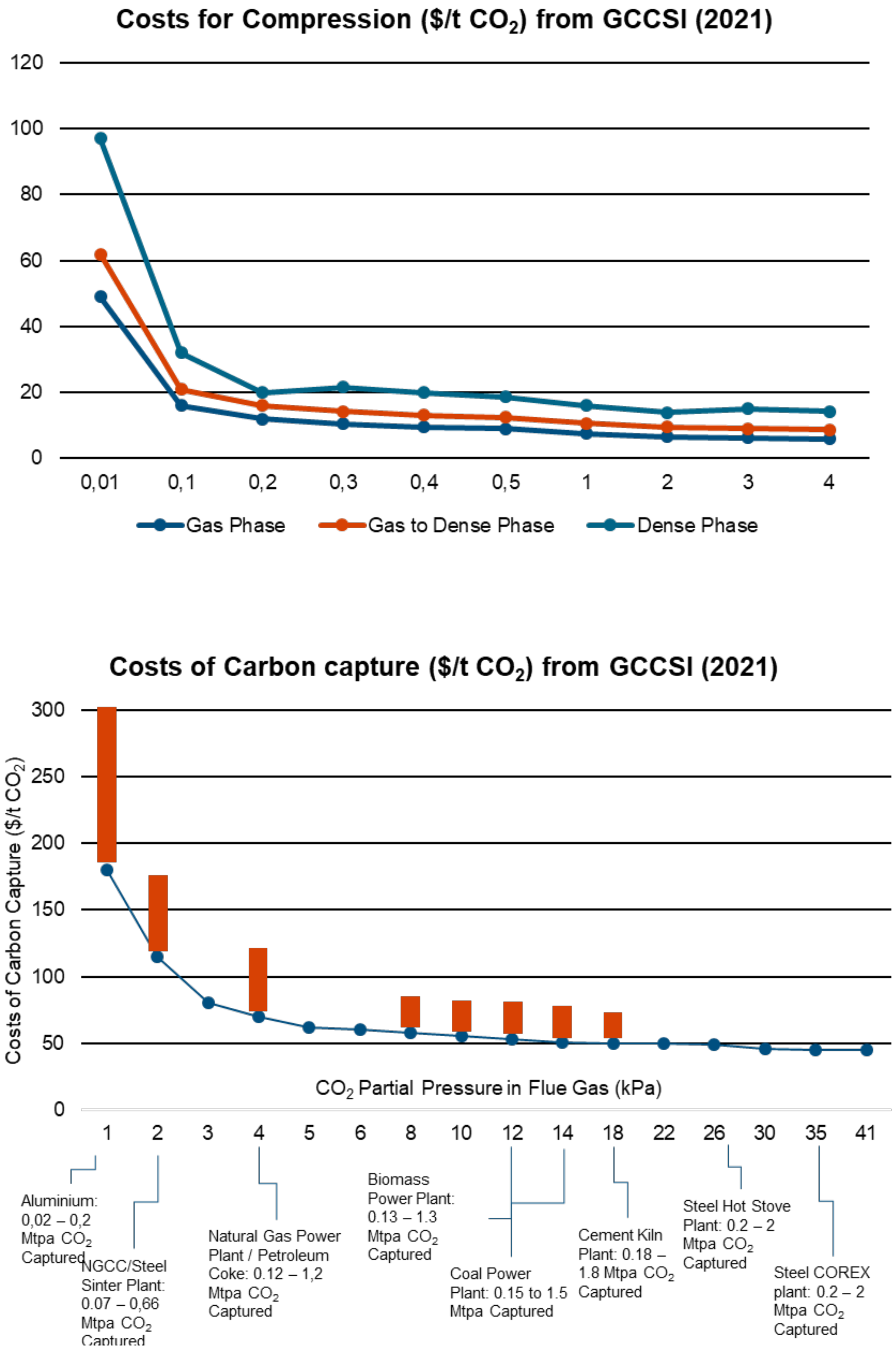
[36] Expert Interview

Figure 20: Overview of the effect of the plant size and CO_2-concentration on the costs of carbon capture. Figures are derived from Global CCS Institute (2021a, 2021b).



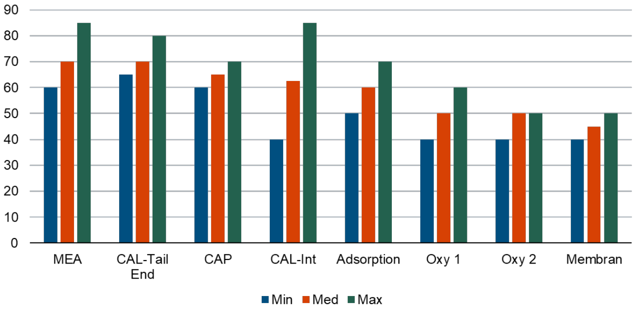
Summary with focus on Chinese perspective

The use of this technology is particularly suitable for processes with CO_2 concentrations above 20 %. Given the high proportion of coal in the power grid, its initial implementation may be considered less prioritized. However, for specific facilities, it may be feasible when renewable energy is readily available at low costs.

4.1.4 Cost comparison

From Figure 19, it can be observed that the use of different separation technologies is suitable for specific CO_2 concentrations (Global CCS Institute 2021a, 2021b). Therefore, there are processes that can capture CO_2 at lower costs due to the lower CO_2 partial pressure in the exhaust gas when dealing with lower concentrations. However, these processes have a disadvantage compared to processes that can capture CO_2 more efficiently at higher concentrations. For this reason, comparing the technologies without reference to the CO_2 concentration or the corresponding industry with its specific CO_2 concentration range is not advisable. Figure 21 illustrates the costs of separation at cement plants for various technologies. Despite the improved comparability, it should be noted that site-specific conditions do not allow for a blanket statement about which is the most cost-effective separation technology.

Figure 21: Cost comparison of different carbon capture technologies in the cement industry.



In general, it can be concluded that sources with high CO_2 concentrations have the lowest costs. This effect is particularly noticeable at very low concentrations, as can be seen in Figure 20. Furthermore, the size of the facility plays a crucial role. Costs for separation, compression, and pipeline transport are significantly higher until emission quantities reach 100 kt. This is exemplified in Figure 20 for compression as well.

4.1.5 Cost evaluation for power plants

The following chapter was created by the "Energiewirtschaftliches Institut an der Universität zu Köln (EWI)" - Energy Economics Institute at the University of Cologne (EWI) as part of the project. EWI's objective was to examine the deployment of Carbon Capture at coal-fired power plants in China through a techno-economic analysis. Initially, this analysis examines the impact of CC on the LCOE and then compares it to renewable alternatives. Below, the basic assumptions and their derivation for the calculations are explained.

Geographic dimensions

A retrofit of an existing plant can only be economically reasonable if the plant produces sufficient electricity, i.e., if the operating hours exceed a certain threshold to recover its fixed costs. Therefore, higher utilization of a plant corresponds to lower levelized cost of electricity (LCOE) supply.

Few studies investigate the regional suitability for retrofitting coal-fired power plants with CCS. IEA (2016) define the following criteria as suitable for a retrofit with CC:

- Age <= 40 years in 2035
- Size >= 600 MW or >= 10 Mt.CO_2 pa.
- Load factor >= 50 %
- Distance to storage <= 800 km
- Location: No regional coal phase-out

IEA (2016) find that about 55 % of Chinese coal-fired units are suitable for a retrofit with CCS given these criteria. The highest potentials occur in the East and Northeast of China due to high plant densities and close location to storage sites, whereas the southeastern coastline and West yield rather low potentials. Eastern China also has the lowest levelized additional cost of electricity, which can be used as an indicator of economic feasibility. In this context, the LCOE accounts for the additional cost required for an equipment or retrofit with CCS (IEA 2016).

A more recent analysis from Yuan et al. (2023) calculates region-specific LCOE for abated coal and finds a range from 347 to 731 CNY/MWh, whereas the LCOE of plants without CC ranges between 188 and 381 CNY/MWh (Yuan et al. 2023). The lowest cost among the regions occurs in the North, with Inner Mongolia, Xinjiang, and Ningxia being the cheapest. The Asian Development Bank supports this finding saying "Large-scale coal-fired power plants are likely to be built in the Inner Mongolia Autonomous Region, Ningxia Hui Autonomous Region, Xinjiang Uygur Autonomous Region (…)" (Asian Development Bank 2022). However, Eastern regions are only slightly more expensive. The highest cost, on the other side, is found in Yunnan, Shanghai, and Qinghai.

In addition to the plant-specific parameters, the regional development of electricity demand is also crucial for the potential of coal-fired power plants with CCS. In the case of a strong increase in demand with limited RE potentials, abated coal units could enable low-emission power generation. Both the land potential and specific yield for RE technologies vary across China, and so does the competitiveness of alternatives such as abated coal.

Technical dimensions

Technical dimensions highly affect the suitability and economic viability of coal-fired power plants equipped with CC. In the following we review the most critical technical dimensions.

Coal plant

Most coal plants in China were built in the past 15 years (Liu et al. 2022a; Liu et al. 2022b). Almost every second coal-fired power plant is less than ten years old and thus still has an expected remaining lifetime of more than 30 years. Consequently, most plants can be considered efficient, which is an important prerequisite for a potential retrofit with CC. Generally, the efficiency of a plant is linked to the underlying technology. The key technologies are subcritical, supercritical, ultra-supercritical, and an integrated gasification combined cycle (IGCC), which vary in the temperature and pressure of the steam cycle and thus yield different efficiencies. This study and the quantitative assessment neglect the IGCC technology as it does not seem market-ready nor politically pushed soon.

Table 1: Efficiency by plant technology

Technology	Subcritical	Supercritical	Ultra-supercritical
Efficiency [%]	≈ 34	≈ 39	≈ 43

Due to policies, IEA assumes smaller coal-fired power plant units do not have a sustainable future in China. Only units of 600 MW (net) and larger are considered potential candidates for retrofitting (IEA 2016). According to the IEA, a 600 MW unit with 35 % efficiency would result in an efficiency of about 26 % and an output of 440 MW; retrofitting is conducted with amine CO_2 capture using steam extraction from the turbines (IEA 2016). Other studies approximate a loss of efficiency of 11 % - 13 % percentage points using CC (Dave et al. 2011; Wu et al. 2013). Facing such losses results in higher fuel consumption of coal to enable the power plant to generate the same output power without CC and potentially additional generation capacity to compensate for losses.

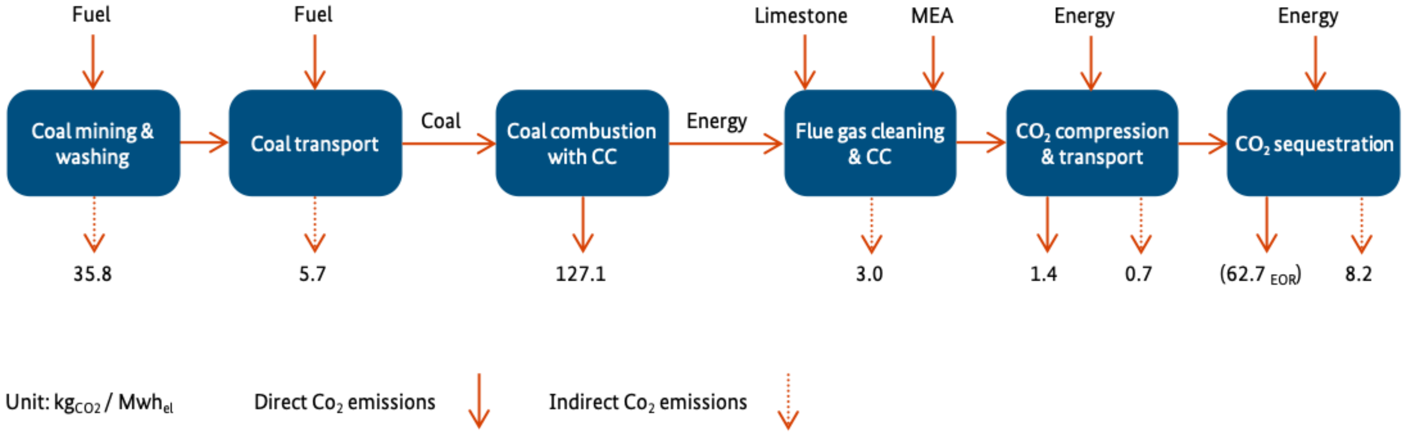
To put this into perspective with an exemplary calculation: Assume China would retrofit half of its existing coal-fired power plant fleet with CCS and generate the same amount of electricity with coal plants with an average efficiency of 40 % without CC and 30 % with CC. Then, it would face an additional coal demand of about 585 Mt, which is 17 % of Chinese total thermal coal consumption in 2021.

CC unit

Installing a CC unit in a power plant generally results in aggravated handling and efficiency losses. The degree to which CO_2 can be extracted is uncertain, though most studies indicate that capture rates over 90 % are possible (Morris et al. 2021). The IEA states that capture rates may increase over time, and the average aggregated capture rate of coal-fired power plants could reach 96 % in 2030 and 98 % in 2060 (IEA 2021a), though today's operating units often do not reach 90 %.

Currently, three leading CC technologies can be realized: Pre-Combustion, Oxyfuel method, and Post-Combustion (Zhao et al. 2013). They are still in development, but the Post-Combustion method is widely considered the most mature and cost-effective technology (Hammond and Spargo 2014; Yun et al. 2020). Capturing CO_2 after the combustion process enables this method to be applied in existing power plants for retrofitting and in the ongoing construction of new coal-fired power plants in China.

Figure 22: Operating CO_2 emissions of a coal-fired power plant with CCS. Source: EWI. Based on data from Wu, Y., Xu, Z. and Li, Z (2014).



Technology readiness

The technology development stage of different CC technologies varies significantly. The first-generation CO_2 capture technologies (post-combustion, pre-combustion, oxyfuel combustion) have gradually matured. Xu et al. (2021) state that the oxyfuel combustion technology is still in the research phase in China. In contrast, pre-combustion is at the demonstration phase, and post-combustion technology is the most mature as it is already seen as economically feasible under specific conditions (Xu et al. 2021b).

The second-generation technology[37] (such as new membrane separation, new absorption, pressurized oxyfuel combustion, etc.) is at a lower technology readiness and is mainly deployed in laboratory research or a small-scale test stage. Second-generation technology can reduce energy consumption and costs by more than 30 %. The technology is expected to be widely applied around 2035 (Liu et al. 2022a). To meet the climate targets for 2060, a ramp-up of CCS in coal plants is expected between 2025 and 2035. Thus, the key period of CCS technology is around 2030, and the commercialization time of second-generation capture technologies might be too late, although improving those would be beneficial (Fan et al. 2020). However, in the IEA Net zero emissions scenario for China, around 45 % of the cumulative emission reductions from carbon capture use and storage come from technologies that are currently still at the prototype or demonstration stage (IEA 2021a).

Upstream and downstream emissions

The capture rate of CC only looks at the emissions during the conversion of chemical energy to electrical energy. However, in reality, upstream and downstream emissions do exist. Life cycle analyses quantify all greenhouse gas emissions in the process, from extraction of coal to potential leakages in the transport and storage of CO_2. Figure 22[38] illustrates operational greenhouse gas emissions in the life cycle of a coal-fired power plant equipped with CCS. In the figure, construction and decommissioning, as well as minor process steps, such as wastewater disposal, are neglected. Furthermore, the pipeline is assumed to be 50 km long, and the direct CO_2 emissions for sequestration only appear if enhanced oil recovery is used instead of deep saline aquifer storage (Xu et al. 2021a; Yu et al. 2021). The capture rate is assumed to be 90 %.

The residual emissions, which cannot be avoided in the process, add up to 182 kg CO_2/MWh_{el}. The life cycle emissions of a corresponding unabated coal unit can be determined by neglecting the downstream emissions for the capture and storage process, adjusting upstream emissions as the coal demand per MWh electricity is lower (higher efficiency), and calculating the emissions in the combustion process. Assuming a net efficiency of 38 %, the life cycle emissions of unabated coal add up to about 850 kg CO_2/MWh_{el}, which is almost five times more than the emissions of abated coal.

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[37] The aim of this meta study is to give an overview and understanding of the current technological and economic development of coal-fired power plants equipped with CC. Therefore, the quantitative analysis in A.1 does not differentiate between different stages of the capture technology.

[38] A net efficiency of 29.7 % is assumed for the power plant with CC.

4.2 CO_2-Transport and Storage

Below is a brief overview of the developments in Germany and Europe concerning CO_2-transport. It is divided into pipeline, ship, train, and truck transport, as well as an assessment of the impacts of impurities and the potential of CO_2 hubs. Finally, the current project developments are discussed.

4.2.1 Pipeline

Projects in Germany and Europe

So far, there are no existing CO_2 pipelines in Germany. However, efforts are underway to establish a pipeline network in Germany. There are plans to build a CO_2 start-up network which should be able to transport up to 18.8 Mt of CO_2 annually in the first phase. Ideally, the construction of the pipelines will take about 5 years. There are also plans to build a CO_2 pipeline to the Norwegian North Sea (equinor 2022). Further plans look to plan pipelines to deliver hydrogen as well as pipelines for the transport of CO_2 to the same locations.

Excursus impurities

The different emitters connected to a pipeline network result in different compositions of CO_2 streams. Accompanying substances in the CO_2 stream lead to changes in the transport properties as well as in the chemical behavior of CO_2 streams (Rütters et al. 2022):

Acid condensation

Acid formation can occur in the CO_2 stream through reactions of H_2O, O_2, SO_x, NO_x, and/or H_2S to form nitric acid (HNO_3), nitrous acid (HNO_2), sulfurous acid (H_2SO_3), and/or sulfuric acid (H_2SO_4). The most important accompanying substance is H_2O. Acid generation can be limited if the water content in the CO_2 stream is severely limited (the pipeline is kept nearly dry).

Usage characteristics

The extent to which acids or water that condense on the inside of pipelines and lead to increased corrosion of pipeline steel depends in part on the wetting properties of the system - steel, CO_2 stream, and water or the acid.

Hydrate formation and phase behavior

During the transport of CO_2, there is a possibility of the formation of gas hydrates from wet CO_2 phases depending on pressure and temperature conditions. Hydrates can cause blockages in pipelines or damage to compressors and pumps. For this reason, it is important for these concomitants not to fall below the minimum pressure (Rütters et al. 2022).

Current discussion in Germany and Europe

Table 2: Overview of the maximum concentrations for the Northern Lights project and the food & beverage industry.

Component	Unit	Northern Lights	EIGA (Food & Beverage)
Water (H_2O)	ppm	≤ 30	≤ 20
Oxygen (O_2)	ppm	≤ 10	≤ 30
Sulphur Oxides (SOX)	ppm	≤ 10	0,1
Nitric oxide/Nitrogen dioxide (NOx)	ppm	≤ 10	≤ 2,5 (each)
Hydrogen sulphide (H2S)	ppm	≤ 9	≤ 0,1
Carbon monoxide	ppm	≤ 100	≤ 30
Amine	ppm	≤ 10	Not defined
Ammonia (NH3)	ppm	≤ 10	≤ 2.5
Hydrogen (H2)	ppm	≤ 50	Not defined
Formaldehyde	ppm	≤ 20	Not defined
Acetaldehyde	ppm	≤ 20	≤ 0.2
Mercury (Hg)	ppm	≤ 0.03	Not defined
Cadmium (Cd), Thallium (Tl)	ppm	Sum ≤ 0.03	Not defined

Current ISO process

Currently, the ISO 27913 is undergoing revision until October 2024. The current version of ISO 27913 recommends a CO_2 purity of at least 95 % for pipeline transport. It includes 17 general guidelines to prevent issues such as corrosion caused by certain impurities. In Germany, the DVGW-Arbeitsblatt C 260 specifies the quality of CO_2 streams in pipelines. The DVGW is also updating its regulations.

The ongoing revision of the standard is considering a CO_2 purity of 99.5 % with limitations on specific impurities that have been identified as critical for pipeline integrity and investment security in the context of CO_2 capture and storage. The advantage of aiming for high CO_2 purity lies in the ability to easily mix CO_2 streams from different emitters without significant chemical reactions from the impurities. Additionally, the transition between different transport modes, such as tank transport on ships, becomes easier with this level of purity. Furthermore, pipelines designed for highly contaminated CO_2 require significantly thicker walls, leading to higher costs.

The high CO_2 purity also facilitates cross-border transport, as neighboring countries will not encounter issues with the higher purity. The discussion on the specific purity limit is ongoing internationally and has not been finalized. The aim is to have a new version of C260 by October 2024. Various stakeholders are involved in the process, including the cement industry, waste management, pipeline operators, and European neighboring countries.

Conclusion for Chinese context

The ongoing discussions in Germany and within the ISO regarding CO_2 purity specifications can serve as indicative guidelines that may also apply to the Chinese context. Overall, it is evident that aiming for very high CO_2 purity offers several advantages. It reduces the likelihood of encountering issues during intermodal transport, making it easier to mix CO_2 streams from different sources without significant complications. Moreover, with a high CO_2 purity, there might be no need for additional purification steps at the storage facilities and, in some cases, during utilization processes.

Costs

In Germany, for the initial phase of pipeline transport excluding compression costs, a range of 20 to 40 €/t CO2 is estimated. For the planned German infrastructure, diameters of 24-28 inches (DN600-700) are assumed, which significantly reduces specific costs compared to smaller diameters.

Current challenges

A possible delay in the construction of pipelines may be accompanied by uncertainties in financing. Pipeline operators have to make advance payments to potential emitters, because of the high CAPEX share. Likewise, construction and operation are tied to a ramp-up of personnel, which also requires planning and investment certainty. A politically guaranteed planning security is discussed in Germany in order to prevent these uncertainties.

Conversion of existing gas/oil pipelines

In Carbon Limits AS and DNV AS (2021), the extent to which existing gas infrastructure in Europe can be converted to transport CO_2 has been investigated. The authors assume that a very small proportion of onshore pipelines can be converted to transport CO_2 in dense phase (main transport conditions). The study calculates cost savings potentials of 53 - 83 % (Carbon Limits AS and DNV AS 2021).

The authors emphasize that cracking in the dense phases is the main criterion to be investigated in order to assess whether conversion to CO_2 utilization is possible. It should be noted that it is important to assess ongoing ductile fracture for CO_2 in the dense phase and fatigue crack growth (in conjunction with H_2 embrittlement) at an early stage as part of the requalification process, as this can significantly limit capacity and thus economic interest in reuse (Carbon Limits AS and DNV AS 2021).

For this reason, the conversion of gas/oil pipelines to CO_2 pipelines usually only applies to gaseous transport. This mode is suitable for short distances but not for a branched and long transport network.

Furthermore, it should be noted that the existing pipelines are expected to be converted to hydrogen. Therefore, the conversion in Germany and Europe has low relevance. A similar situation can be expected in China.

Possible Leakage

There are three possible causes of pipeline failure for CO_2 pipelines: increased internal pressure, hydraulic shocks, and long-running cracks.

One of the potential causes of pipeline failure is the development of cracks. If the crack leads to leakage, CO_2 escapes from the pipeline, reducing the operating pressure until it reaches the phase boundary. During the transition, the pressure remains at the same level until it fully converts into the gaseous phase. This could then propagate the crack further. Appropriate pipe materials must therefore be selected to allow for crack arrest in case of such an event.

For pipelines transporting CO_2 in the liquid phase, there are additional potential causes of pipeline failure related to hydraulic shocks and increased internal pressure. Both potential causes can be avoided through proper pipeline design to eliminate the risk of occurrence.

Conclusion for the Chinese context

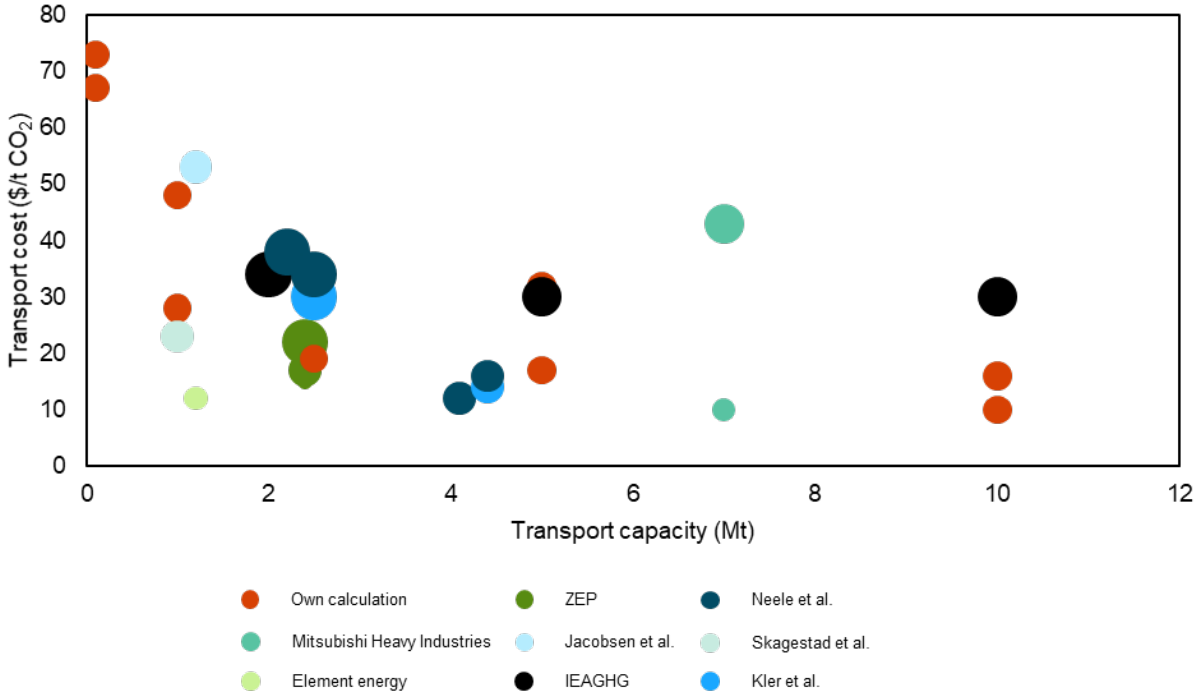
Transporting CO_2 through pipelines is anticipated to be the most economically efficient mode of transportation in China, as stated in the CCS Report of 2023. Nevertheless, the establishment of a comprehensive pipeline network poses significant challenges. Key obstacles include defining precise specifications for CO_2 stream purity, formulating a robust regulatory framework, and seamlessly integrating the pipeline infrastructure into the broader context of infrastructure planning. Addressing these challenges is essential to effectively enable the successful implementation of the CO_2 pipeline network in China.

4.2.2 Ship

Current status in Germany / Europe

The transport of CO_2 by ship is discussed for the connection of ports to offshore storage sites. Furthermore, transportation by barge is discussed due to the possibility of connecting remote facilities that cannot be connected to a first pipeline network. In this context, transportation by ship offers increased flexibility. A differentiated consideration is necessary since the capacities differ considerably due to the limitations of the possible transport capacity resulting from the transport on rivers. The TRL for the already existing transport projects is to be classified as 9 (Al Baroudi et al. 2021).

Figure 23: Overview of costs for the ship transport from different studies.



Project Overview

The "Northern Lights" project emerges as a prominent example, with two vessels currently under construction. These are designed to carry 7,500 m^3 of liquid CO_2. Furthermore, ongoing design studies aim to explore the feasibility of ships with even greater capacity, reaching up to 12,000 m^3.

Concurrently, the CETO– Project (CO_2 efficient transport via ocean) aims to investigate CO_2 transportation over extended distances for larger vessels with a capacity of up to 30,000 m^3 (DNV 2023).

In a parallel endeavor, Danish company Dan-Unity, in collaboration with Belgian firm Victrol, has proposed the construction of inland ships tailored for CO_2 transport. The projected timeframe for building the requisite number of vessels and barges is estimated at 27 to 28 months, rendering CO_2 transport feasible by 2025/2026 (The Maritime Executive 2022). Notably, Dan-Unity had previously revealed designs for ships with capacities of 12,000 m^3 and 22,000 m^3, which have obtained preliminary approval from the American Bureau of Shipping (The Maritime Executive 2022).

Additionally, TES is in the process of establishing a terminal to import methane, generated through methanation from green hydrogen and CO_2, from countries endowed with abundant renewable energy resources.[39]

Costs

Figure 23 shows an overview of shipping costs based on the quantity of CO_2 being transported. When considering the potential costs associated with CO_2 transportation via ships it is essential to emphasize that ship transport entails significantly lower CAPEX compared to pipeline transport.

Challenges

There is a lack of experience in handling CO_2 at the terminals as well as the procedures at the respective ports. This challenge may be eliminated by the first commercial projects. Several challenges arise in transportation, including limitations on tank size. These limitations, in combination with route classes, lead to restrictions on the total transport volume. Furthermore, in the summer months, there is the problem of the drafts of the barges, which run the risk of running aground due to low water levels.

Conclusion for Chinese context

In China, the maritime transport of CO_2 to offshore storage sites will play a significant role in coastal cities, similar to the considerations made for Germany and Europe.

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[39] The scientific discourse surrounding these initiatives also highlights certain challenges. For instance, constraints encompass a maximum ship size ranging between 40 to 60,000 m^3, necessitating tank flushing during ship unloading, and demanding warming procedures due to the differential transport temperatures between LNG (-163 °C) and CO_2 (-50 °C).

4.2.3 Train

Current status

The transport of CO_2 in tanks by rail is industrial practice. Transport in tanks is also suitable for CO_2 flows from various technical sources, especially the chemical industry, for smaller quantities or temporary CCU/S projects.

Projects Europe/Germany

Currently, all projects in Europe with a realization period until 2030 have a backup plan for rail transport. The extent of rail transport is expected to depend on the development of the pipeline network. Overall, it is anticipated that between 2028 and 2030, at least 5 to 10 Mt CO_2 per year could be transported by rail to the respective terminals in Germany.

Costs

Various factors influence the costs of CO_2 transport by rail. Due to these factors, it is not possible to provide universally applicable statements about transport costs. An estimation of the costs indicates a realistic range of approximately 10 – 60 €/t CO_2. These costs cover the pure expenses of train transport without including liquefaction, interim storage, and further potential conditioning steps.

Challenges

One challenge can be space requirements, particularly concerning track lengths, as they may not be easily adaptable at the designated site. The track length determines the number of tank cars that can be loaded, thereby affecting capacity.

Finally, the development of electricity costs is a major challenge for transport, given that transport chains are energy-intensive, and rail transport, in particular, relies on electricity.

Conclusion for Chinese context

The relevance of rail transport in China is expected to be lower than in Germany due to the overall higher CO_2 capture volumes in China. However, during the ramp-up phase and for the development of initial projects with access to the railway network, train transport will also play a significant role in China's infrastructure. The challenges in China will likely include the capacity of the railway network and the initial procurement of tank cars for CO_2 transport.

4.2.4 Truck

Transporting CO_2 in tank cars by road has been practiced for decades for commercial purposes, so their TRL can be stated as 9 (European Commission, 2021c). Tank transport is also suitable for CO_2 streams from various technical sources, especially the chemical industry, for smaller volumes or for temporary CCU/S projects.

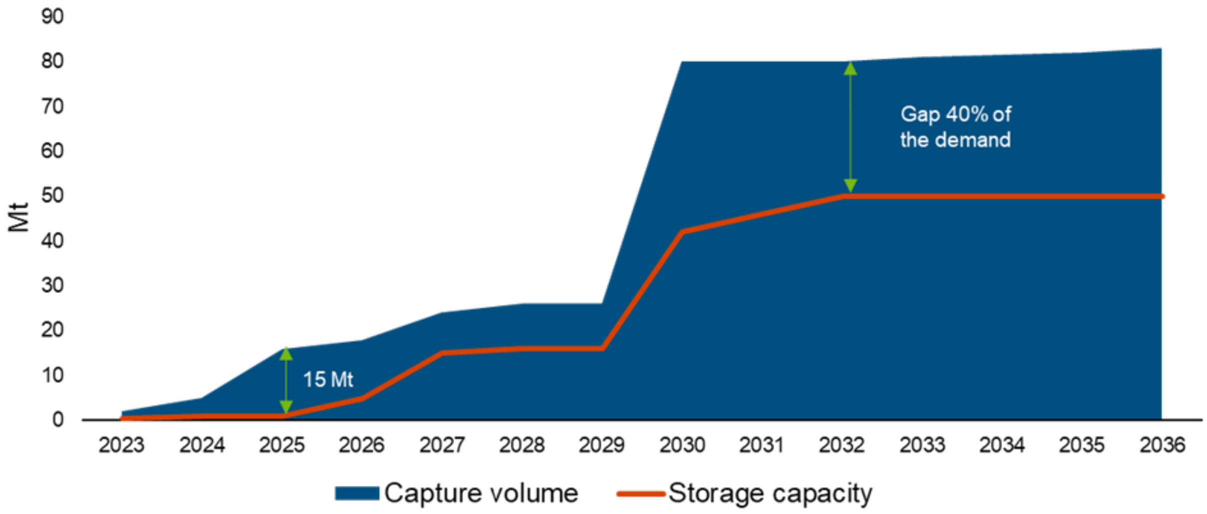
Conclusion for the Chinese context

Transportation by truck will be of little relevance in China. Initially, it is conceivable that transportation by truck may be suitable for projects that are not connected by train, inland waterway, or pipeline, and for quantities below 100 kt CO_2.

4.2.5 CO_2-Hubs

At so-called "multimodal" hubs, various CO_2 streams can be brought together and collected, and modes of transportation for CO_2 streams can be changed and conditioned as needed. In many cases, compression or liquefaction occurs during CO_2 capture, but it is also possible to combine local gaseous pipelines with a central liquefaction site.

Figure 24: Projected development of the storage capacity and capture volumes in Europe, derived from Clean Air Task Force (2023)



Synergies

The cluster approach offers various qualitative aspects that can be considered either in favor of or against adopting a cluster variant:

Risk Minimization - Concentrating infrastructure at centralized locations within a cluster can minimize risks.

Acceleration - Clusters can accelerate the development process, as a single cluster may require fewer regulatory approvals, site investigations, and connections to existing rail or pipeline networks compared to multiple individual facilities. Furthermore, the use of existing transport infrastructure allows for quicker planning, approval, and construction compared to building pipelines. In the initial phase of CO_2 capture market development, hubs can provide more ambitious timelines.

Integration of decentralized facilities - In the later stages, hubs can enable the integration of smaller and/or more distant emitters into the overall system.

Flexibility and Resilience - In case of disruptions or failures in pipeline or storage operations, multimodal concepts allow the use of alternative transport modes, enhancing the overall system's resilience.

However, certain advantages can still be found in individual solutions compared to clusters, especially when significant synergies exist between the capture facility and other process steps like compression and liquefaction. For instance, utilizing waste heat from liquefaction or compression facilities to provide heat for the capture process (e.g., amine scrubbing).

Different configurations of CO_2 transfer hubs

CO_2 transfer hubs are not a well-defined concept with clear definitional prerequisites. Three variants could be considered:

1. Transfer hubs located at existing larger industrial complexes, primarily leveraging the advantages of shared infrastructure.
2. Transfer hubs at partially centralized locations, intended to connect smaller facilities in the surrounding area to the pipeline network and infrastructure. In this concept, multimodality plays a more significant role.
3. Transport of both CO_2 and other energy carriers such as liquefied gas or ammonia at the same terminal. The idea is to transport energy carriers and CO_2 in opposite directions. This concept requires a combination of CO_2 and energy transfer hubs.[40]

Monitoring of CO_2-Storage

The current monitoring practices in Germany are as follow. As per the German Carbon Dioxide Storage Act, the operator is required to develop a site-specific monitoring concept for each storage facility based on identified risks at the location. This monitoring concept must be submitted to the relevant permitting and supervisory authority during the storage application process and obtain their approval. A plethora of monitoring methods are available for assessing CO_2 storage sites, applicable both in marine and terrestrial environments. The monitoring process takes into account the behavior of the injected CO_2 stream and potential consequential processes, such as formation water migration, ground uplift, and the occurrence of (micro) earthquakes.

Over the course of approximately 25 years, diverse monitoring methodologies have been developed, rigorously tested, and implemented in ongoing large-scale demonstration projects for CO_2 storage across the globe, as well as in pilot sites like Ketzin, natural CO_2 seepage locations, and controlled release experiments conducted as part of various research initiatives, which include CO2ReMoVe, STEMM-CCS, RISCS, and E-NOS.

Challenges

Legally and regulatory-wise, several challenges may arise from the operation of CO_2 transfer hubs. These include questions concerning ownership and property rights of the CO_2. Another question pertains to monitoring obligations, which initially lie with the operator of the transfer hub. The influence of impurities is another consideration at a CO_2 transfer hub, where CO_2 streams from various sources can contain accompanying substances.

The issue of access to the hub also needs to be considered. If there is a public interest, and the emitters meet the requirements of the regulations, a Third Party Access model may be feasible, where access cannot be denied.

Conclusion for the Chinese context

Hubs could be particularly attractive for China, especially at the initial stages to exploit economies of scale. On a provincial level hubs become of greater interest, especially in cases where a national pipeline network does not exist and where rail and inland waterway transportation play a more prominent role. Hubs located at ports offer significant potential at the outset due to their proximity to emitters, transportation facilities, and storage options.

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[40] However, due to the distinct transportation and transfer requirements for these different substances, this concept is currently considered too complex (Wetenhall et al. 2014)

4.2.6 CO_2-Storage

The chapter on CO_2-storage is intentionally kept brief, as CO_2 is already being stored in EOR projects in China. Therefore, the focus is on challenges arising in Europe concerning storage capacities and their development, as well as regulatory aspects. The main challenge in Europe is that the amount of capture exceeds the available storage capacity in the near future (until 2040), making storage capacity a bottleneck. The available supply of storage sites in the North Sea region by 2030 is not expected to meet the demands of European CO_2 emitters. Carbon Limits and the Clean Air Task Force expect, based on the list of announced capture and storage projects in Europe, that even from 2030 to 2036, the available developed storage capacity will only be able to meet 50 to 60 % of the storage needs for captured CO_2 (Figure 24).

There are different reasons for the potential gap between storage capacity and captured CO_2 volume, but one of them will be discussed in what follows.

According to Zero Emissions Platform the time required to prepare the storage application and the application process in accordance with the EU Storage Directive (Directive 2009/31/EC) is between three and ten years. In addition, the construction of the storage infrastructure can also be estimated to take at least one year. Planning, exploration and development costs vary depending on the storage option (aquifer or hydrocarbon reservoir) and area (onshore or under the North Sea).

The use of depleted natural gas reservoirs for CO_2 storage could be more rapid in their exploration than the use of previously unexplored saline aquifers as the exploration effort is likely to be less, but existing infrastructure may be used. For example, Neptune Energie anticipates a time period of three to four years from storage application to the start of injection in the Dutch offshore reservoirs. Gas reservoirs with older wells may require tightness verification and upgrading of existing wells to demonstrate storage safety.

For the Northern Lights project the CO_2 injection into the subsurface of the Norwegian North Sea is expected to begin in 2024. For the second phase of the project, it is expected to take only about five and a half years from concept study to the planned start of operations in early 2026 as the storage and the license are already issued.

4.3 CO_2-Utilization

The following presents the essential technologies for the utilization of CO_2 in the chemical industry. These are the technologies required to provide the raw material needs for basic chemicals. This includes:

- Methanol synthesis followed by processes for the production of olefins and aromatics (MtO/MtA),
- Fischer-Tropsch synthesis,
- Methanation.

No further methods for the utilization of CO_2 are discussed. At the end of the chapter, an overview of the energy requirements and costs for the processes is provided.

As described in chapter 3.5.4, these processes will only become necessary in the coming decades to achieve the Chinese climate protection goals. The cost-effective availability of coal is likely to keep the current chemical industry viable for several more decades and prevent a transition to the processes presented subsequently, at least from an economic perspective.

Table 3: Energy demand for the production of fuels and chemicals via CCU processes

Synthetic Fuel	Total power demand for synthesis (kWh / kg fuel)	Energy density (kWh / kg fuel)	Ratio
Gasoline	19.11	12.08	1.58
Kerosene	21.92	12.03	1.82
Methane	25.13	13.89	1.81
Methanol	9.44	5.53	1.71
Hydrogen	50.00	33.33	1.50

4.3.1 Methanol synthesis

Methanol synthesis involves the conversion of CO_2 and hydrogen or syngas ($CO + H_2$) into methanol (CH_3OH), the simplest alcohol. Two main reactions are as follows:

$1: CO_2 + 3\,H_2 \rightleftharpoons CH_3OH + H_2O,$
$2: CO + 2\,H_2 \rightleftharpoons CH_3OH.$

The energy efficiency for this process is 48 % (Prognos 2021). The TRL for methanol synthesis is estimated to be between 5 and 8 (Agora Energiewende 2021).

4.3.2 Methanol to Olefins/Aromatics

Methanol-to-Olefins/Aromatics describes the catalytic conversion of methanol, the simplest alcohol, into olefins/aromatics[41]. Olefins and aromatics are essential building blocks in the chemical industry.

In MtO and MtA processes, methanol reacts to various aromatic compounds and longer-chain olefins. The products and their proportions strongly depend on the reaction conditions and choice of catalyst.

MtO and MtA processes have the potential to make the production of olefins and the basic aromatics, such as benzene, toluene, and xylene (BTX), GHG-neutral, provided that the methanol used is not of fossil origin.

Technological Readiness

With optimal technology development, large-scale utilization could be possible between 2025 and 2030. The current TRL is estimated to be 8 for MtO and 6 for MtA (Agora Energiewende 2021).

Current Developments in China

The Shanghai Institute of Advanced Studies of the Chinese Academy of Sciences has built a demonstration project for CO_2 hydrogenation with a 5,000-tonne capacity.

4.3.3 Fischer-Tropsch synthesis

The FT synthesis is a known process for the production of liquid hydrocarbons, also known as "coal liquefaction," dating back to 1920. However, the worldwide capacity for this process accounts for less than one percent of the oil demand (Prognos 2021). To produce liquid hydrocarbons from CO_2 and hydrogen, synthesis gas (CO and hydrogen) must first be generated through the Reverse Water Gas Shift reaction (RWGS) according to the following equation:

$$CO_2 + H_2 \rightleftharpoons CO + H_2O.$$

Depending on the pressure, temperature, and catalyst used, the FT synthesis can produce alkanes, alkenes, and alcohols with different chain length distributions. The reaction equations are as follows:

$1: n\,CO + (2\,n + 1)H_2 \rightleftharpoons C_nH_{2n+2} + n\,H_2O\ (alkanes),$

$2: n\,CO + 2\,n\,H_2 \rightleftharpoons C_nH_{2n}n\,H_2O\ (alkenes),$

$3: n\,CO + 2\,n\,H_2 \rightleftharpoons C_nH_{2n+1}OH(n-1)\,H_2O\ (alcohols)$

Further steps are required for the synthesis of olefins and aromatics, as well as for their use as naphtha in the steam cracker process.

Technological Readiness

The TRL of the FT synthesis is estimated to be between 5 and 8 (Agora Energiewende 2021). To better assess the TRL, the ICO2CHEM project can serve as an example. In this project, the world's largest pilot plant for power-to-liquid production of synthetic fuels and e-chemicals is being constructed at the Frankfurt Höchst site. The goal is to produce 4.6 million liters of synthetic fuels through the FT process in the year 2023, using up to 10,000 tons of CO_2 from a biogas plant (infraserv höchst 2023).

Chinese context

Notably, the Shanghai Institute of Advanced Studies of the Chinese Academy of Sciences has embarked on a demonstration project that transforms carbon dioxide into synthesis gas at a scale of 10,000 m^3.

Furthermore, the Dalian Institute of Chemical Physics of the Chinese Academy of Sciences has successfully executed a 1,000-tonne scale liquid sunlight demonstration as well as a 1,000-tonne scale conversion of carbon dioxide to gasoline.

However, the prevailing challenges associated with cost-effectiveness and profitability render these technologies somewhat less competitive against traditional methods. In assessing their technological maturity, they are likely situated between TRL 6 and 7. By approximately 2030, we envisage widespread promotional demonstrations, with the expectation of rolling out a series of commercially operational projects by 2035. This assessment concludes for all of the three described technologies.[42]

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[41] Olefins are cyclic or acyclic hydrocarbons with at least one C-C double bond. Aromatics are planar, cyclically conjugated hydrocarbons with an odd number (2n+1) of π-electron pairs (C-C double bonds).

[42] Expert Interview

4.3.4 Methanation

Methanation can be carried out, similar to methanol synthesis, using both CO_2 and hydrogen, as well as syngas. In this process, the oxygen from CO_2 is completely bound in the by-product water. The reactions proceed according to the following equations:

$$1: CO_2 + 4\,H_2 \rightleftharpoons CH_4 + 2\,H_2O,$$
$$2: CO + 3\,H_2 \rightleftharpoons CH_4 + H_2O.$$

The method has been researched since 1902 and is currently applied on a large scale in the Haber-Bosch process for removing traces of carbon monoxide (Harms et al. 1980). The use of synthetic methane theoretically allows for the continued operation of existing natural gas infrastructures ("drop-in fuel"). Methanation achieves an overall efficiency of 45 percent (Prognos 2021).

Technological Readiness

With optimal development, methanation can be implemented on a large scale between 2025 and 2030. The TRL of methanation ranges from 4 to 8, depending on the type of reactor used (Agora Energiewende 2021).

4.3.5 Costs and energy demand

Table 3 illustrates the energy requirements and the need for hydrogen and CO_2 in the various processes. The most significant challenge in the implementation of CCU becomes apparent from these figures — the energy requirements and the resulting costs. The demand for hydrogen is the key driver. For a greenhouse gas-neutral production, the production of green hydrogen is essential. This is only possible in regions with high potentials for solar and wind energy, especially when CO_2 from DAC (Direct Air Capture) facilities is to be supplied. DAC facilities also require approximately 1000 kWh per ton of CO_2 in primary energy, which translates to around 1400 kWh of electricity per ton of methanol. In addition, for one ton of methanol, approximately 10,000 kWh of electricity is needed (50 kWh/kg H_2). In total, slightly over 11,000 kWh of electricity per ton of methanol are required for production.

This translates into costs, as depicted in the figures. For 2030, in comparison to current costs for products on the global market, there is no profitability at hydrogen prices ranging from 3 to 5 €/kg H_2 (see Figure 25 & Figure 26).

Figure 25: Costs for the production of methanol in Germany in 2030

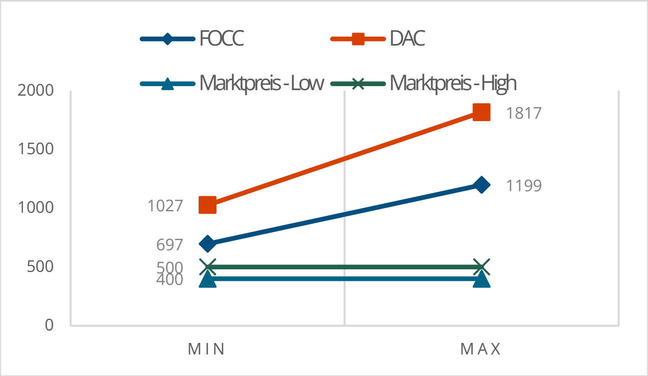
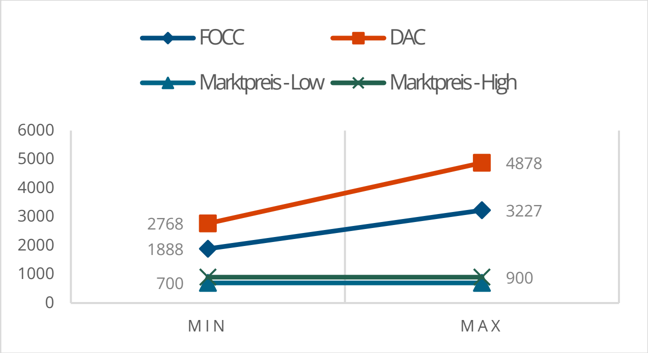


Figure 26: Costs for the production of olefines in Germany in 2030



In summary, the significant energy demand raises several questions: When will the energy be available for commercial production? To what extent can biomass/recycling reduce the demand for CCU and, consequently, the energy requirements?

4.3.6 Conclusion for Chinese context

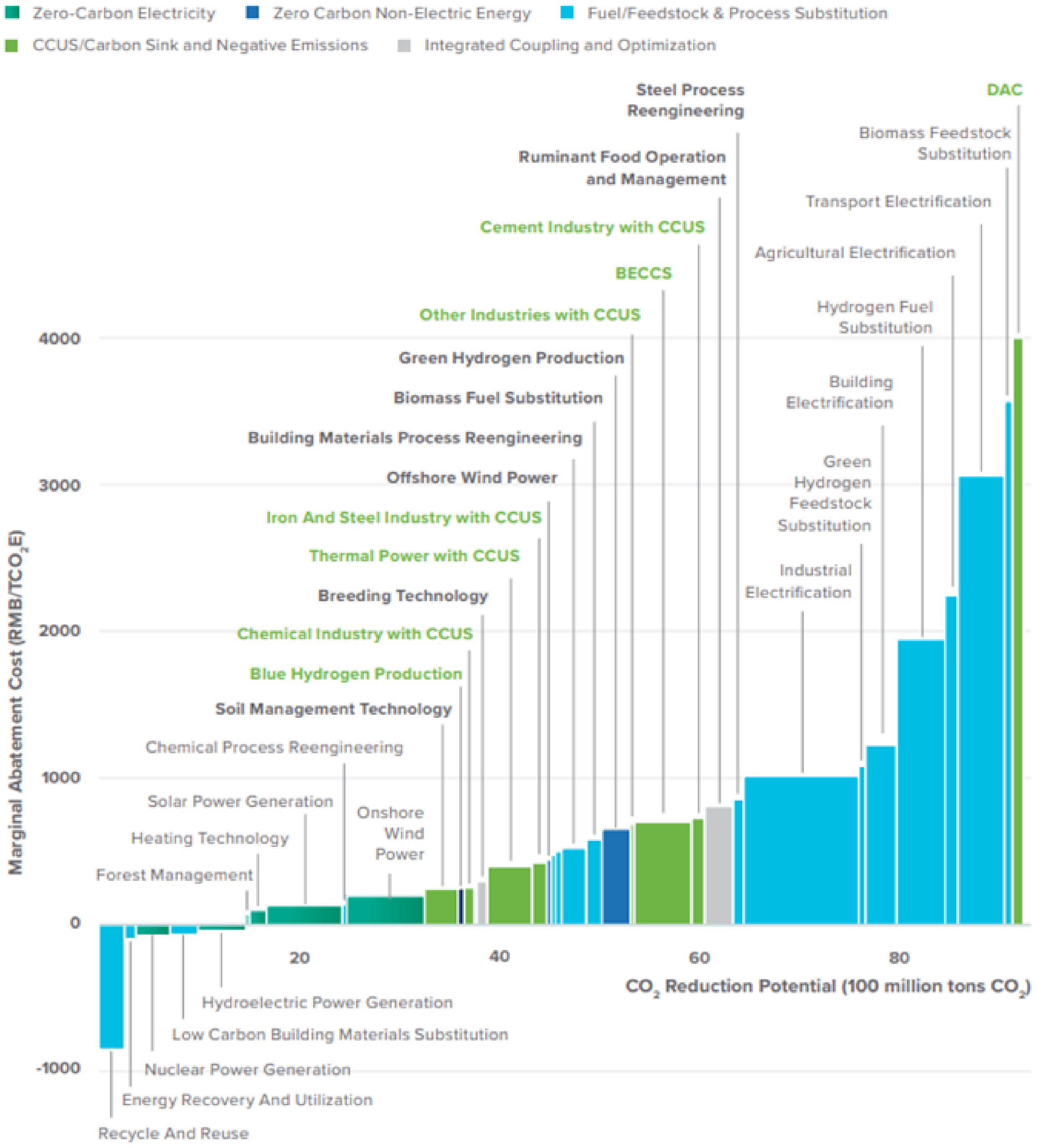
For China, it can be noted that CCU will initially have no relevance. Nevertheless, early research and further scaling of the technology are necessary because it is expected that the use of CCU for the production of basic chemicals will become necessary to achieve climate protection goals. This conclusion can also be drawn from the findings of transformation studies in the German chemical industry, which indicate that the potential for sustainable biomass and the recycling of plastic waste are limited, and the use of CCU will be necessary. This is also expected for China. Alternatives should receive at least similar attention and corresponding support to enhance resilience in achieving climate protection goals.

4.4 Economic analysis

Firstly, it is necessary to consider how CCU/S compares in terms of costs to other mitigation options. It should be noted that, as described in chapter 4, for certain industries, the technologies depicted in Figure 27 may not be sufficient to fully decarbonize the entire sector. From the illustration, it can be discerned that CCU/S can also exhibit lower abatement costs compared to other technologies, indicating that costs are not seen as a hindrance (see Figure 27).

Subsequently, a more detailed exploration of power plants and their costs is undertaken in comparison to renewable energies. This is because a sole comparison of Levelized Cost of Electricity (LCOE) is insufficient, as the necessity of these plants within the overall grid cannot be fully incorporated. Accordingly, the following section ventures into incorporating hydrogen technologies and renewable energies into the LCOE analysis, striving for an approximation of a systemic perspective.

Figure 27: Marginal abatement costs for different technologies, derived from Zhang et al. (2023)



Source: authors

4.4.1 Cost analysis coal power plants with CC in the power system

Below, the results of the EWI analysis (see chapter 4.1.5) are presented.

Introduction

In the following, we define three scenarios for the installation of a carbon capture unit at a coal-fired power plant in China. By doing so, we explicitly define certain parameters influencing the LCOE generation as well as avoidance cost. Further, key influencing parameters will be identified in a cost driver analysis. Finally, we extend the cost analysis of coal-fired generation with carbon capture by investigating alternative mitigation options, i.e., combinations of renewable energies with storage and hydrogen technologies.

Methodology and scenarios

The aim of the quantitative assessment is to analyze and compare the LCOE for coal-fired power plants equipped with CCS with varying underlying assumptions. The set of assumptions is mainly based on the findings in chapter 4.1.5. The variation in the assumptions is defined within the scenarios listed below. If not mentioned explicitly, the remaining assumptions are determined by average values from chapter 4.1.5 considering publications not older than 2014. The efficiency penalty, i.e., the decrease in efficiency by the installation of CC, for 1. Generation CC technology is set to 10 %pt. whereas the penalty for 2. Generation CC technology is assumed to be 8 %pt.

The following formula describes the calculation of the LCOE. Here, Investment_t denotes the investment cost, $\text{O\&M}_t$ the operational and maintenance cost, Fuel_t the cost for coal, CO2_t^{cap} the cost of the capturing process and CO2_t^{em} the cost for allowances for residual emissions that were not captured. The sum of these costs discounted over all time periods T is divided by the Generation_t over the lifetime, which is discounted as well. The discount rate r is set to 6.18 % for all calculations and is based on an average from the literature reviewed in the meta study.

$$\boldsymbol{LCOE} = \frac{\sum_{t=1}^{n} \frac{\boldsymbol{Investment_t + O\&M_t + Fuel_t + CO2_t^{cap} + CO2_t^{em}}}{\boldsymbol{(1+r)^t}}}{\sum_{t=1}^{n} \frac{\boldsymbol{Generation_t}}{\boldsymbol{(1+r)^t}}}$$

The detailed description of the scenarios can be derived from the annex. The following Table 4 gives an overview over the key assumptions.

Table 4: Key assumptions per scenario

Unit	Scenario 1	Scenario 2	Scenario 3
New plant	No	Yes	No
Efficiency w | w/o CCS [%]	43 | 33	43 | 35	39 | 29
Lifetime [a]	25	35	20
CAPEX plant | CC [CNY/kW]	0 | 5,025	4,871 | 5,528	0 | 5,528
OPEX plant | CC [CNY/kW*a]	140 | 120	140 | 120	140 | 120
Capture rate [%]	80	90	80
CO_2 transport cost [CNY/t]	5.37	85.95	32.23
CO_2 storage cost [CNY/t]	54.5	54.5	54.5
CO_2 price [CNY/t]	120	120	120
Full load hours [h/a]	3,500	5,500	3,000
Biomass co-firing [%]	0	20	0

Cost drivers

To investigate key drivers for the LCOE of coal-fired power plants equipped with CCS, we analyze the levelized cost components for each of the three scenarios. Figure 30 summarizes the contribution of each cost component to the total LCOE.

Generally, a high plant utilization gives more weight to the operational cost than to the initial investment cost as the contribution of marginal cost rises. Despite the higher initial investment cost in scenario 2, where a newly built plant is assumed, the contribution of investment cost (plant and capture unit) to total LCOE is in the range of scenarios 1 and 3, which assume a retrofit. This is due to the high operating hours of scenario 2. The contribution of operation and maintenance (O&M) cost lies between 10 % and 16 %, depending on the scenario. The most relevant factor in each case is the cost of coal, causing more than one-third of the LCOE. The rather low efficiency in scenario 1 leads to the highest contribution of fuel cost of about 41 %.

The downstream cost for captured CO_2 varies significantly between the scenarios, as the transportation distance differs. In scenario 2, transportation exhibits the highest cost component, whereas in scenarios 1 and 3, it is the storing process. The biomass markup costs in scenario 2 consist of fuel cost, caused by a lower energy density of biomass compared to coal, as well as a 15 % investment surcharge[43] for aggravated complexity in the co-firing process. These additional costs are reduced by lower cost for residual emissions, as the plant operates with net zero emissions through biomass co-firing.

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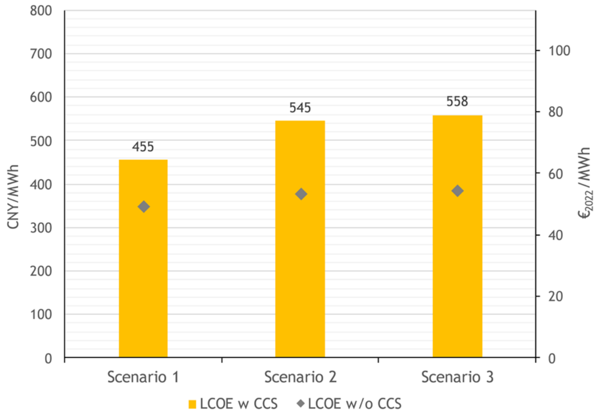
[43] The surcharge is based on own assumption.

Emission intensity

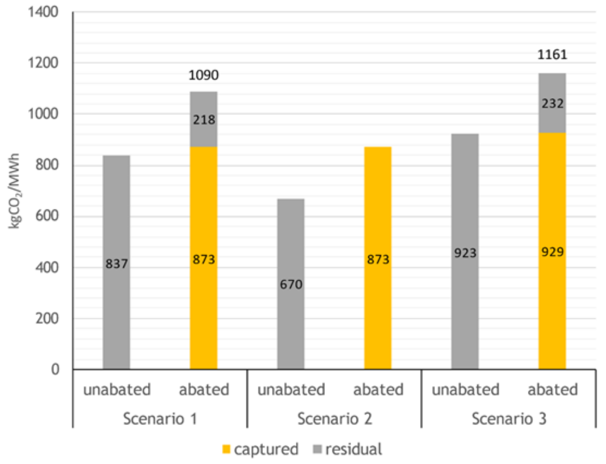
The emission intensity of coal-fired power plants varies significantly between unabated and abated coal. Generally, the installation of a CC unit decreases the efficiency of the plant, resulting in higher fuel requirements per electricity generated. Therefore, the gross emission intensity rises compared to unabated coal. From the increased emission intensity, 80 % (scenarios 1 and 3) and 90 % (scenario 2) are being captured. By comparing the net emission intensity between unabated and abated coal, we can derive that the emissions only decrease by about 75 %.

Figure 28: LCOE of coal-fired power plants with CCS



In scenario 2, we assume a biomass co-firing rate of 20 %, which is applied for abated and unabated coal. As a result, the emission intensity of unabated coal is significantly lower than in scenarios 1 and 3. Further, the co-firing of biomass in combination with a high plant efficiency leads to net-zero emissions for the abated coal plant. However, not all emissions are physically captured.

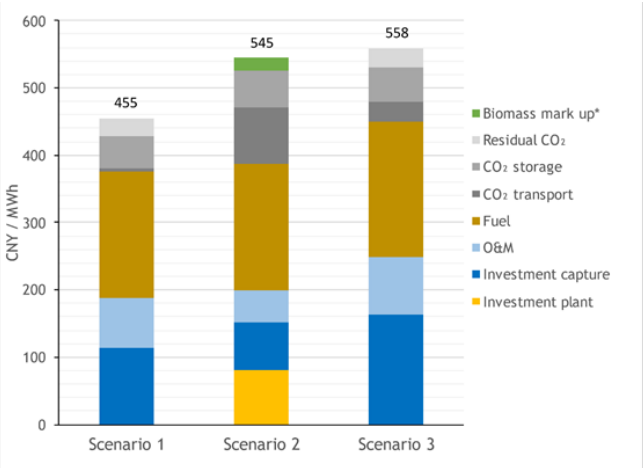
Figure 29: Emission intensity of unabated and abated coal for the scenarios



Avoidance costs

The analysis of LCOE for coal-fired power plants equipped with CCS is extended by the calculation of avoidance costs. The avoidance costs for each scenario are calculated by dividing the difference between the LCOE with and without CCS (ref) by the corresponding difference in specific CO_2 emissions. This can be interpreted as the additional levelized cost required to capture one ton of CO_2 with coal-fired CCS plants.

Figure 30: LCOE costs components per scenario



The lowest avoidance cost occurs in scenario 1, which is almost more than 30 % lower than the avoidance cost in scenarios 2 and 3. The difference in emission intensity between the scenarios, i.e., the denominator, is rather low, varying between about 620 and 700 $kgCO_2/MWh$ (see Figure 29). However, the additional investment requirements in scenario 2 and the rather low efficiency in scenario 3 lead to a higher cost delta between unabated and abated coal in those scenarios compared to scenario 1. This results in higher avoidance costs.

Literature indicates that the price for CO_2 in China is likely not to exceed 120 CNY in the next ten years. Against this background, CCS might not be profitable in the short term. In the long run, though, carbon prices may exceed the avoidance cost of coal-fired plants equipped with CCS. As an example, the Asian Development Bank assumes a carbon price of more than 700 CNY in 2050, which would significantly increase the profitability of coal with CCS (Asian Development Bank 2022).

$$\boldsymbol{Avoidance\ Cost\ [\frac{CNY}{tCO2}] = \frac{LCOE_{CCS} - LCOE_{ref}}{(tCO2/MWh_{ref}) - (tCO2/MWh_{CCS})}}$$

Alternative mitigation options

In this section, we aim to analyze to which degree coal-fired power plants equipped with CCS can be competitive against other options for mitigating CO_2 emissions. Unlike the weather-dependent technologies PV and wind power, coal plants with CCS can be considered dispatchable or controllable. To ensure a certain degree of comparability, we define alternative mitigation options that can ensure dispatchability. The volatile nature of RE is assumed to be supplemented by a storage technology.

For the following analysis, we define the options RE+Bat, consisting of RE and battery storage, as well as RE+H_2, consisting of RE and hydrogen technologies. Table 4 lists the available technologies for both options.

Table 5: Definition of alternative mitigation options

Option	Technologies
RE + Battery	PV - wind onshore - wind offshore battery
RE + H2	PV - wind onshore - wind offshore electrolysis - hydrogen storage –combined cycle hydrogen turbine

Methodology

To calculate the LCOE of the alternative mitigation options, the installed capacity of each technology is required. Generally, LCOE can be considered independent of capacity as the unit is referenced to energy (MWh) and not power (MW). As the alternative options consist of a set of technologies, the individual capacities need to be defined. We calculate the capacity of each technology within an optimization tool, which minimizes the total levelized cost of an option under the premise of a constant load serve; i.e., a normalized flat demand must be served in each hour of the year. This premise corresponds to the dispatchability or controllability characteristic a coal-fired power plant fulfills (except for planned and unplanned outages).

As the condition of full controllability (100 %) is rather restrictive and may result in overcapacities, thus, ultimately high LCOE, we gradually relax the controllability condition by assuming 90 %, 80 %, and 70 % controllability, respectively. The optimization given the relaxed controllability condition for controllability <100 % is computed such that the demand is lowered by 50 % in a subset of hours in a year (8,760 hours), i.e., in 876 h (for 90 % control), in 1,752 h (for 80 % control) and in 2,628 h (for 70 % control) only 50 % of the electricity demand has to be served by the alternative mitigation option.

The rationale behind the choice of a certain hour with reduced demand is closely connected to the renewable yields. We sort the hourly availabilities of RE ascending and reduce those hours in demand, which show the lowest availability. This way, the most critical hours in a year (dark lulls) are gradually excluded from the controllability condition, which in reality could translate to the requirement that other technologies (e.g. hydropower) have to serve load while dark lulls occur.

The assumptions for investment cost, as well as O&M cost for the alternative mitigation options are based on IEA’s WEO2022 scenario Announced Pledges. The hourly availabilities for PV and wind power highly depend on regional yields. As we vary the location between the scenarios, the hourly availabilities of renewables are assumed to vary as well. The feed-in time series are based on the weather characteristics of the year 2019. The resulting capacities of each technology within an alternative mitigation option can be found in the appendix.

LCOE – comparison of coal with alternative mitigation options

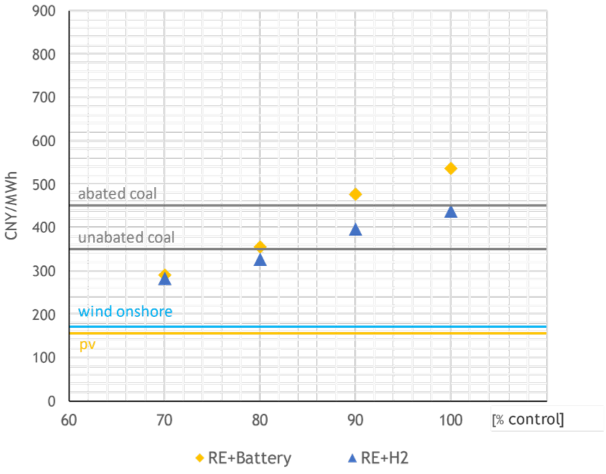
The following figures show the LCOE of alternative mitigation options RE+Battery and RE+H_2 for different levels of controllability. Further, the horizontal lines show the LCOE of coal with CCS (abated coal), coal without CCS (unabated coal), as well as the LCOE of PV and wind power without controllability condition for each of the scenarios. The description of the different scenarios can be derived from the appendix.

Scenario 1 assumes a location of generation units in Inner Mongolia. This region is characterized by high solar and wind yields, which translate into low LCOE for the single renewable technologies without controllability condition (horizontal lines). The LCOE of alternative mitigation options are generally higher than those of single renewable technologies, as we assume a controllability requirement. The LCOE of alternative mitigation options increase with the level of controllability, which can be explained by higher storage requirements in hours, where renewable yields are rather low.

The comparison between alternative mitigation options shows that the difference in LCOE between RE+Battery and RE+H_2 increases with the controllability requirement. This is mainly due to the temporal characteristic of storage technologies. Battery storage usually has a low energy-to-power ratio, i.e., the storage balances short-term fluctuations. Hydrogen storage, on the other hand, can be used to balance seasonal variations as well. This is important to counteract seasonal variations in renewable yields, ultimately resulting in lower LCOE for advanced controllability requirements, which can be seen in every scenario.

The LCOE of abated coal in scenario 1 is lower than in scenario 2 and scenario 3. However, the low-cost alternative mitigation options favor the installation of renewables over abated coal. The results indicate that a retrofit of an ultra-supercritical coal plant in Inner Mongolia could be an option, nonetheless, investments in RE and hydrogen technologies might be beneficial. Against the background of higher cost in the other scenarios, the low LCOE of abated coal, and alternative mitigation options in scenario 1, Inner Mongolia is likely to be a net exporting region in the future.

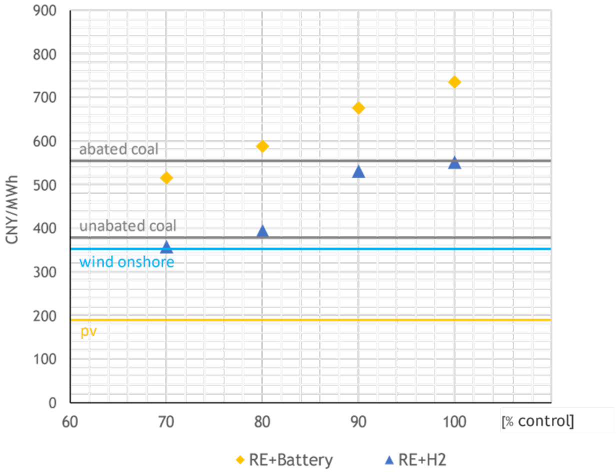
Figure 31: LCOE of alternative mitigation options in scenario 1



The RE yields in scenario 2 (Guangdong) are lower than in Inner Mongolia, especially for wind onshore. Therefore, the LCOE of renewable technologies, as well as of the alternative mitigation options, turn out rather high. Therefore, the difference between the options *RE+Battery* and *RE+H*$_2$ is significant. This is due to increased mid-term storage requirements in scenario 2 for certain levels of controllability (see Figure 32 for details). The requirement to endure days of low renewable yields is not suitable for short-term battery storage technology, resulting in increased cost for the option *RE+Battery*.

Despite the moderate cost level of unabated coal, the LCOE of abated coal in scenario 2 is significantly higher than in scenario 1. The increased cost of abated coal over unabated coal is caused by the increased investment requirements, as the plant in scenario 2 is assumed to be newly constructed, though the efficiency of the plant operation and capture process are assumed to be rather high.

Figure 32: LCOE of alternative mitigation options in scenario 2



The comparison between abated coal and alternative mitigation options exhibits the competitiveness of abated coal under specific conditions. If conventional generation units are phased out of a regional power system, the requirement for controllability of renewable technologies increases, as these should be able to supply electricity at any point in time. With higher levels of controllability, abated coal can be equally or even less costly than alternative mitigation options. Summarizing these findings, coal with CCS in Guangdong can be an attractive transition technology to significantly reduce the emission intensity of power generation in the medium term.

Scenario 3 is assumed to be located in the Shanghai region. The LCOE of PV is highest among the scenarios, and the LCOE of wind onshore is between scenario 1 and scenario 3. This also results in a mediocre cost level for alternative mitigation options, which are comparable to the LCOE of scenario 2.

Like in scenario 2, the LCOE of abated coal is significantly higher than those of unabated coal. In this case, the increased costs occur due to the lower efficiency of a supercritical coal technology as well as 1. Generation capture technology.

The cost level of abated coal is competitive with the alternative mitigation option RE+Battery for advanced requirements of controllability. Compared to RE+H$_2$, abated coal exhibits higher LCOE even for high requirements for controllability. Nevertheless, it must be taken into account that ancillary hydrogen infrastructure, such as pipelines, is not included in the cost of RE+H2 and that there is significant uncertainty about the cost of hydrogen storage. However, abated coal could be a considerable investment option for the Shanghai region on the way towards carbon neutrality.

Figure 33: LCOE of alternative mitigation options in scenario 3

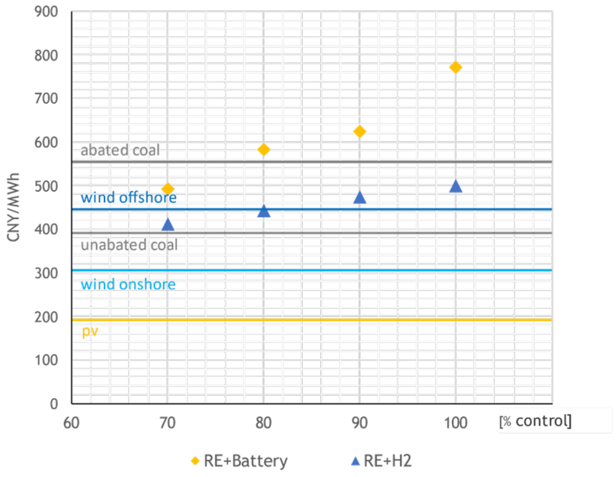
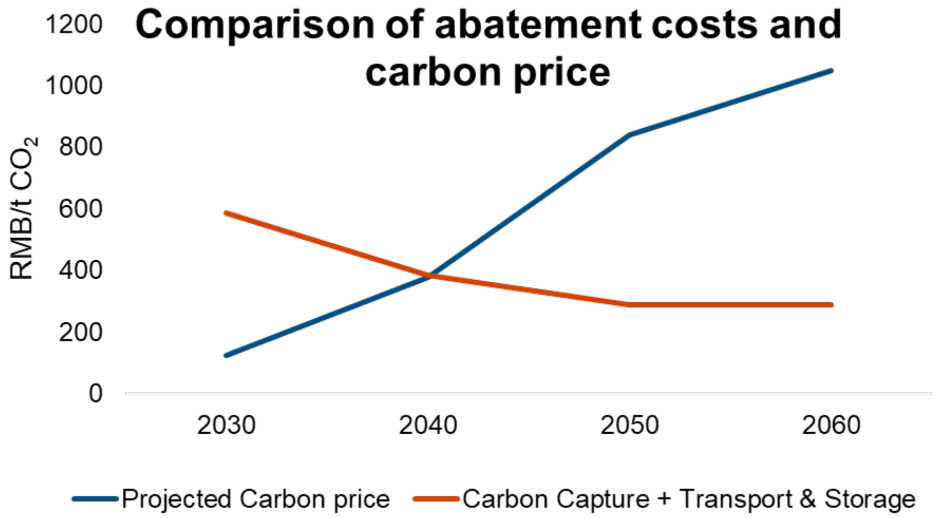


Figure 34: Comparison of abatement costs and projected carbon price (Asian Development Bank (2022)



4.4.2 Cost analysis of the CCS components

When considering the costs of the CCS chain, they can be divided into three cost components: storage, transportation, and capture. Capture represents the significant portion of the costs (40 - 70 %) when dealing with quantities of CO_2 (min. 100 kt). In an earlier phase, storage and transportation can account for a similarly high proportion of the costs. This depends on factors such as distance and the amount of CO_2 a.o (Gardarsdottir et al. 2019).

The costs for CO_2 capture offer potential for cost savings, stemming from both economy of scale effects and learning effects for CAPEX. The cost reduction through these effects is expected to be around 25 – 50 % until 2045 in Germany. Furthermore, OPEX can be lowered through second-generation technologies, for example, employing more efficient solvents that require less energy. Moreover, as explained in Chapter 4.1.4, the concentration of CO_2 has a significant impact on costs, as the energy demand for capture decreases, and other technologies can be utilized.

In transportation, costs for pipeline transport can mainly be reduced through scale effects (see chapter 5.1.4). Learning effects can be neglected. Similarly, in maritime transport, scale effects are substantial, although maritime transport has a considerably lower CAPEX share compared to pipeline transport. Nevertheless, uncertainties in costs remain due to potential delays in approval and planning processes, as well as inadequate regulatory certainties.

Regarding storage, learning effects are also negligible due to existing experiences in the oil and gas industry. In storage, costs can likewise be primarily lowered through scale effects. It should be emphasized that this varies from project to project, as local conditions can significantly impact costs. Further uncertainties arise from lengthy planning and approval processes, as well as the exploration of potential storage sites.

In Figure 35, it can be observed how CAPEX and OPEX, divided into Fixed OPEX and energy costs, behave over a project duration of 25 years for carbon capture at cement plants. In this context, OPEX constitute a proportion of mostly over 50 %, making them the primary cost driver. CAPEX are particularly relevant at the outset and notably for pipelines. When solely considering pipeline transport without compressors, CAPEX play a crucial role, amounting to around 90 % or more of the costs (Albicker et al. 2023).

Considering the potential cost evolution of the ETS price allows us to infer from the abatement costs when the deployment of CCS can become economically viable. This is illustrated for potential CCS chain costs in China in Figure 34. Under the assumed CO_2 price, the deployment could already be economically viable before 2040. This factor should be taken into account when considering potential incentives.

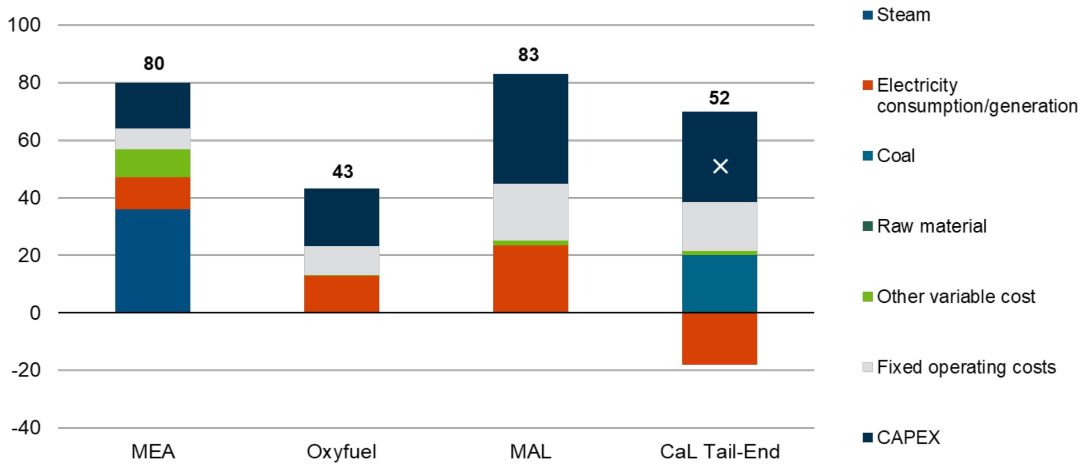
In the preceding years, a clear economic gap becomes evident, which is also recognized in the literature as the main reason for the lack of commercialization of the process.

4.4.3 Possible funding Instruments

ETS

The eligibility of CCS in the ETS provides an incentive for emission reduction through CO_2 capture. When the CO_2 price exceeds the costs of CCS, a direct economic incentive for CCS emerges. The ETS thus sends investment signals in a market-based manner without burdening the state budget.

Figure 35: Abatement costs for different carbon capture technologies, derived from Gardarsdottir et al. (2019)



Carbon Contracts for Difference (CCfDs)

In light of uncertainties regarding the development of CO_2 prices, there is a discussion about the use of Carbon Contracts for Difference (CCfD), to provide sufficient investment security for climate protection measures. Since the product-specific CO_2 mitigation costs are expected to be significantly higher than the anticipated CO_2 prices in the coming years – but lower in the future – businesses are faced with the dilemma of having to invest in technologies that may not yield certain returns. CCfDs are agreements between companies and the government that partially compensate the extra costs of climate-friendly technologies compared to conventional technologies. This type of support creates predictability for businesses. If the CO_2 costs exceed the agreed-upon price, the company repays (part of) the money (while saving on the costs of CO_2 emissions that would occur without investment in climate-friendly production).

Because of the market-based allocation through tenders and alignment with actual mitigation costs, overcompensation can be avoided. Another advantage of CCfDs is the effective control of goal achievement, which is almost guaranteed with the signing of the contracts.

However, especially for technologies with high specific mitigation costs, there can be high costs for the state budget unless there is an alternative financing method. In sector-specific tenders for CCfDs for energy-intensive industries, there is also the risk that alternative mitigation options, such as timber construction or material efficiency, may be disadvantaged since they cannot participate in the CCfDs auctions.

Green lead markets

Green lead markets are a demand-side instrument that aims not to initially persuade the entire economy or an entire industry to purchase climate-friendly products but instead focuses on a smaller group, such as government institutions, in the beginning. Due to this initial demand, an entirely new market can emerge, and it can grow due to economies of scale and/or an expansion of the instrument to include additional target groups (up to the entire industry/economy). One way to establish green lead markets is by introducing shadow prices for specific institutions, often involving the government.

Quota rules - Quota rules are more of a regulatory instrument. They compel consumers to meet a portion of their demand with climate-friendly products. While it guarantees (future) market opportunities for providers and thus incentivizes investments in climate-friendly technologies, quotas can result in particularly high prices from the consumer's perspective. In the worst case, demand may not be met due to an insufficiently large supply. Therefore, it is always advisable to gradually increase the quotas over a specific period.

Apart from the uncertainty about how quickly the market and supply will develop, choosing the right quotas and defining climate-friendly products is challenging. This can lead to distortions of competition and welfare losses.

A climate surcharge on end products would be a market-based, causality-based, and technology-neutral instrument for decarbonizing the basic materials industry, which could help counteract market distortions caused by the externalization of greenhouse gas emissions costs.

Surcharge - When selling products to end consumers in Germany, a surcharge could be levied based on the emissions associated with the product. This would provide an additional incentive for low-carbon products and could help finance climate protection measures such as climate protection contracts. There is no increased risk of carbon leakage with this instrument if the surcharge is applied to all products sold in Germany (including imports) but excludes exports.

Another advantage of a surcharge on end products is its high visibility, which, similar to high CO_2 prices but with fewer potentially problematic social and economic impacts, can accelerate behavioral changes. If greenhouse gas emitters pay CO_2 taxes, they will also pass these costs on to consumers, but the carbon content will not be visible.

One potential issue when introducing a climate surcharge is the overlap with existing carbon pricing mechanisms. To avoid market distortions and double pricing, the surcharge would need to be limited to specific products. However, this would entail higher administrative complexity. Alternatively, minor market distortions and double pricing could be tolerated. If Scope 2 and Scope 3 emissions were also included, a significant portion of emissions not previously priced could be covered by the surcharge.

In practice, such an end-consumer surcharge would likely be more feasible for simple materials like construction materials. For products with many components and processing steps, implementation would be more complex because tracking the gray emissions of complex supply chains would be required. Here, flat rates and benchmarks could be helpful. In the chemical industry (e.g., plastics), the surcharge could also provide an incentive to reduce Scope 3 emissions by using climate-friendly feedstocks.

Labeling - A less binding instrument is the labeling of GHG emissions. While this would clearly indicate the emissions caused by a product, unlike other supply or demand-side instruments (emissions trading, taxation, surcharge, shadow price, quota), there are neither direct financial nor legal consequences if only climate-harming products continue to be purchased.

Subsidy of investment costs

High investment costs and market risks for CCS can lead to companies being unable to raise sufficient capital from the financial market at viable terms, which can result in a lack of investment. The government can counter this with various investment cost support instruments, some of which are examined below. In general, there is a choice between grants, providing low-interest loans (debt capital), investing in companies with equity capital, or hybrid instruments.

Political Support for DAC

U.S.

Q45 - Q45 is a tax credit which provides 35 \$/t CO_2 used in enhanced oil recovery and 50 \$/t CO_2 stored. The credit is available for DAC only if the capture capacity of the plant is above 100 000 tCO_2/a. There are proposals to increase the value of the 45Q tax credit, which would provide 180 \$/tCO_2 for DACCS (Build Back Better Act).

California Low Carbon Fuel Standard - DAC projects anywhere in the world are eligible to receive LCFS credits, if the projects meet the requirements of the Carbon Capture and Sequestration Protocol. The LCFS credits is traded at an average of around 200 \$/tCO_2 in 2020.

Infrastructure Investment and Jobs Act - The act includes almost \$12 billion in CCUS support. This includes \$3.5 billion in funding to establish four DAC hubs incl. Transport & Storage (1 $MtCO_2$ per year and above). DAC projects are also eligible for additional CCUS funding support included in the act of around \$0.5 billion.

Canada

Net Zero Accelerator - The fund provides a total of \$6.4 billion over seven years to support the decarbonisation of the industrial sector. DAC with CO_2 use is eligible as a climate-neutral CO_2 feedstock to produce low-carbon products.

Clean Fuel Standard - The standard will require liquid fuel suppliers to gradually reduce the carbon intensity of the fuels they produce and sell. Low-carbon-intensity fuels include those made from sustainably sourced biomass and DAC.

European Union

Horizon Europe - DAC projects are eligible for support under Horizon Europe with a total budget across all areas of around \$113 billion.

Innovation Fund - The \$11.8 billion fund supports innovation in low-carbon technologies and processes, including CCUS and DAC.

United Kingdom

DAC and GHG Removal Competition - This will provide funding for technologies that enable the removal of GHGs from the atmosphere. Total budget is up to \$137 million.

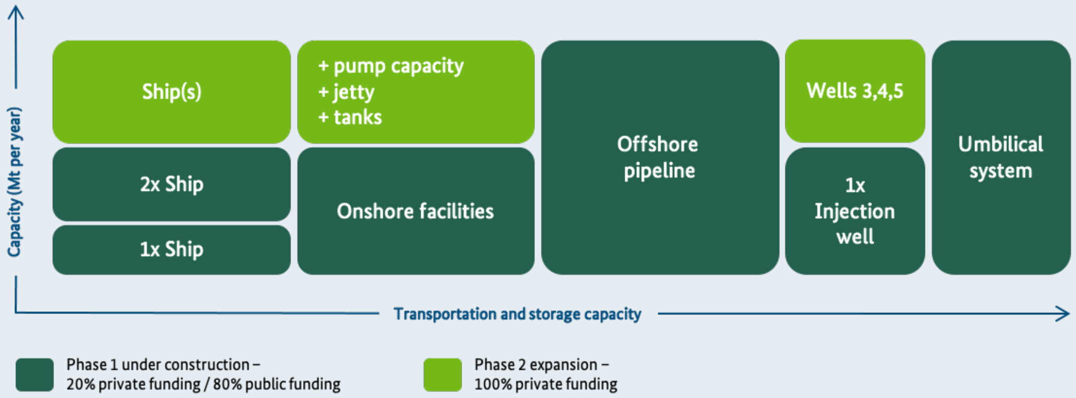
Net Zero Strategy - In the strategy a need for 75-81 Mt CO_2 of DACCS and BECCS by 2050 was identified.

Examples for Funding

Norway

In Norway, the government significantly supports initial CCU/S projects. As illustrated in the diagram for the Northern Lights project, approximately 80 % of the costs are initially covered by the government. This funding applies to First-of-a-Kind (FOAK) projects. Similarly, the projects in Brevik (cement plant) and Oslo (Waste-to-Energy) are supported in a similar manner by the Norwegian government.

Figure 36: Funding scheme of Northern Lights. Source: dena.



Denmark

The CCUS Fund and NECCS Fund are subsidy schemes aimed at reducing CO_2 emissions through carbon capture, usage, and storage.

1. **CCUS Fund**:
    - Purpose: Market-based and technology-neutral fund designed to support CCU/S (Carbon Capture, Usage, and Storage).
    - Implementation: First disbursement planned to begin in 2025/2026.
    - Annual Disbursement: A maximum of €110 million per year can be distributed to recipients.
    - CO_2 Reduction Target: Expected to contribute to achieving a reduction of 0.9 Mt CO_2 per year from 2030.
    - Phases: Divided into two phases; the first phase aims to reduce CO_2 by 0.4 Mt per year starting in 2025/2026.
    - Funding Allocation: Funding can be allocated to either one major carbon source or a consortium of smaller carbon sources, which will handle transport and storage.
    - Coverage: The fund covers the costs of carbon capture and storage at all stages of the value chain, from capture to storage. Funding is provided per tonne of CO_2 captured and permanently stored.
    - Adjustments: The subsidy is paid out per tonne of CO_2 reduced and is adjusted for fluctuations in CO_2 taxes, including any negative taxes for negative emissions and the ETS (Emission Trading System) price.

2. **NECCS Fund:**
    - Purpose: The NECCS Fund will support the achievement of negative emissions from CO_2 capture of biogenic sources and subsequent geological storage as well as carbon captured directly from the atmosphere (DACCS).
    - Implementation: From 2025 onwards
    - Disbursement: Subsidy fund of € 330 Mio.
    - CO_2 Reduction Target: Expected to contribute to achieving a reduction of 0.5 Mt CO_2 per year from 2025.

Together, these subsidy funds aim to achieve a total reduction of 1.4 Mt CO_2 annually by 2030 as part of efforts to address climate change.

3. Current developments

On May 15 2023, the Danish Energy Agency announced that the .that, together with Ørsted Bioenergy & Thermal Power A/S, they have finalized negotiations of a contract concerning state aid for Denmark's first project with full-scale capture, transport, and storage of CO_2 (CCS). The project will capture and store 430 kt CO_2 annually from 2026.

5

Systematic classification of CCU/S as a climate mitigation option

5 Systematic classification of CCU/S as a climate mitigation option

The analyses from chapters 4 and 5 regarding potential avoidance options apart from CCU/S, as well as the analysis of the entire infrastructure chain provide the basis for the following ranking of the utilization of CCU/S in the different industrial sectors.

5.1 Methodical approach

The primary objective of the ranking is to give an overview for a strategic approach for CCS in China, helping to ensure that deployment is maximized in areas where it has most significance, while restricting its use where it may be less advantageous. The ranking seeks to offer a framework to inform decision-making to achieve substantial emissions reductions and support China's climate objectives by focusing resources on the most significant applications and planning infrastructure accordingly.

However, the ranking does not intend to provide conclusive determinations. Rather, it is a tool in which value propositions may vary, and criteria evolve over time due to changing circumstances and technological advancements.

For a conclusive overview, the ranking assesses and compares CCS with other decarbonization technologies and strategies as shown in chapter 4.

The following applications for CCS are being evaluated:

I. Cement & Lime
II. DACCS
III. BECCS
IV. Waste incineration
V. Chemical Industry: Steam Cracker
VI. Chemical Industry: Coal Fischer-Tropsch synthesis
VII. Hydrogen from Coal/Gas
VIII. Coal Power (Retrofit / Greenfield)
IX. Steel: Blast Furnace / Basic Oxygen Furnace BF BOF (Retrofit / Greenfield)
X. Steel: Natural Gas Direct Reduction Iron / Electric Arc Furnace NG DRI-EAF (Greenfield)

5.2 Assessment

The ranking from A to E indicates whether the use of CC in the respective industries is efficient/inefficient, a good/poor mitigation option, and therefore to what extent its deployment in the respective industry sector is advisable in the corresponding timeframes. The evaluation is conducted based on six distinct criteria, as presented in Figure 37, encompassing the key factors affecting the decision-making process. Each application is assigned a rating on a scale from 1 to 5, following predefined assessment parameters outlined in Figure 37. The evaluation is carried out in three temporal phases:

- circa 2030 (scaling-up phase)
- the period between 2040 and 2050 (technological maturity / transition phase)
- 2060 (carbon neutrality target year).

The scoring as well as weighting of those factors varies throughout these periods due to evolving circumstances, including ETS price dynamics, technological advancements, and climate targets.

For 2030, CCS should reduce emissions as fast as possible and contribute to technology scale up. Thus, emphasis is placed on cost and technical availability, as CCS will still face technological and economic challenges at this time due to limited commercialization and low ETS prices. Meanwhile, the availability of alternatives is less important, as they will need time to scale up. The long remaining time to net-zero reduces risks of lock-ins.

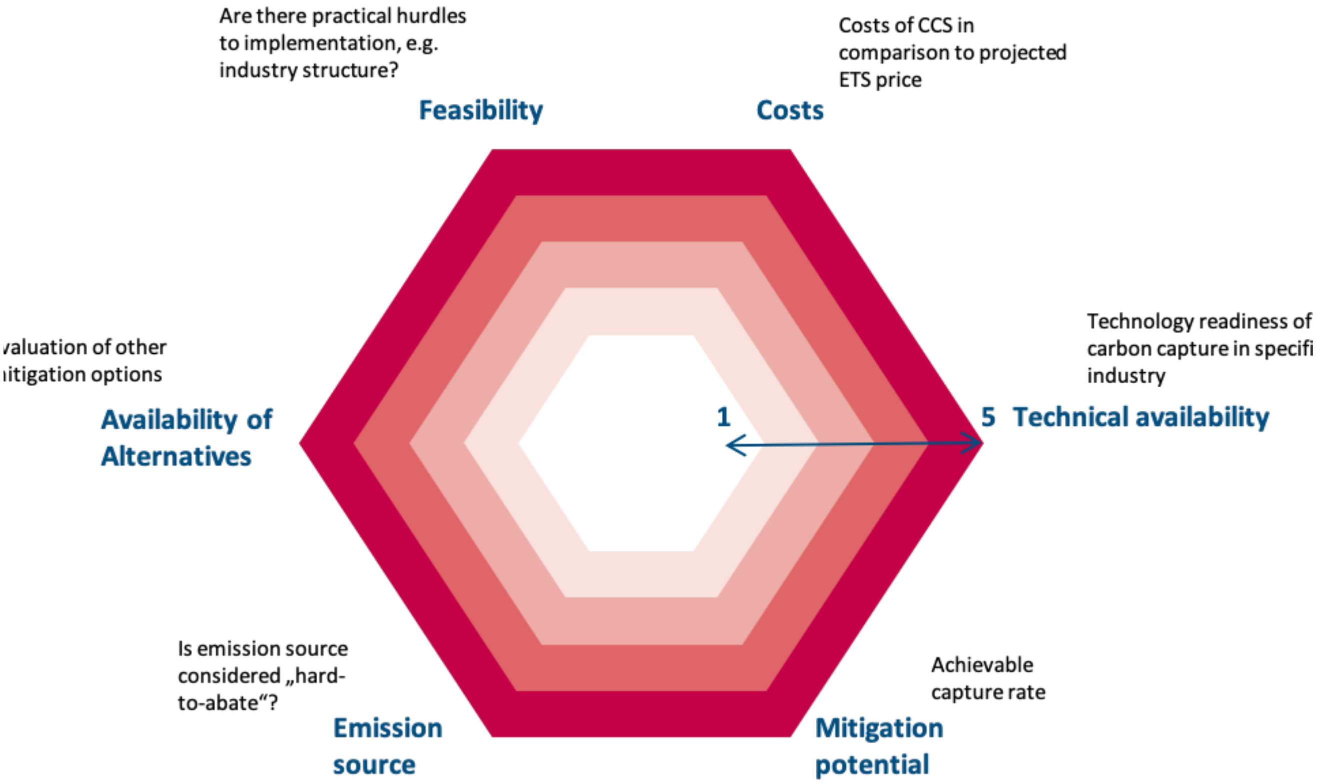
BECCS

In facilities where sustainable biomass is used in any form, such as cement plants or waste with biogenic components, carbon capture automatically leads to the capture of biogenic CO_2 (BECCS) and has therefore the potential for CDR.

BECCS should be regulated in a way as to not increase the total demand for biomass, especially not in inefficient applications, as higher biomass consumption could conflict with greenhouse gas mitigation efforts if biomass is not sustainably managed.

Within this ranking, “opportunistic BECCS” is assumed to occur as described above and is therefore not at risk of contributing to unsustainable biomass utilization.

Figure 37: Criteria for a CCS Ranking. Source: dena.



Between 2040 and 2050, both CCS technology as well as alternative mitigation options are expected to be mature, and investment decisions should be looking at compatibility with long-term goals. Thus all criteria are assigned equal weight.

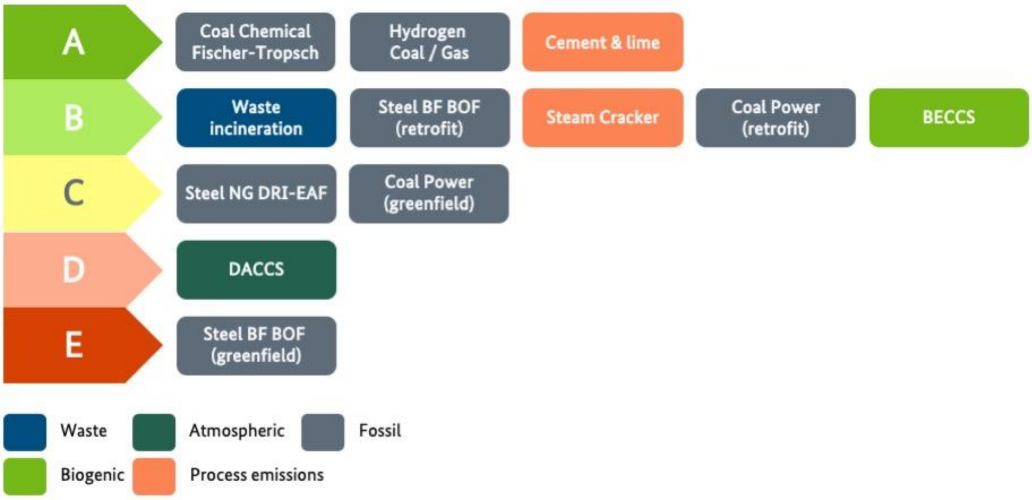
By approximately 2060, when carbon neutrality needs to have been achieved, cost and technical availability are perceived as subordinate, as ETS prices will be high enough to render CCS economically viable, and all technologies should have attained a TRL of 9 by this time. However, the emission source and availability of alternative criteria retain paramount importance, as they ascertain whether CO_2 capture is compatible with Net-Zero. This aspect is thoroughly examined in chapter 4, and the resulting insights are incorporated into the quantification process.

The five rated catories are ("feasibility" is not part of the rating):

- Costs: Costs of capture, transport and storage in comparison to the projected ETS price.
- Technical availability: The technology readiness (as TRL) of carbon capture in the specific industries.
- Mitigation potential: Share of CO_2 emissions of the different industrial processes which can be captured.
- Emission Source: Whether emissions sources are "hard to abate" in the long term. Technically not avoidable process emissions (cement, lime, waste) and CDR (DACCS, BECCS) are in the highest category.
- Availability of alternatives: Comparison with other mitigations options as conducted in detail in chapter 4.

5.3 Classification

Figure 38: CCS Ranking for 2030. Source dena.



5.3.1 2030: Initial scale-up

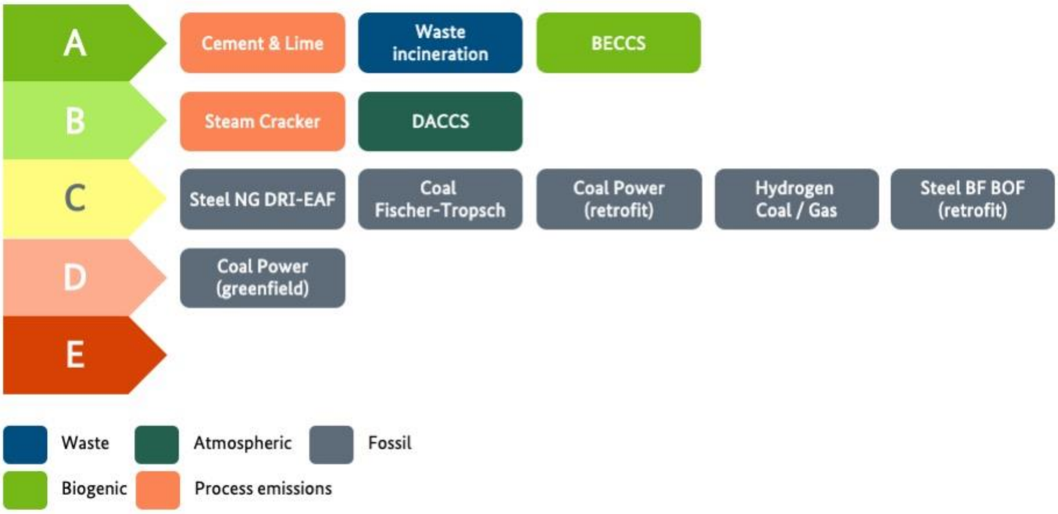
In 2030, sources in the chemical industry have the highest score in the ranking for 2030 due to the low capture cost (resulting from high CO_2 concentrations), the few alternatives available during this period, and the technical feasibility for carbon capture. Parts of the coal chemical industry can thus be considered the “low-hanging fruit” of Carbon Capture, although more sustainable mitigation options are available.

Cement and lime plants are on the same level due to their high potential for emissions reduction, lack of available alternatives, and the fact that technically unavoidable process emissions can be captured.

One level below are coal-fired power plants (retrofit), waste incineration, steel (retrofit), steam crackers, and BECCS.

Coal-fired power plants are especially noteworthy due to their high potential for emissions reduction, moderate costs, technical feasibility, and implementation potential. Coal-fired power plants will continue to play a role in the energy system for the foreseeable future, especially as backup power sources for times when renewable energies cannot generate electricity. However, this function can also be provided in the long term by renewable alternatives such as batteries or hydrogen power plants. This also applies similarly to steel production. The crucial factor is the retrofit, which can prevent these facilities from becoming "lock-ins" as new construction does not take place; instead, existing facilities are improved. The fundamental assumption here is that new construction will occur with renewable alternatives (such as renewable energy or H_2-DRI). In contrast, waste facilities and steam crackers have a high rating on emissions reduction potential and the source of emissions.

Figure 39: CCS Ranking for 2040/2050. Source: dena.



The use of CCS in the steel industry competes with the use of hydrogen (blue or green). Therefore, alternatives are available. At the same time, only a portion of emissions can be captured at blast furnaces, as CO_2 is generated in various processes, resulting in lower emissions reduction potential. For this reason, the construction of new steel plants with CCS is rated more negatively overall. It is important to distinguish between BF BOF and CH_4-DRI with CCS, with CH_4-DRI having the advantage of being convertible to hydrogen in the future. The construction of new BF BOF plants with CCS has a significant risk of fossil lock-ins.

The use of DACCS is initially not to be considered outside of pilot-scale projects due to its high costs, limited emissions reduction potential due to high energy demand, and the lack of technical maturity.

5.3.2 Transitional phase (2040 – 2050)

For cement, lime, and waste facilities, a TRL of 9 is expected for carbon capture, and the costs are expected to be below the ETS price. Therefore all three are firmly in the top category.

Steam crackers are not on the same level, as electrification is a viable option in the long term, however, there are still technical and energetic hurdles, which make CCS a reasonable mitigation option in the mid-term.

Costs for DACCS are anticipated to significantly decrease by this time, and the technology will be mature enough for industrial-scale deployment. However, due to the high energy demand, the costs remain high.

Fossil fuel derived CO_2 starts moving down the ranking, as renewable alternatives are expected to be mature and competitive by that time. This is particularly applicable to the construction of new power plants, where the analysis has shown that renewable energy sources can lead to lower overall costs on a systemic level.

5.3.3 Carbon Neutral (Target: 2060)

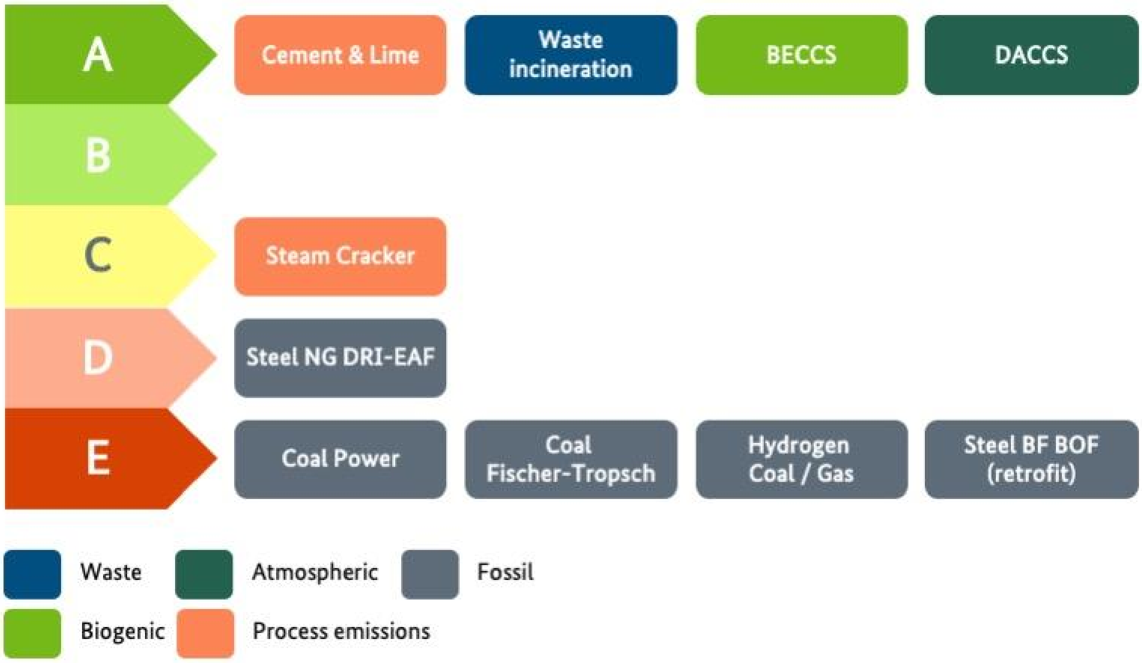
In 2060, CCS applications will have to be compatible with Net-Zero in order to meet China's climate commitment. This means that for the applications listed in A, CCS is either required in the long term to reduce emissions, or it can provide negative emissions to offset residual emissions.

The use of carbon capture at steam crackers can also occur in a carbon neutral industry because the pre-combustion process allows for the conversion of offgas into hydrogen and CO_2 or its utilization in other ways, thereby avoiding a potential fossil lock-in. However, by that time, alternatives through the electrification of steam crackers or new technologies exist, making the use of carbon capture not necessary.

The use of carbon capture in the steel industry may still be relevant if there is an insufficient supply of green hydrogen for the H_2-DRI process. However, transitioning to H_2-DRI offers a GHG-neutral alternative, and there is no expectation that CCS in the steel industry is needed, except for potential residual emissions from the use of carbon for adjusting the carbon content in steel.

By 2060, the remaining fossil technologies should have been superseded by carbon-neutral options based on renewable energy, making the deployment of CCS in those applications obsolete.

Figure 40: CCS Ranking for 2060. Source: dena.



6

Policy Recommendations

6 Policy Recommendations

Various recommendations for the ramp-up of CCU/S and policy recommendations have been made. The following recommendations complement the existing literature and are enriched with insights from current developments in Europe and Germany, providing valuable additional information for the discourse in China.

6.1 Basic recommendations in the overall context of the transformation towards carbon neutrality

The top priority in the low-carbon development of China should be emissions avoidance. Reducing the emission intensity of the electricity grid by integrating renewable energies, phasing out fossil fuels in the industry through the electrification of industrial processes and deployment of green hydrogen, and the increase in energy and resource efficiency, including the establishment of a circular economy, should have top priority.

Furthermore, it is essential to prevent “fossil lock-ins”. CCU/S must not reduce efforts to transition to renewable energy. Therefore, a CCU/S strategy should:

- focus on abating “no-regret” applications such as process emissions
- Implement policy instruments that maintain incentives to phase out fossil fuels
- Provide guidelines for the implementation of CCU/S projects
- Avoid any delays in the defossilization process

For a better overview, we recommend classifying emissions from different industries according to their avoidability (see CCU/S classification). Suitable categories could be “technically unavoidable” and “hard-to-abate”:

"Technically unavoidable" emissions comprise the cement and lime industry, waste management, and glass manufacturing, where CCS will be required in the long term. "Hard-to-abate" emissions should include processes like steam cracking and the steel industry, where renewable alternatives will be available, but are either too expensive, too scarce, or not mature for the near-term future.[44]

6.2 Legal adjustments

The analysis in chapters 1 and 2 shows that there is currently no detailed legal and regulatory framework for CCS in China, e.g. no regulations concerning purity requirements, monitoring, and other aspects of storage operations. From chapter 4 we deduce that the relevant technologies exist and are not a prohibitive factor for establishing a legal framework.

Therefore, we recommend to develop an appropriate framework for CO_2 storage in China in order to provide operators of facilities and storage with a clear regulatory framework. Below, recommendations based on the key aspects of the CCS Directive in Europe are listed for this purpose.

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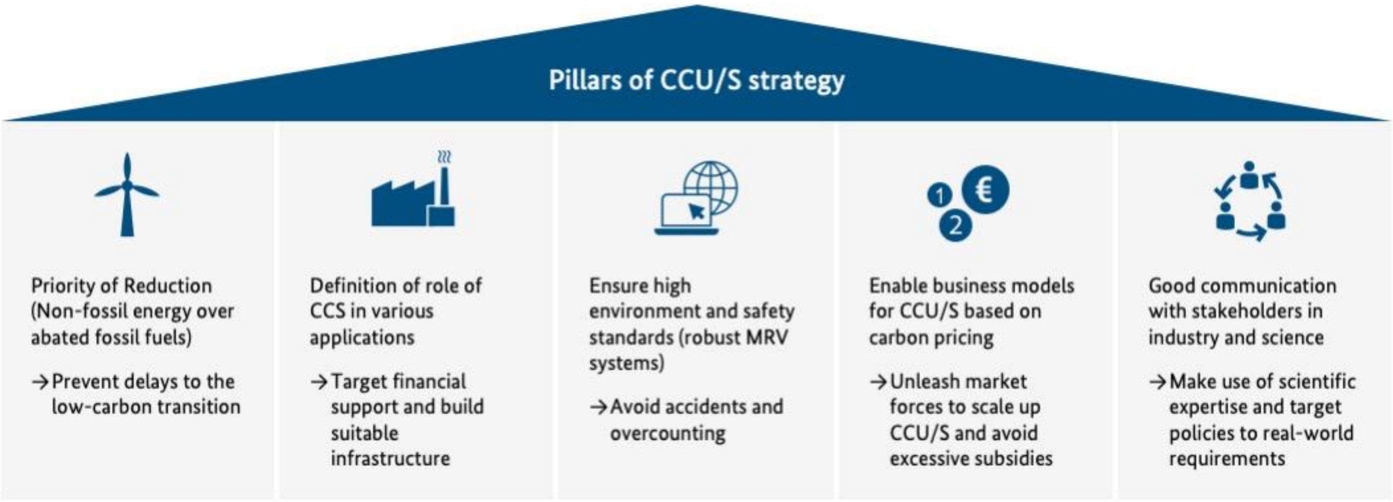
[44] Every recommendation is italic

Figure 41: Recommended pillars of CCU/S strategy. Source: dena.



1. Regulation of site selection for storage facilities and exploration permits:
    - *Establish a dedicated federal or provincial agency responsible for presenting criteria for evaluating a storage site and conducting potential assessments on a nation. Issue exploration permits through these agencies to gather data for assessing the suitability of the storage site.*

2. Issue storage permits:
    - *Ensure that no storage site operates without a permit, restrict each storage site to a single operator, and avoid conflicting uses.*
    - *Set conditions for storage permits, including requirements for the storage process, pressure limit values for reservoirs, and CO_2 stream composition.*

3. Operation, closure, and post-closure obligations:
    - *Monitor, report, and verify (MRV) the CO_2 streams to be injected.*
    - *Monitoring should cover aspects such as comparing actual and modeled behavior of CO_2 in the formation water of the storage site, detecting significant irregularities, CO_2 migration, leaks, significant adverse effects on the environment, and evaluating the effectiveness of remedial actions.*
    - *Conduct inspections.*
    - *Take measures in case of leaks or significant irregularities: Inform the operator and the competent authorities, and require necessary remedial actions to be taken at any time.*

4. Closure and post-closure obligations:
    - *Establish regulations for when and how a storage site can be closed.*
    - *Define responsibilities after the closure of the storage site, linked to a report that demonstrates the actual behavior of the storage, indicating the absence of detectable leaks, etc.; specify a minimum storage time (20 years).*

5. Third-party access:
    - *Potential users should have access to transportation networks and storage sites for the purpose of geological storage of produced and sequestered CO_2.*

The analysis shows that China is expected to have one or more interconnected CO_2 pipeline networks in the future, complemented by other transportation measures. The purity requirements for transportation, which also apply to the capture and storage processes, need to be regulated as well. In addition to legal regulations for storage, a functioning CCU/S chain must have regulations for the transport of CO_2.

We recommend that clear rules are in place to ensure the possibility of CO_2 transport within China and between individual provinces. A law should stipulate standards for the construction of pipelines and other transportation modes. It is recommended to align this standard with ISO guidelines. This standard can be legally mandated within the law, or the responsibility for establishing standards can be delegated to an authority (German model).

6.3 Regulatory measures

The construction of a pipeline system is initially associated with high costs as well as uncertainty regarding which facilities will be connected in the future. Therefore, operators seek a stable framework for various aspects, such as third-party access, tariff systems and revenue regulations, or incentives for overcapacity planning for the future. This creates the need for regulation.

For these reasons, we recommend including considering regulatory aspects early in the process.

Based on current discussions in Germany, it is evident that detailed regulation at the beginning may not be necessary. Instead, it is important to ensure the necessary financial security for pipeline construction.

Therefore, we recommend working with operators to address security and regulatory questions during the scaling-up process.

The construction of pipelines could become a bottleneck, and the necessary framework for construction and planning must be provided even before the corresponding scale-up of carbon capture facilities.

In order to prevent bottlenecks, a pipeline network should be planned and developed simultaneously with the construction of capture facilities. Similarly, for the development of storage sites, we recommend enabling timely exploration of storage areas and acquisition of relevant licenses.

The transportation of CO_2 interacts with other infrastructures, especially in the case of CO_2 utilization, where hydrogen is required for energy in the carbon capture facilities. Given the expected length of the CO_2 pipeline network in China (15,000 km according to IEA), it is likely that coordination with other networks is needed. This includes the future hydrogen network and existing oil and gas pipelines, which may require conversion in certain cases.

Therefore, we recommend developing a future network plan for CO_2 pipelines at both the provincial and national levels. Through the plan, various companies that are planning a deposition can be provided with a perspective for connection.

This plan can then be integrated into an overall network plan that includes gas, hydrogen, oil, electricity, and CO_2 networks, allowing for a comprehensive analysis of the entire network infrastructure.

In addition to pipeline transportation, there are other modes of transport, such as shipping and trains. As a pipeline network expands with time, certain areas will not have a connection to the network for a longer time. In order to identify these potential gaps in transportation coverage the network plan can indicate which regions are affected and how these can be explored. This can provide assurance for operators of shipping and train transport, enabling them to plan for early access to these regions.

Therefore, train and ship (vessel & marine) transportation should also be included in the network plan.

This also applies to clusters and their economies of scale, as well as hubs that can serve as transshipment points. Early identification of these elements provides certainty for the respective locations.

Therefore, hubs should also be integrated into the network plan.

6.4 Economic viability and funding

Carbon market / CO_2 price

The adoption of CC technologies will not occur without sufficient incentives. This could be achieved through two approaches: Carbon pricing or financial support schemes.

Carbon pricing could set the costs for emitting CO_2 higher than the costs of the CCU/S chain. This approach is particularly relevant for storage, as there is no other possibility of generating profit. When considering CCU processes, profits can be generated from selling the captured CO_2, but this has not been feasible on a large scale outside of EOR projects. The analysis shows also that CCU may not be economically viable in the long term compared to other processes. China’s ETS prices (50 RMB/t in 2021[45]) are not yet sufficient to cover the cost of CCS, which is relatively high in comparison to other mitigations options such as renewable energies, ranging for most processes excluding high concentration CO_2 sources from 250 to 500 RMB/t CO_2. Also, the ETS currently doesn’t include all industries, provides copious free allocation, and doesn’t take into account emissions reductions via CCS. In the future, the carbon price should provide the necessary incentive as the cost of capture will be lower than the price of ETS certificates.

The sectors of steel, chemicals, cement, lime, waste management, paper, and others should be fully integrated into China's Emissions Trading System (ETS) to provide an incentive for transition.

Effects of CBAM

In order to avoid carbon leakage due to terittorial carbon pricing exceeding levels of carbon pricing in other countries, the EU is planning to implement the so called carbon boarder adjustment mechanism (CBAM). The CBAM will create a level playing field between native production and products from countries with lower carbon pricing in such way that imports will be charged a customs duty amounting to the difference between the carbon tax the respective product is being charged in the EU and the exporting country. This is putting an incentive for Chinese exports to improve emission intensity e.g. by the application of CCU/S.

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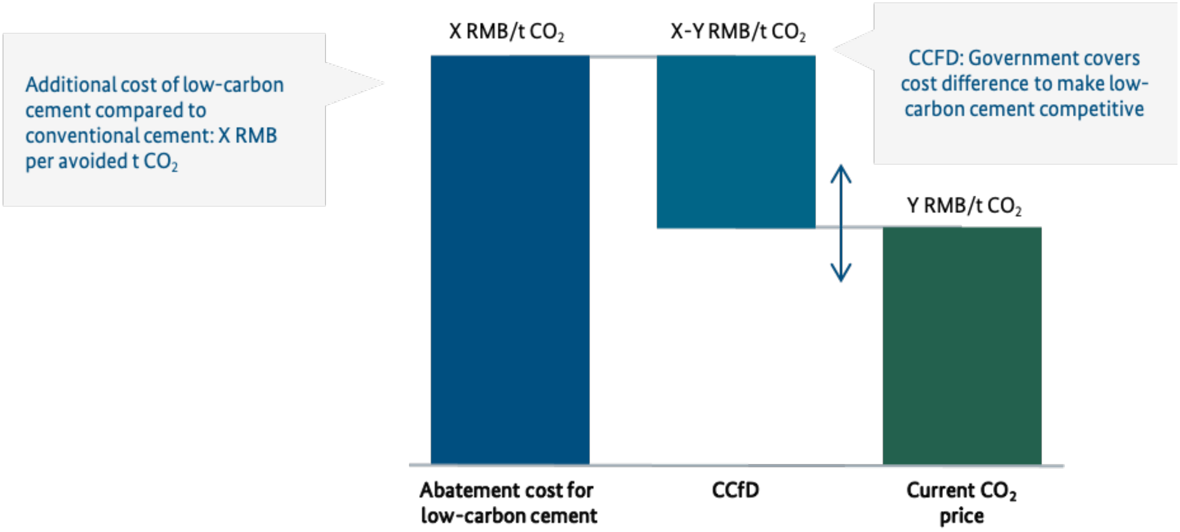
[45] Expert Interview

Figure 42: Concept of Carbon contracts for difference. Source: dena.



Financial support

As long as the ETS price is not sufficient, additional instruments are needed to promote CCU/S. Especially at the current stage of projects, capital expenditure (CAPEX) grants can be a meaningful measure to demonstrate a complete CCU/S chain. This is because First-of-a-kind (FOAK) facilities often incur significantly higher investment costs.

Therefore, we recommend supporting such FOAK projects with investment cost grants.

The exact amount of funding will be based on the specific projects and Front-End Engineering Design (FEED) studies.

Based on current knowledge the projected ETS price will surpass the avoidance cost by 2040 at the latest, based on an analysis of avoidance cost compared to the potential development of the ETS price in China.

In order to incentivize an earlier ramp-up of no-regret measures (such as cement and lime industry and waste incineration), we advise promoting the difference in costs to the ETS price through Carbon Contracts for Difference (CCfDs).

The support approach should occur at the point of capture since the respective facility operators have to bear the costs of transport and storage. Suitable regulations for transportation should ensure the safety of transport companies.

Therefore, we advise to not provide additional support for transportation.

Until 2030-2035, the gap between the ETS price and avoidance costs in China is still so significant that the implementation of CCfDs is feasible but leads to significant costs for the government. Another approach during this time is a flat-rate subsidy based on fixed contributions per avoided/stored ton of CO_2. An example of this is the Q45 subsidy in the USA (see box p.67 Overview political support on DAC). The advantage of this approach is the low bureaucratic effort as there is no need for a detailed evaluation of projects; instead, companies themselves must decide whether the project is viable for the corresponding subsidy. For projects where CO_2 is captured at high concentrations and low costs, this subsidy can lead to a positive investment decision at an early stage.

This measure should be examined in the Chinese context. We advise limiting the subsidy period and consider to switch to CCfDs or phasing out the subsidy as the ETS price increases.

We advise not subsidizing Enhanced Oil Recovery (EOR) since it already generates profit through the sale of CO_2.

The funding of carbon capture at power plants needs to be considered separately. If a subsidy is considered it should be ensured that it does not hinder the expansion of renewable energies and the future transition to power plants using hydrogen, battery storage, and other flexibility options. In order to avoid this, specific requirements for the power plants eligible for subsidies should be set.

These requirements could be based on the CO_2 intensity for different types of coal-fired and gas-fired power plants.

This would also ensure that measures to increase energy efficiency are not postponed. Another option is to limit the subsidy based on the size of the power plants and whether they undergo retrofitting or are newly constructed.

In addition to financial support opportunities, the implementation of carbon capture at power plants could also be achieved through emission limit requirements (see EPA regulatory approach). These emission thresholds must be adhered to by facilities in China. This could ensure that inefficient plants are no longer operated and that plant operators would have a clear incentive for transition. This is particularly suitable for China as a significant portion of power plants are operated by state-owned enterprises.

We advise establishing different limits for newly constructed power plants as opposed to existing plants. For new constructions, emission limits could be set as early as 2030, necessitating the use of carbon capture technology. For existing power plants, limits could be formulated to initially incentivize efficiency measures without immediately mandating the retrofitting of carbon capture technology. Initially, parallel limits could be established in combination with incentives, which would then also require the construction of carbon capture facilities.

6.5 Handling of CCU

From the analysis of the future of the chemical industry, it is evident that the transformation requires new technologies and a shift towards non-fossil feedstock. In China, the challenge is further compounded by the current reliance of the chemical industry on coal as a primary raw material. In the short and medium term, transitioning to gas as feedstock can lead to significant emissions reductions. Additionally, CO_2 capture can reduce emissions in the manufacturing process. Both approaches, however, still rely on fossil resources.

An analysis by Agora Industrie & Carbon Minds (2023) shows that Scope 3 emissions account for approximately 60 % of the total emissions of the chemical industry in Germany (Agora Industrie and Carbon Minds 2023). In order to reduce these emissions, switching to non-fossil feedstocks is necessary. Potential options include recycled plastics, sustainably produced biomass, and CCU with atmospheric or biogenic CO_2. Discussions in Germany and Europe indicate that CCU will likely be necessary to some extent, as the supply from recycled plastics and biomass may not be sufficient. This decision is complex and forward-looking, as its implications extend beyond the chemical industry and affect almost every other energy-relevant sector as it affects the distribution of biomass.

Therefore, we recommend conducting a strategic assessment of feedstock supply for the chemical industry under the assumption of a near-defossilized feedstock approach. This assessment should address the following aspects: The contribution of recycled plastics, the potential of biomass as feedstock, energy quantities for CCU (renewable energy & hydrogen) and in conclusion the scope and necessity of CCU.

In the future, the chemical industry will be particularly dependent on the availability of biomass as feedstock. Biomass is a limited resource with diverse applications, and it should be utilized as efficiently as possible to achieve climate protection goals.

In order to gain an early overview of the distribution of biomass in China and its major consumption sectors and, subsequently, to identify potential future applications and prioritize them, we recommend designing a biomass strategy.

The analysis has revealed that the technologies for converting CCU are not ready for commercial deployment and currently have a TRL ranging from 5 to 8. The basic functionality at a smaller scale has already been investigated and successfully tested. In the future, scaling up to demonstration and commercial levels is necessary.

Therefore, we recommend allocating research funding for the technologies Methanol to Olefins / Methanol to Aromates (MtO/MtA) and the Fischer-Tropsch synthesis using CO_2 and H_2.

The high energy demand for CCU, resulting from the need for hydrogen in the product synthesis, is the most significant challenge for the future implementation of CCU. In a time when renewable hydrogen is a scarce resource and there is no functional hydrogen economy yet, scaling up CCU would only lead to further competition for hydrogen.

Therefore, we recommend first pursuing other options for decarbonizing the chemical industry while simultaneously promoting the rapid development of the green hydrogen economy.

An early development of clear legal regulations is crucial in order to avoid legal uncertainties arising from the production of chemical products through CCU processes and their eligibility in the ETS.

Therefore, we recommend including CCU processes and their certification into the ETS system at an early stage to provide clarity and certainty.

Additional challenges for CCU processes are possible double counting of certificates, distinguishing between biogenic and fossil CO_2, and determining emissions throughout the life cycle. These challenges should be evaluated when implementing a policy. The EU is currently working out regulations as part of its “Sustainable Carbon Cycles” process.

Due to the lack of immediate urgency in making a decision, we advise prioritizing and implementing other aspects first, such as the creation of a legal framework for CCS.

6.6 Carbon Management Strategy

Based on the conducted analysis of the implementation of CCU/S, significant differences emerge in the necessity, time frame, role in the transformation to carbon neutrality and utilization of carbon capture compared to existing studies. This work highlights the necessity for CCS in the cement and lime industry, thermal waste treatment, as well as in generating negative emissions through BECCS and DACCS. CCU is required for providing CO_2 for the production of basic chemicals. This contradicts the focus of other studies on steel, power plants, and the chemical industry by the year 2060.

In the coming years, the results of our analysis resemble the projected trends in the examined studies. For 2030, the focus lies on the chemical industry and power plants due to high CO_2 concentrations (low separation costs), as well as a lack of alternatives and significant overall emissions reductions in the case of power plants. The only differences emerge in the steel industry, where our study emphasises the significance of the conversion to hydrogen-based DRI. The use of carbon capture is of limited relevance in this context, as carbon capture can also take place during hydrogen production if there is insufficient green hydrogen available. In a transition phase, retrofitting existing blast furnaces could be an option for China. The construction of new blast furnaces with CO_2 capture is not recommended due to existing overcapacity and possible lock-ins.

We therefore recommend implementing a strategic process for the role of CCU/S in China, which can serve as a guiding principle for the use of CCU/S.

Through this process, fossil lock-ins that could result in future additional costs for the Chinese economy could be avoided. Furthermore, such a strategic approach would make it possible to delineate the potential and role for different regions. As shown in the techno-economic analysis for the use of CCS at coal-fired power plants, regional differences can have a significant impact on the necessity of CCU/S, as other factors such as the availability of renewable energy must be taken into account.

When competing with renewable energy sources, it is advisable to derive strategies and instruments that prevent retrofitting CC from hindering the expansion of renewable energy.

6.6.1 Cement & lime industry

A carbon labelling system should be established for low-carbon cement and building materials to guide green market demand. In the cement industry in China, significant emission reduction potentials through efficiency measures still exist. The realization of these potentials could be jeopardized by retrofitting with CC, as the incentive from CO_2 capture could be reduced.

For these reasons, we recommend to formulate additional efficiency goals for the cement sector.

6.6.2 Waste-to-energy

Firstly, foundational policies must be instituted, addressing waste sorting, zero-waste cities, plastic pollution management, and carbon neutrality.

Secondly, there is a need for the implementation of policies that support waste-to-energy plants, particularly those offering subsidies and tax incentives. At present, China is transitioning from landfilling to waste incineration. Future plans foresee a shift towards endorsing waste sorting facilities, naturally promoting waste reduction and resource utilisation. Given that sorted plastics require processing, the provision of government investment or subsidies for plastic processing could make plastic raw materials both more affordable and more readily available. Both waste sorting and resource utilisation goals fundamentally rely on external forces to aid in reducing the difficulty and cost of obtaining plastic waste for plastic recycling enterprises. The resolution of these two issues sets the groundwork for discussions on carbon capture plants.[46]

We recommend supporting these measures with a long-term study on the development of waste volumes in China to avoid potential overcapacity in thermal waste treatment facilities.

6.6.3 Chemical industry / Hydrogen

As already presented in the previous chapter, the chemical industry is facing a challenge in its transformation towards greenhouse gas neutrality, which encompasses multiple levels and thus constitutes a complex endeavor. Decarbonizing Scope 1 & 2 emissions and reducing Scope 3 emissions are associated with different technologies while facing simultaneous challenges such as the availability of renewable electricity, sustainable biomass, adequate recycling infrastructure, reinvestment cycles, and synergies at integrated sites.

For this reason, we recommend developing a strategy early on that provides the necessary framework for this transformation, including legal/regulatory rules and the corresponding incentive systems.

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[46] Expert Interview

6.6.4 Steel industry

We recommend the establishment of a systematic low-carbon standard aimed at addressing climate change in the steel industry.

This would involve the implementation of standardisation work in low-carbon areas in a gradual and orderly manner. The introduction of carbon emission grading performance evaluation standards for the steel industry is essential to facilitate comprehensive low-carbon performance evaluation within the industry. The results of such evaluations should be linked with local policies including differential water prices, electricity prices, and production restrictions and suspensions.[47]

6.6.5 Power sector

The results of the cost analysis show, firstly, that regional differentiation is necessary to quantify the potential role of CCU/S in China. For instance, in Inner Mongolia, we can expect low capacity utilization hours and high availability of renewable energy. In contrast, in regions like Shanghai where the potential for renewable energy is limited, coal-fired power plants might be needed for a longer duration as a reserve.

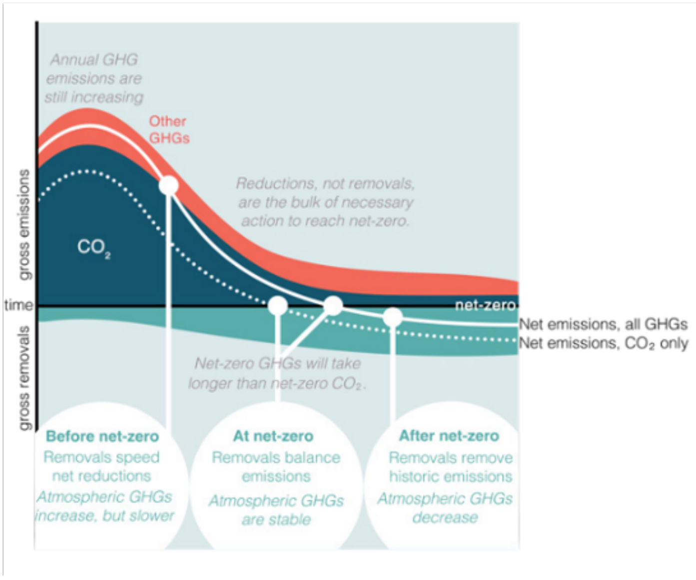
Therefore, we recommend considering regional circumstances when scaling up the retrofitting of CC technology for coal-fired power plants.

Some of the studied reports continue to assume CO_2 capture until 2060. In a greenhouse gas neutral power system, this would only be possible if sustainable biomass is used to some extent in CC-equipped facilities. As mentioned earlier, it is important to first investigate whether sustainable biomass is available for this purpose.

Hence, we endorse the recommendation mentioned above to examine the alignment of biomass use in power plants with a biomass strategy and potential cascade utilization.

Furthermore, considering the cost analysis conducted, coal-fired power plants may not necessarily be a part of a greenhouse gas neutral energy system. Instead, they can be fully replaced by batteries, flexibility measures, and hydrogen (H_2) power plants for balancing renewable energies by 2060. Thus CC at coal power points will likely serve as a transitional technology, especially in regions with limited renewable energy resources and increasing energy demand.

Figure 43: Role of CDR. Derived from IPCC 2022.



1. **Supplement** to **rapid reductions in emissions,** therefore accelerating net reductions and **decreasing the speed of global warming**
2. **Balance remaining** (mainly fossil) **GHG** to **maintain „net-zero“**
3. Achieve a netto-negative state **characterized by decreasing GHG in the atmosphere**

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[47] Expert Interview

6.7 CDR / Negative emissions

The analysis shows that, by 2060, there will be a significant need for (technical) negative emissions. Therefore, the role of DACCS and BECCS should be evaluated. In Germany, a strategy is being developed to comprehensively assess the topic of negative emissions, encompassing both natural and technical approaches. This strategy aims to determine the requirement for technical negative emissions to complement natural ones, and should determine suitable regulatory options.

We recommend a targeted and comprehensive examination of the topic. Such a strategy is also recommended for China.

Furthermore, it is essential to ensure that the support for CCS/CCU and negative emissions (CDR) is done separately and considered distinctively. While CCS/CCU primarily focuses on avoidance, CDR involves the removal of CO_2 from the atmosphere.

For this reason, we recommend setting specific targets for CDR and CCS/CCU to emphasize the necessity of negative emissions.

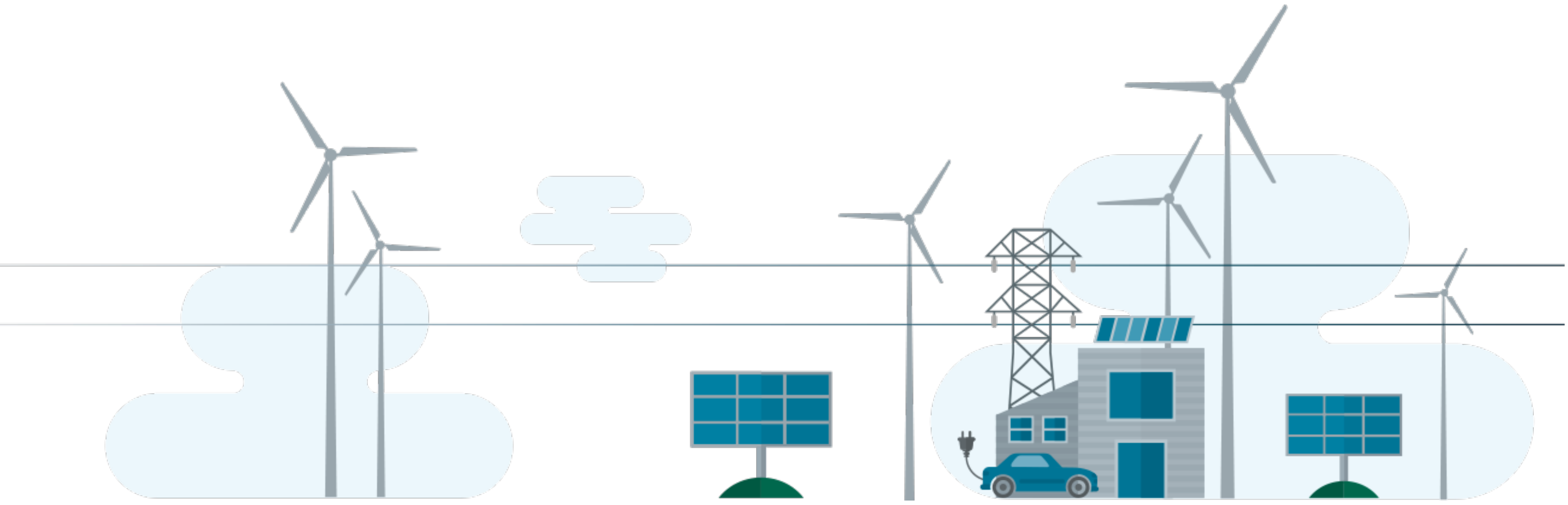
Especially in the case of BECCS, the boundaries between mitigation and carbon removal can become blurred. Therefore, when considering potential support mechanisms in a future carbon market, it is essential to ensure that the cascade use of biomass is maintained.

Currently, there are no incentives for capturing CO_2 emissions from biomass energy or material utilization facilities, nor for establishing DAC plants. Therefore, incentives are necessary to encourage such practices.

We first recommend setting targets at the policy level. For promoting these activities, it may be beneficial to take inspiration from the incentive mechanisms in the USA and Canada, given that it is mainly still in the research phase. China could utilize similar funding mechanisms for these purposes.

For further promotion, a flat-rate subsidy similar to the Low Carbon Fuel Standard (LCFS) in California could provide a strong incentive for constructing such facilities. When providing incentives, it is essential to assess suitable regions for DAC plants, considering the high energy requirements. Regions with high renewable energy potential, sufficient space, available storage capacities, or facilities for CCU would be advantageous.

It is also advisable to explore the possibility of providing support for facilities located abroad while ensuring that the corresponding captured emissions are appropriately credited to China.



Abbreviations

AFOLU	*Agriculture, Forestry, other Land-Use*
ASU	*Air seperation unit*
ATR	*Autothermal reforming*
BECCU/S	*Bioenergy Carbon Capture and Storage/Utilization*
BEHG	*Fuel Emissions Trading Act - Bundesemissionshandelsgesetz*
BF-BOF	Blast Furnace-Basic Oxygen Furnace
BTX	*Benzene, toluene, and xylene*
$Ca(OH)_2$	*Calcium hydroxide*
CACE	*China Association of Circular Economy*
$CaCO_3$	*Calcium carbonate*
CaO	*Calcium oxide*
CCfD	*Carbon Contracts for Difference*
CCS	*Carbon Capture and Storage*
CCU	*Carbon Capture and Utilization*
CCU/S	*Carbon Capture and Utilization/Storage*
CDR	*Carbon Dioxide Removal*
CHS	*Calcium Hydrosilicate*
CMS	*Carbon Management Strategy*
CNBM	*China National Building Material Group*
CPU	*Compression purification unit*
CSA cements	*Calcium Sulfoaluminate Cements*
DACCU/S	*Direct Air Carbon Capture and Storage/Utilization*
DME	Dimethyl ether
DRI	*Direct reduction of iron*
ECBM	*Enhanced coal bed methane recovery*
EOR	*Enhanced Oil Recovery, Enhanced Oil Recovery*
EU ETS	*EU Emission Trading System*

FEED	*Front-End Engineering Design*
FOAK	*First-of-a-kind*
FT	*Fischer-Tropsch*
GCCSI	Global CCS Institute
GHG	*Greenhouse gases*
H_2SO_3	*Sulfurous acid*
H_2SO_4	*Sulfuric acid*
HNO_2	*Nitrous acid*
HNO_3	*Nitric acid*
HVC	*High-value chemicals*
IEA	*International Energy Agency*
IGCC	*Integrated gasification combined cycle*
IPCC	*Intergovernmental Panel on Climate Change*
K_2CO_3	*Potassium carbonate*
KOH	*Potassium hydroxide*
KSpG	*Carbon Dioxide Storage Law - Kohlenstoffdioxidspeicherungs-Gesetz*
LCFS	*Low Carbon Fuel Standard*
LCOE	*Levelized Cost of Electricity*
LT-LEDS	*Long Term Low Emissions and Development Strategies*
LULUCF	*Land Use, Land Use change and Forestry*
MEA	*Monoethanolamine*
MRV	*Monitoring, report and verify*
MSW	*Municipal solid waste*
MtA	*Methanol-to-Aromatics*
MtO	*Methanol-to-Olefines*
NaOH	*Sodium hydroxide*
NECP	*National Energy and Climate Plans*
ORC	*Organic Rankine Cycle*
PCI	*Projects of Common Interest*
PHA	*Polyhydroxyalkanoates*
PLA	*Polyactic acid*

POX	*Partial Oxidation*
PSA	*Pressure Swing Adsorption*
PV	*Photovoltaic*
RE	*Renewable energy*
RWGS	*Reverse Water Gas Shift*
TRL	*Technology Readiness Level*
Tt	*Trillion tonnes*
VCM	*Voluntary carbon markets*
VCS	*Voluntary Carbon Standard*
WtE	*waste-to-energy*

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Appendix

Scenario 1 (EWI)

Scenario 1: Retrofit of an ultra-supercritical coal power plant in Inner Mongolia, Northeast China in 2030

The autonomous region Inner Mongolia is one of the leading electricity-exporting regions in China, with a net electricity export of around 150 TWh in 2020. It has the largest share in China's coal production, with 30 % in 2020, and the highest installed capacity of coal-fired power plants, with 102.5 GW in 2023, while also offering great potential for CO_2 storage across the whole province.

However, the province also has very high renewable capacity factors, with 20 % for solar photovoltaic (PV) and 48 % for wind turbines, as well as a vast amount of space for RE power plants due to its low population density of 20 people/km^2. In 2020, the province was already leading in wind power capacity with 36 GW. To export electricity, it is well connected to regions with large industries in East and North China via two high-voltage direct current (HVDC) transmission lines.

Due to the above-described characteristics, it is assumed that in Inner Mongolia, the existing coal power plants will still be used in the future. However, the addition of additional power capacity is assumed to mainly focus on RE. Therefore, the scenario assumes an existing ultra-supercritical power plant to be retrofitted with a CCS system setting the following parameters:

Population
25,418,000

Coal capacity
103 GW

Consumption
395.7 TWh

Renewable share
24 %

Factsheet scenario 1

Parameters for Scenario 1 "Inner Mongolia, Northeast China"

Parameter	Value	Reasoning
Efficiency[48]	43 %	Ultra-supercritical power plant technology
Full load hours[49] Ø over lifetime	3,500 hours	Good grid connection for electricity export; Excellent renewable area potential and yield
Lifetime	25 years	
CO_2-transport	5.37 CNY/ton_{CO2}	50 km distance to potential CO_2 storage
CO_2-Capture Rate	80 %	1. generation CCS technology for retrofitted plants

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[48] Efficiency without capture process.

[49] We assume that with the expansion of renewables, full load hours of coal fired power plants decrease with advancing years. To reduce complexity, our assumption states an average value for the full load hours over the plant lifetime. Further factors influencing the assumption on full load hours are the plant efficiency as well as the grid connection.

Scenario 2 (EWI)

Scenario 2: Newly built ultra-supercritical coal power plant in Guangdong, South-east China in 2030

Guangdong is one of the provinces with the highest energy consumption in China. In 2020, it had a net electricity import of 200 TWh. The capacity of coal power plants was 68.4 GW in 2023, and with its broad coastline, coal can easily be imported. CO_2 storage potential is very low and only accessible at large distances; however, due to its broad coastline, there is potential for deep water CO_2 storage. The province has mediocre renewable capacity factors, with 16 % for solar PV, 24.7 % for wind onshore, and 30 % for wind offshore. However, due to its high population density of 700 people/km², the space for RE power plants could be limited. Furthermore, it is only connected to the South China regional electricity grid, showing only the potential to import electricity from Guangxi, Guizhou, and Yunnan.

Due to the above-described characteristics, it is assumed that with the trend of increasing electricity consumption, Guangdong will add additional coal power capacity along with RE capacity and increased imports from neighboring provinces. Therefore, the scenario assumes a newly built ultra-supercritical power plant with the following parameters:

Population
134,340,000

Coal capacity
68 GW

Consumption
786.7 TWh

Renewable share
29 %

Factsheet scenario 2

Parameters for Scenario 2 "Guangdong, South-east China"

Parameter	Value	Reasoning
Efficiency	43 %	Ultra-supercritical power plant technology
Full load hours[2] Ø over lifetime	5,500 hours	Mediocre grid connection for electricity import; Mediocre renewable area potential and yield; Newly built power plant
Lifetime	35 years	
CO_2-transport	85.95 CNY/ton$_{CO2}$	1000 km distance to potential CO_2 storage; Deep water CO2 storage might be a cheaper option
CO_2-Capture Rate	90 %	2. generation[50] CCS technology for newly built plants
Biomass co-firing	20 %	biomass feedstocks from agricultural and forestry residues available

Scenario 3 (EWI)

Scenario 3: Retrofit of a supercritical coal power plant in Shanghai, East China in 2030

Shanghai and its neighboring provinces, Zhejiang and Jiangsu, are one of the leading industrial regions in China. With 74 TWh of net electricity import, Shanghai imported almost 50 % of its electricity in 2020. The capacity of coal power plants was 15.7 GW in 2023, the broad coastline coal favors coal imports, and the neighboring regions show good CO_2 storage potential. The province has good renewable capacity factors, with 16 % for solar PV, 29 % for wind onshore, and 32 % for wind offshore. However, due to its extremely high population density of 3,900 people/km², which is also reflected in the neighboring provinces with 550–850 people/km², the space for RE power plants might be limited. However, it is well connected with multiple electricity exporting regions such as Inner Mongolia, Xinjiang, and Shanxi via HVDC.

Due to the above-described characteristics, it is assumed that in Shanghai, the existing coal power plants will still be used in the future. However, the future electricity demand is assumed to be mainly covered by electricity imports. Therefore, the scenario assumes an existing supercritical power plant to be retrofitted with a CCS system with the following parameters:

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[50] 2. Generation capture technology is assumed to have a 10 % markup on investment cost (own assumption).

Population
26,365,000

Coal capacity
16 GW

Consumption
175.0 TWh

Renewable share
32 %

Factsheet scenario 3

Parameters for Scenario 3 “Shanghai, East China”

Parameter	Value	Reasoning
Efficiency	39 %	Supercritical power plant technology
Full load hours[2] Ø over lifetime	3,000 hours	Excellent grid connection for electricity import; Good renewable yields but limited renewable area potential
Lifetime	20 years	
CO_2-transport	32.23 CNY/ton$_{CO2}$	300 km distance to potential CO_2 storage
CO_2-Capture Rate	80 %	1. generation CCS technology for retrofitted plants

CCS Ranking

2030							
Weighting factor	1,5	1,5	1	0	0,5	0,5	
	Costs	Technical Availability	Mitigation Potential	Feasibility	Availability of Alternatives	Emission Source	**Overall Score**
Cement	3	4	5	3	5	5	**21**
Lime	2	3	5	3	5	5	**18**
Waste – waste incineration	2	3	5	3	5	5	**18**
Hydrogen – coal / gas	4	5	4	5	4	2	**21**
Steam Cracker	3	3	4	4	5	4	**18**
Chemicals – Coal Fischer-Tropsch	4	5	3	5	4	2	**20**
Power – coal post combustion (retorfit)	3	5	4	4	3	1	**18**
Power – coal post combustion (greenfield)	3	5	3	5	2	1	**17**
Steel Industry (BOF)	3	4	2	4	2	3	**15**
Steel Industry (DRI - Coal/gas)	3	4	3	4	3	3	**17**
BECCS	2	3	5	3	5	5	**18**
DACCS	1	1	3	1	5	5	**11**

2040/2050							
Weighting factor	1	1	1	0	1	1	
	Costs	Technical Availability	Mitigation Potential	Feasibility	Availability of Alternatives	Emission Source	**Overall score**
Cement	4	5	5	4	5	5	**24**
Lime	4	5	5	4	5	5	**24**
Waste – waste incineration	4	5	5	4	5	5	**24**
Hydrogen – coal / gas	5	5	3	5	2	2	**17**
Steam Cracker	5	5	4	4	3	4	**21**
Chemicals – Coal Fischer-Tropsch	5	5	3	5	3	2	**18**
Power – coal post combustion (retorfit)	5	5	3	3	2	1	**16**
Power – coal post combustion (greenfield)	5	5	1	3	1	1	**13**
Steel Industry (BOF)	5	5	1	3	1	3	**15**
Steel Industry (DRI - Gas/Coal)	5	5	3	3	2	3	**18**
BECCS	5	4	5	3	5	5	**24**
DACCS	3	3	4	3	5	5	**20**

2060							
Weighting factor	0	0	1	0	1	1	
	Costs	Technical Availability	Mitigation Potential	Feasibility	Availability of Alternatives	Emission Source	**Overall score**
Cement	5	5	5	4	5	5	**15**
Lime	5	5	5	4	5	5	**15**
Waste – waste incineration	5	5	5	4	5	5	**15**
Hydrogen – coal / gas	5	5	2	1	1	2	**5**
Steam Cracker	5	5	3	2	2	4	**9**
Chemicals – Coal Fischer-Tropsch	5	5	1	1	1	2	**4**
Power – coal post combustion (retorfit)	5	5	1	1	1	1	**3**
Power – coal post combustion (greenfield)	5	5	1	1	1	1	**3**
Steel Industry (BOF)	5	5	1	1	1	3	**5**
Steel Industry (DRI - Gas/Coal)	5	5	2	1	1	3	**6**
BECCS	5	5	5	5	5	5	**15**
DACCS	5	5	5	5	5	5	**15**

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