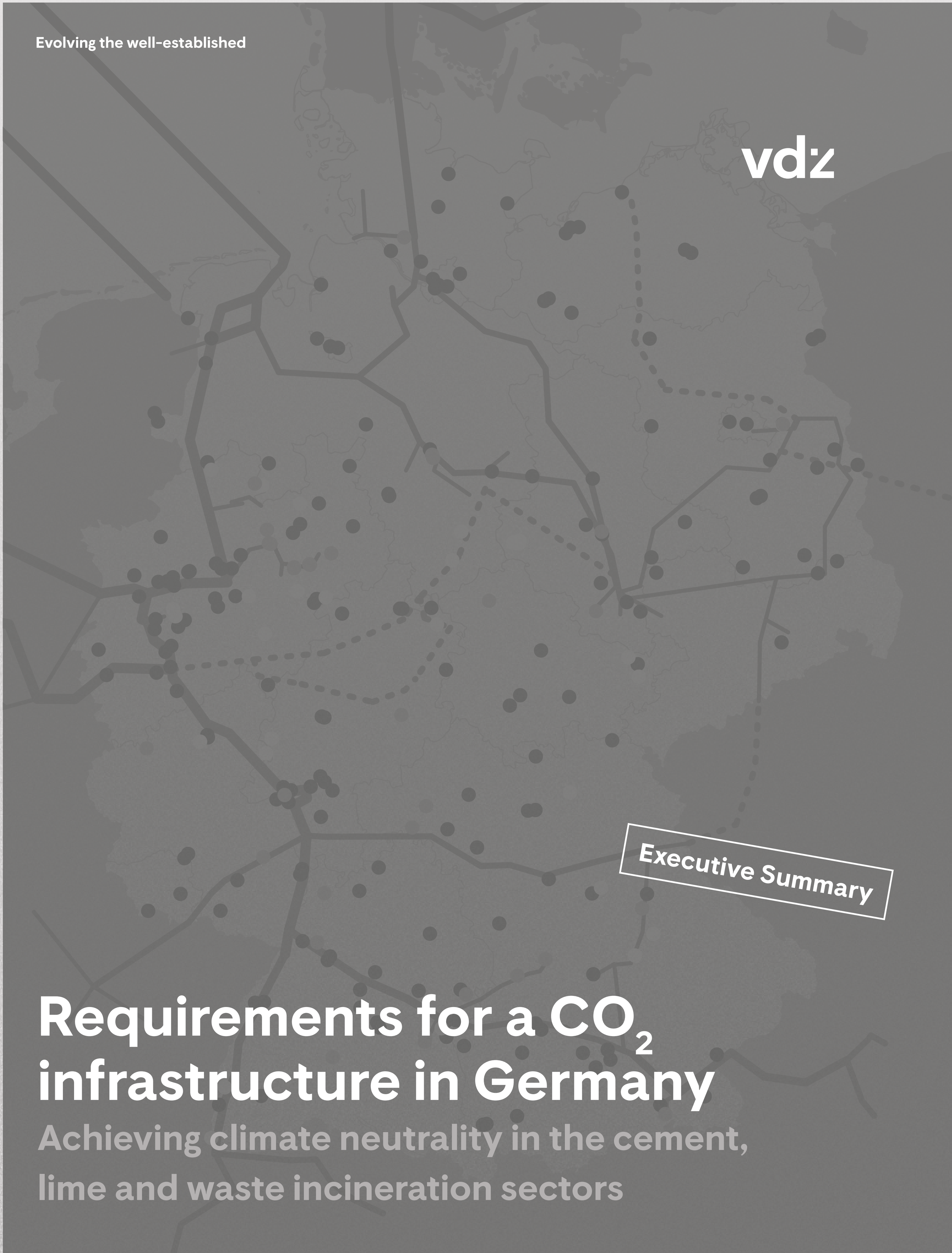

Evolving the well-established

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Executive Summary

Requirements for a CO_2 infrastructure in Germany

Achieving climate neutrality in the cement, lime and waste incineration sectors

Requirements for a CO_2 infrastructure in Germany

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Unavoidable CO_2 emissions and the need for a CO_2 infrastructure to achieve climate neutrality

With the EU Green Deal and the German Climate Protection Act, the EU and Germany have committed to climate neutrality by 2050 and 2045 respectively. In order to achieve this ambitious goal, the industry is dependent on a wide range of climate protection technologies and the corresponding political framework conditions.

Sectors with long-term high and unavoidable CO_2 emissions include cement and lime production as well as waste incineration. Even if every effort is being made to reduce CO_2 emissions here, a proportion will remain, which cannot be avoided with the processes currently in use. In order to still achieve the climate targets and not jeopardise local industrial value creation, there is no way around the capture of these unavoidable CO_2 quantities with subsequent storage and utilisation (CCS/CCU) in these areas. There is a growing consensus on this in climate policy at international and national level. In Germany, the national Carbon Management Strategy will set the political framework for the use of CCS and CCU.

CO_2 capture and subsequent utilisation or storage needs the transport of CO_2 from the source to the sink. This requires a CO_2 infrastructure, which must be developed quickly and, above all, pragmatically, because time is of essence. For industrial plants in the EU Emissions Trading Scheme (EU ETS) in particular, the annually decreasing volume of CO_2 allowances is the key indicator for the pace of decarbonisation. If the current legal framework continues, no more new CO_2 allowances will be issued around 2040. Conversely, this means that EU ETS plants will have to operate in a largely climate-neutral way by then. In order for CO_2 capture to function on time, a CO_2 infrastructure must be established by the mid-2030s at the latest.

In this study, VDZ presents the expected, unavoidable CO_2 emissions in the three sectors analysed. Based on this, the requirements for CO_2 transport as well as for a national and cross-border CO_2 infrastructure have been derived. Companies and associations were involved along the CCUS chain focussing on the following key questions:

- How will the unavoidable CO_2 emissions develop?
- How must CO_2 capture develop in terms of time and geography?
- What infrastructure requirements does this result in for CO_2 transport?
- What requirements must be met for the CO_2 infrastructure to be set up quickly?

Unavoidable CO_2 emissions

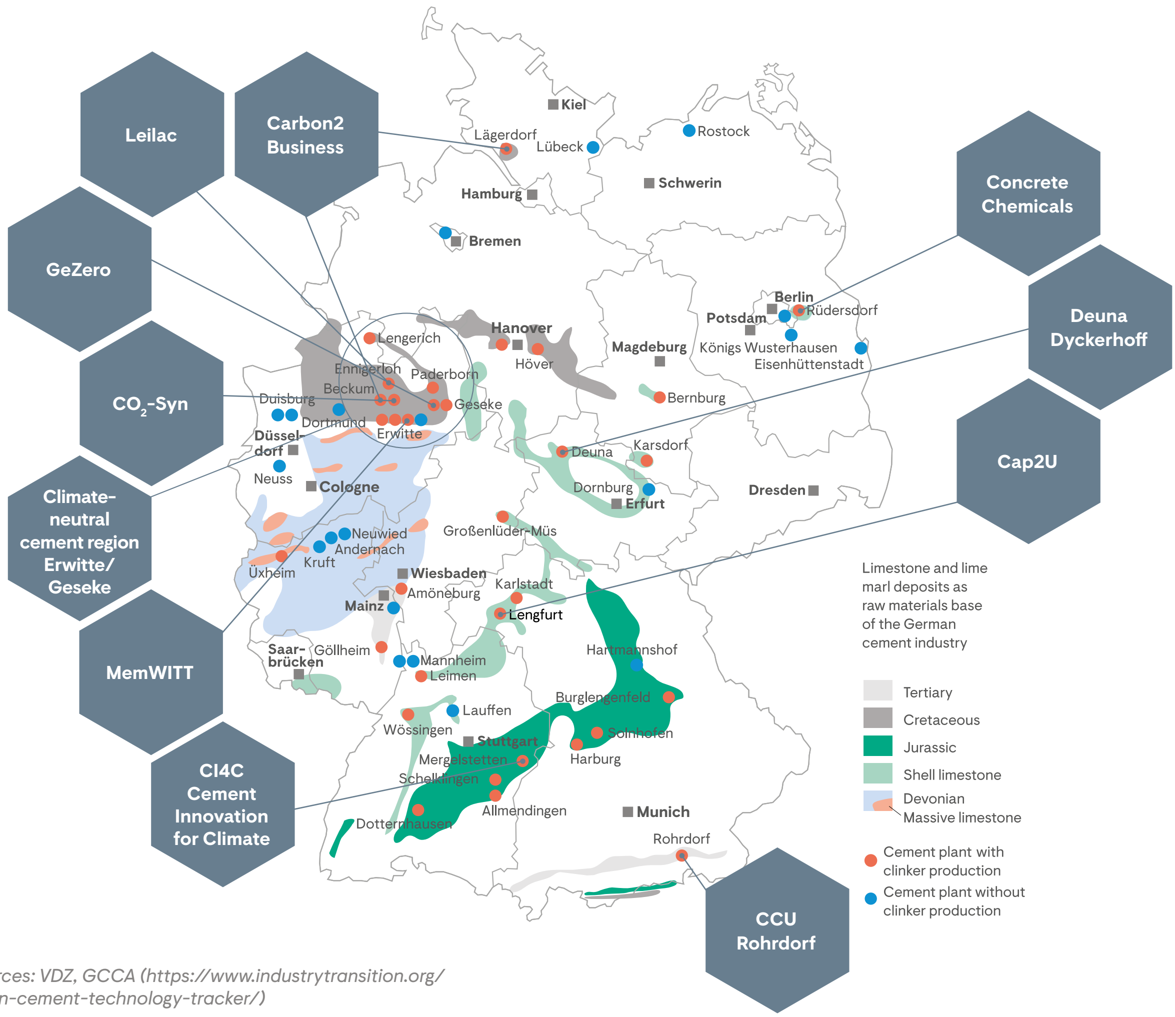
The cement and lime industries as well as the waste incineration are characterised by high unavoidable CO_2 emissions. In addition, CO_2 emissions which are difficult to avoid can also arise in other industrial processes[1]. In cement and lime production, it is primarily the CO_2 emissions from the use of limestone as a raw material. To decarbonise, manufacturers, on the one hand, reduce CO_2 emissions through a broad mix of conventional measures. On the other hand, an unavoidable amount of CO_2 emissions remains, which can only be avoided by capturing the CO_2 with subsequent storage or utilisation.

Against this background, German and European cement manufacturers and VDZ have been researching suitable processes for CO_2 capture under the umbrella of the European Cement Research Academy (ECRA) since 2007. As a result of this extensive research work, various processes are currently being tested on a pilot and demonstration scale; further projects on an industrial scale are already being planned (Figure 1). Corresponding projects have also been announced in the lime industry and in waste incineration plants.

This analysis focuses on the unavoidable CO_2 emissions from cement and lime plants[2] as well as waste incineration plants[3], for which a CCUS application is essential to achieve climate neutrality. In contrast to EU emissions trading, the CO_2 emissions – including their biogenic fractions will be examined. This is based on the fact that negative CO_2 emissions can ultimately be achieved by capturing the biogenic components (BECCS[4]). Climate neutrality in itself can already be achieved if the fossil components of CO_2 emissions (raw material and fuel-related) are fully reduced.

1) The quantities of CO_2 that are difficult to avoid and for which CO_2 capture may also become relevant are currently difficult to estimate. They are therefore not considered in detail in this study. Nevertheless, they must be taken into account when dimensioning a CO_2 infrastructure.
2) Lime production in sugar refineries is not taken into account, as these only produce lime seasonally and to a comparatively small extent, meaning that CO_2 capture will hardly be economically viable in future.
3) Waste incineration plants include thermal waste treatment plants, refuse-derived fuel (RDF) plants, sewage sludge mono-incineration plants and plants for the incineration of waste wood and hazardous waste. The latter were not included in this study.
4) BECCS: bioenergy with carbon capture and storage

Figure 1: CO_2 capture in the cement industry – examples of projects in Germany



Sources: VDZ, GCCA (https://www.industrytransition.org/green-cement-technology-tracker/)

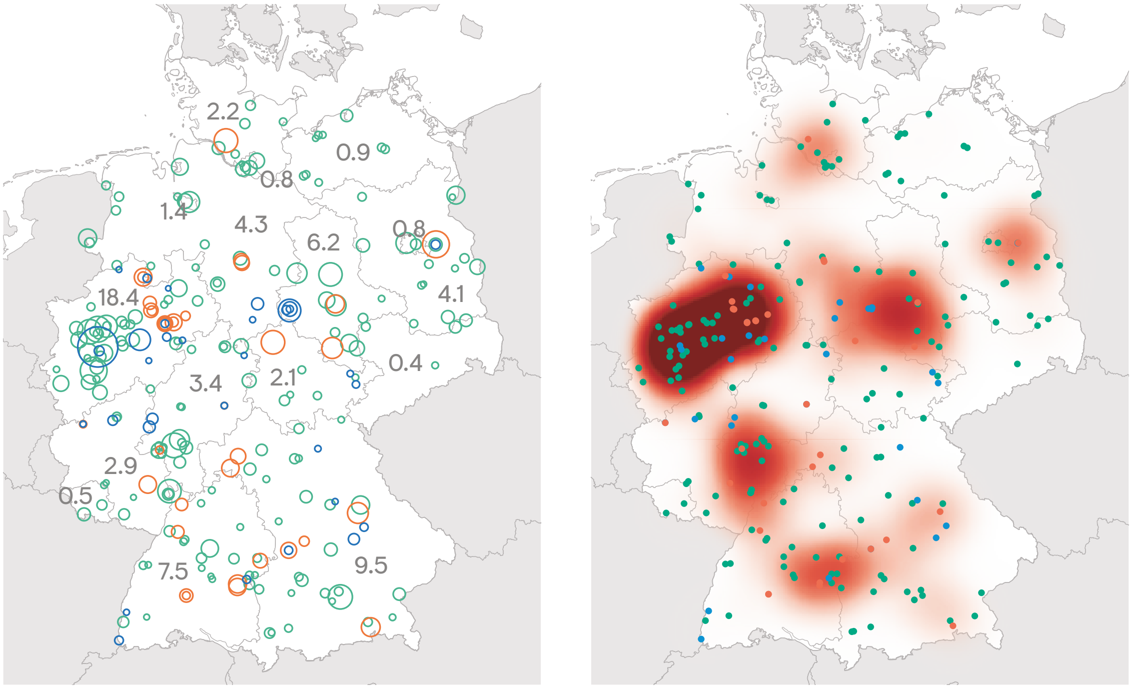
The three sectors currently emit around 65 Mt of biogenic and fossil CO_2 per year. Conventional reduction measures will reduce these emissions to around 58 Mt CO_2 per year by 2045. The majority of the reduction will take place in the cement industry (from 21.7 to 13.5 Mt per year). These figures are based on corresponding studies of the industries and is the starting point for analysing the infrastructure requirements.

CO_2 clusters in Germany

Based on the geographical distribution of emissions from the CO_2 sources under consideration, in Germany around ten clusters with CO_2 emissions of 2 to 7 Mt CO_2/a each can be derived from a density distribution (Figure 2). These serve as the basis for modelling the infrastructure requirements. Other comparatively small CO_2 sources located outside these clusters and CO_2 quantities from neighbouring countries for transit to the north were also included in the analysis of transport volumes.

The decisive factor for the regional and temporal development of CO_2 transport requirements are the assumptions regarding the development of CO_2 emissions in the three sectors over time. The study therefore analyses two scenarios for climate neutrality, each in the years 2040 (CN2040) and 2045 (CN2045), for which the need for CO_2 capture and the requirements for a corresponding CO_2 infrastructure are modelled.

Figure 2: Geographical distribution of CO_2 emissions in the cement, lime and waste incineration sectors (today)



● Cement ● Lime ● Waste incineration

Mt CO_2 /year ○ 1.0 ○ 0.5 ○ 0.1

Figures: Absolute CO_2 quantities per federal state

Sources: VDZ, EU-ETS, E-PRTR, BV Kalk, ITAD

● Cement ● Lime ● Waste incineration

CO_2 density

Low High

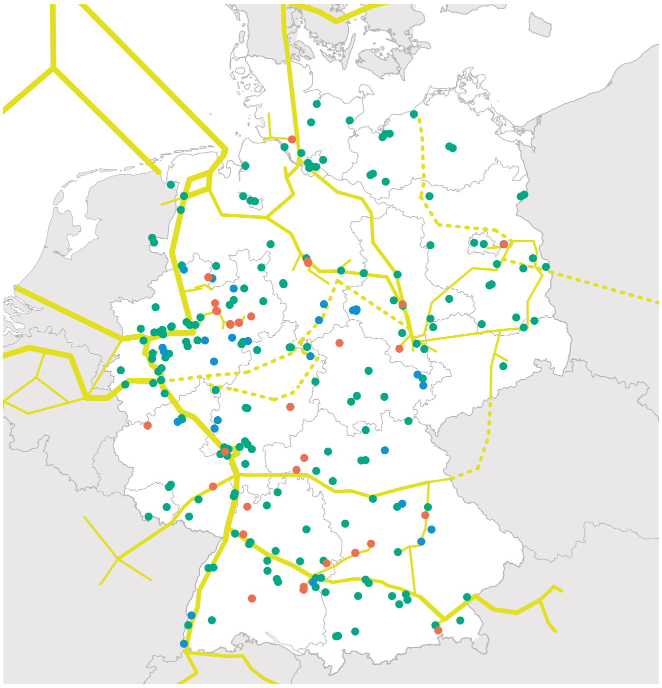
Prospects for a CO_2 transport in Germany

The study looks at multimodal CO_2 transport by pipeline, rail or ship. While transport via pipelines can be carried out continuously, rail and ship transport are discontinuous processes that generally require intermediate storage of CO_2 at the point of origin and at the transfer points. This must be taken into account in the site-specific assessment. Possible restrictions with regard to uninterrupted rail and ship transport must also be taken into account (e.g. strikes, high and low water).

In the medium and long term, the majority of CO_2 transport will have to take place via pipeline in view of the expected volumes. The early establishment of a CO_2 pipeline network is crucial for this. In this regard, initial project announcements have been made by network operators. On this basis, the study presents a perspective for a Germany-wide CO_2 network. In certain cases, trains and possibly ships will also play a role, as the analysed scenarios show. In terms of volume, however, CO_2 transport by rail will only play a minor role in the future.

Each transport option has distinct technical requirements for its respective infrastructure. Additionally, CO_2 needs to meet specific standards for pressure, temperature, and purity. These largely determine the cost-effectiveness and efficiency of CO_2 transport. The effort and requirements differ significantly between the transport options. Overall, pipeline transport is the most efficient choice for transporting large quantities of CO_2.

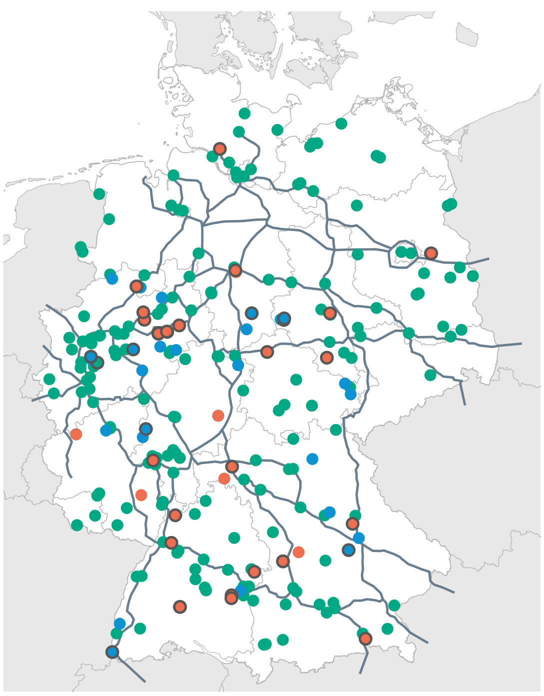
Figure 3: A CO_2 pipeline network for Germany



● Cement ● Lime ● Waste incineration
CO_2 pipelines Alternatives

Sources: VDZ, BV Kalk, ITAD, OGE, bayernets, CapTransCO_2

Figure 4: CO_2 transport by rail – Corridors and rail connections of plants



● Cement ● Lime ● Waste incineration
○ Rail connection available

Sources: VDZ, EU-ETS, E-PRTR, BV Kalk, ITAD, DB, Expert interviews
Note: Analysis of rail connections only for cement and lime plants

Connection of the CO_2 sources

The question of the connection to the future CO_2 infrastructure is decisive for the choice of transport option. If one compares the geographical distribution of the sites in the three sectors with the infrastructure projects for CO_2 transport that are currently planned or announced, the following picture emerges from the analysis:

Almost all cement and lime industry sites are located at a distance of around 50 kilometres from the corridors for CO_2 pipeline networks that have been planned to date. This also applies to a large number of waste incineration plants. Therefore, a connection to a pipeline appears possible for the majority of CO_2 sources (Figure 3).

In general, CO_2 transport by rail is also possible (Figure 4). Many cement and lime plants have a railway siding, but this is not sufficient as a prerequisite. Among other things, a loading infrastructure has to be set up, railway sidings expanded and, if necessary, upstream sections of track have to be upgraded. In addition, reloading the CO_2 at the transfer points to the sink involves a great deal of effort, meaning that this option is only possible in certain cases.

However, transport by inland waterway only seems conceivable at very few locations that are close to larger waterways or have a harbour connection. In addition to the necessary expansion for CO_2 transport, factors such as high and low water levels must also be taken into account.

The same applies to all CO_2 transport options: A site-specific assessment is required for all sources and the respective type of connection has to be determined.

For CO_2 exports from corresponding hubs on the coast (e.g. in Wilhelmshaven and Zeebrugge) to geological CO_2 storage sites under the North Sea, however, transport by sea-going vessel will play a greater role, at least until offshore CO_2 pipelines are available to a sufficient extent.

CO_2 storage and utilisation

In addition to transport, the required capacity of CO_2 sinks is a key factor for the rapid development of CO_2 capture over time. An evaluation of currently planned and published storage projects shows that by 2030, an annual storage capacity of around 30 Mt CO_2 can be expected within the EU and over

50 Mt CO_2 in Europe as a whole[5]. By 2038, the currently known projects indicate annual storage capacities of just under 50 Mt CO_2 in the EU and around 140 Mt CO_2 in Europe as a whole – in each case assuming that the projects can be implemented as planned.

The focus for storage is on the continental European North Sea coast of Denmark, the Netherlands and the Norwegian and British North Sea (Figure 5). At the same time, CO_2 storage projects are also being developed on land, e.g. in France, Denmark and Poland. In the future, onshore storage options will be availabe at significantly lower costs than offshore storage. Due to growing demand and new regulation, it can be assumed that the expansion of storage capacities in Europe will continue to accelerate. The utilisation of existing former gas fields in Central Europe for the temporary storage of CO_2, as planned in Austria, for example, can represent a transitional solution for locations for which a pipeline connection will not be established until later.

There is also considerable CO_2 storage potential under the German North Sea. According to a research project by the Geomar Institute in Kiel, Germany's offshore CO_2 storage potential is estimated to be in the order of 1.9 to 10.4 Gt. An annual storage capacity of around 20 Mt CO_2 is estimated initially and significantly more in the medium term. In addition to CO_2 storage sites under the seabed, there are also geological formations under the German mainland that are generally suitable for CO_2 storage.

Although CO_2 utilisation (CCU) is included in this study, it cannot be explicitly depicted in the infrastructure modelling, because the quantitative, geographical and temporal development of CO_2 demand up to 2045 is still unclear. In addition, it must be clarified how the enormous demand for the required renewable electricity can be met. Overall, this analysis assumes that regional CO_2 utilisation can already make an important contribution to climate protection before 2045 and that a CCS-oriented pipeline network will also serve as the basis for increasing CCU integration.

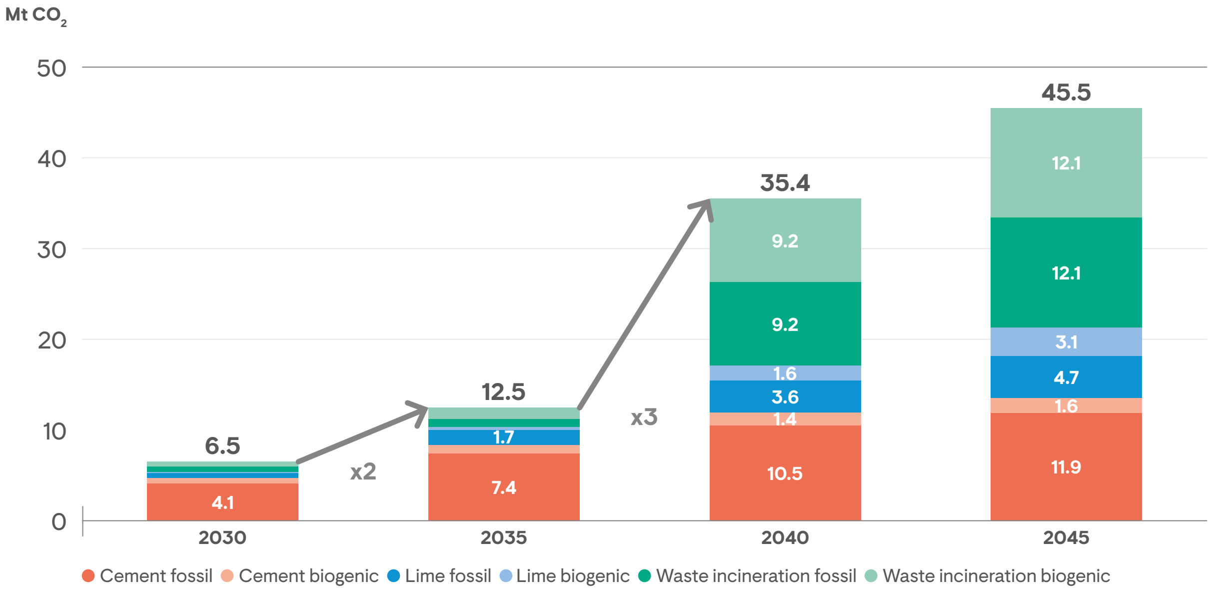
Figure 5: CO_2 storage facilities and hubs in Europe

- Projects with planned CO_2 storage from 2030
- Possible further CO_2 storage facilities
- Planned and possible CO_2 hubs

Sources: VDZ, IOGP, project websites

5) EU, Norway, Iceland, UK

Figure 6: Development of CO_2 capture over time in Germany – CN2040 scenario



Sources: VDZ, EU-ETS, E-PRTR, BV Kalk, ITAD

CO_2 infrastructure ramp-up: Scenarios and assumptions

The development of CO_2 transport is modelled on the basis of two scenarios. In the CN2040 scenario, climate neutrality is to be achieved in 2040. The background to this is the current reduction path of the EU Emissions Trading Scheme. It determines that no new CO_2 certificates will be issued from 2040 at the latest, making largely climate-neutral production necessary. In comparison, a second scenario is considered in which the development of the pipeline network is delayed by five years and climate neutrality is not achieved until 2045 (CN2045). This is based on the national climate target enshrined in the German Federal Climate Protection Act.

For the CO_2 transport requirement, the captured volumes for the years 2030, 2035, 2040 and 2045 are calculated (Figure 6). In the CN2040 scenario, infrastructure development in the form of CO_2 pipelines is assumed to begin as early as 2028, with the first sites connected. Compared to the CN2045 scenario, larger quantities of CO_2 can be transported earlier. In CN2045, starting in 2028, CO_2 will initially only be transported by rail. Afterwards, beginning in 2033 pipeline transport will be implemented at a high expansion rate.

Climate neutrality scenario 2040

The central scenario of climate neutrality in 2040 (CN2040) results in an annual CO_2 transport requirement of around 6 Mt in 2030, around 13 Mt in 2035 and around 35 Mt in 2040. In 2045, this will rise to 45 Mt in Germany (Figure 7). In addition, there will be additional volumes of 15 to 20 Mt CO_2 per year for transit from the neighbouring countries of Austria, Switzerland and France beginning in 2035.

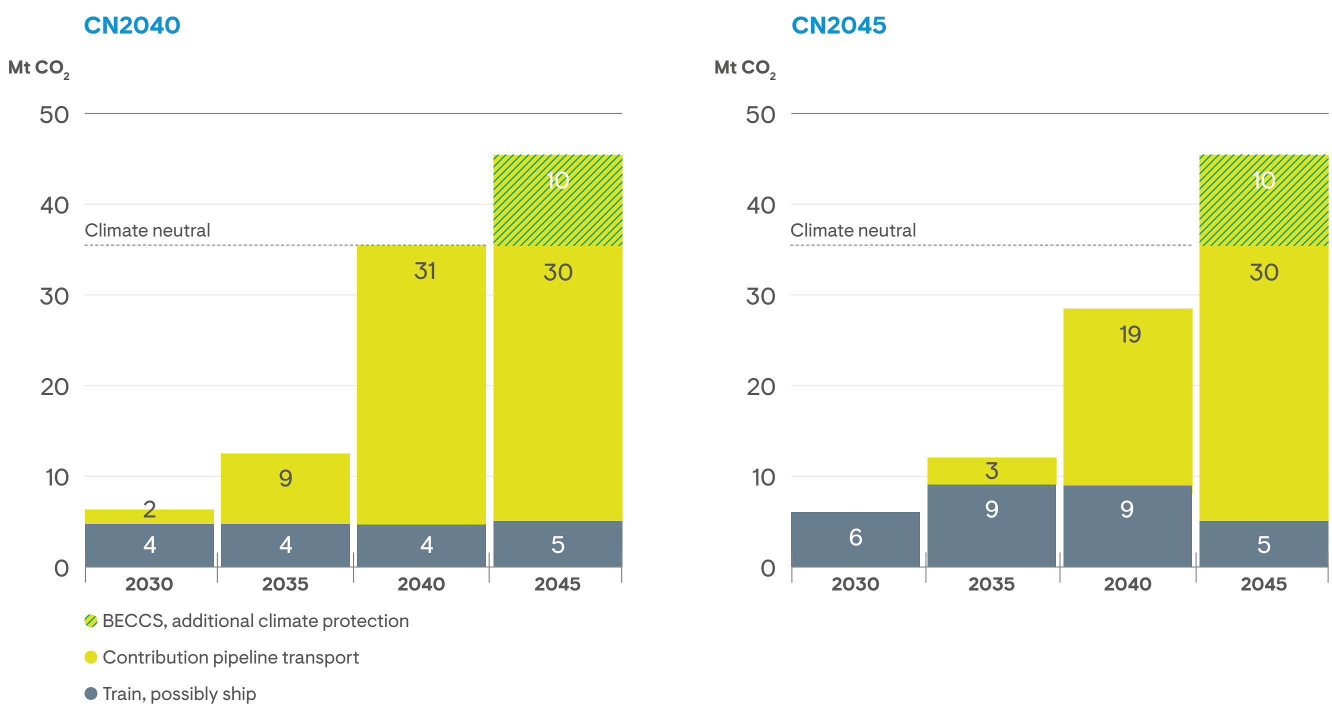
In CN2040, up to 5 Mt CO_2 will be transported by train or ship every year. A very rapid ramp-up of pipeline transport leads to a transport volume by pipeline of 3 Mt CO_2 in 2028, which will be expanded to 30 Mt CO_2 by 2040 and to around 40 Mt in

the long term by 2045. After 2040, the capture of biogenic CO_2 from the co-incineration of sustainable biomass-containing waste will result in negative emission contributions of approx. 10 Mt per year.

There is ultimately no alternative to the rapid ramp-up of CO_2 capture and infrastructure expansion for the sectors under consideration if largely climate-neutral production is to be achieved by 2040. This also results in a highly ambitious pace of expansion for the necessary CO_2 network. By 2035 at the latest, all ten identified clusters must be connected to a transport and storage infrastructure, mostly by pipeline and partly by rail.

In total, around 4,800 km of long-distance pipelines and 3,000 annual trips by 20 block trains with tank wagons are required to transport the CO_2. In the CN2040 scenario, CCUS can save cumulative emissions of around 500 Mt CO_2 in Germany over 20 years; this includes around 50 Mt of negative CO_2 emissions from the capture and storage of biogenic CO_2.

Figure 7: CO_2 transport requirements for pipeline, train and ship transport in Germany



Source: VDZ

Climate neutrality scenario 2045
In this scenario, the CO_2 sources are not connected to a CO_2 pipeline network until 2033, i.e. five years later than in CN2040 (Figure 7). Accordingly, the demand for train and ship transport – after initially around 6 Mt – is now almost twice as high as in CN2040 at 9 Mt CO_2 per year. However, the CO_2 pipeline network will also need to be expanded very rapidly from 2033 onwards. As of 2040, almost 20 Mt of CO_2 per year will be transported by pipeline. From 2045 onwards, 90% of the captured CO_2 will also be transported by pipeline in this scenario, with the proportion transported by train and possibly ship decreasing accordingly.

In the CN2045 scenario, the removal of biogenic CO_2 from the co-combustion of sustainable waste-derived biomass also enables a negative emissions contribution of 10 Mt CO_2 per year after 2040.

Climate protection contribution through CO_2 infrastructure
With the ramp-up of CO_2 transport in the CN2040 scenario, cumulative CO_2 savings of around 500 Mt CO_2 can be achieved over 20 years (from 2028 to 2047)[6] in the sectors under consideration. With a later CO_2 pipeline expansion starting in 2033 according to the CN2045 scenario, emissions totalling around 460 Mt CO_2 will be avoided in the same period. It is worth noting that a further delay in infrastructure expansion of five years – i.e. a start of rail transport from 2033 and pipeline transport beginning thereafter – would only result in cumulative savings from CCUS of around 230 Mt CO_2. In this case, an additional amount of 270 Mt CO_2 would be released into the atmosphere, and climate neutrality in 2045 would not be achieved either. In this respect, both scenarios show that rapid action is crucial when setting up the CO_2 infrastructure in Germany.

Table 1: CO_2 emissions, capture quantities and additional energy demand in the CN2040 scenario

		2030	2035	2040	2045	Cumulative*
CO_2 balance for cement, lime and waste incineration in Germany						
CO_2 formation	Mt CO_2/a	63.3	61.2	57.4	57.9	1,200
thereof fossil		42.2	39.7	35.4	34.7	760
CO_2 capture[7]	**Mt CO_2/a**	**6.5**	**12.5**	**35.4**	**45.5**	**500**
additional energy requirement[8]						
electric	TWh/a	2.0	3.8	9.5	12.3	
thermal	TJ/a	7,800	16,500	76,000	99,000	

**Cumulative: total for the period 2028 to 2047*

6) The study uses a period of 20 years from 2028 as the basis for calculating the cumulative CO_2 savings from CCUS. This is divided into 5-year steps in the modelling of the infrastructure ramp-up in order to make statements about the influence of the expansion speed on the achievable CO_2 savings.
7) In contrast to cement and lime, it is assumed that only around two thirds of the expected long-term amount of CO_2 can be captured during waste incineration due to various restrictions. On average, 50% biogenic CO_2 is assumed, so that the sector nevertheless achieves climate neutrality.
8) The additional thermal energy requirement is mainly due to the use of separation processes such as amine scrubbing. The additional electrical energy requirement results primarily from integrated separation processes such as oxyfuel technology and the energy requirement for the subsequent further concentration of the CO_2. Assumptions for capture technologies: cement – 80% Oxyfuel, 20% post combustion (amine scrubbing); lime – 100% Oxyfuel; waste incineration – 100% post combustion (amine scrubbing).

Investment requirements and costs
The investment required to build the 4,800 km long CO_2 pipeline network identified in this study is estimated to be around EUR 14 billion. Applying this to the estimated transport volumes by pipeline of around 415 Mt CO_2 by 2045 results in calculated costs of around EUR 35 per t CO_2. If the transit volumes from neighbouring countries are also included, these could fall further to around EUR 25 per t CO_2[9)]. The operating costs for the pipeline network are considered to be comparatively low.

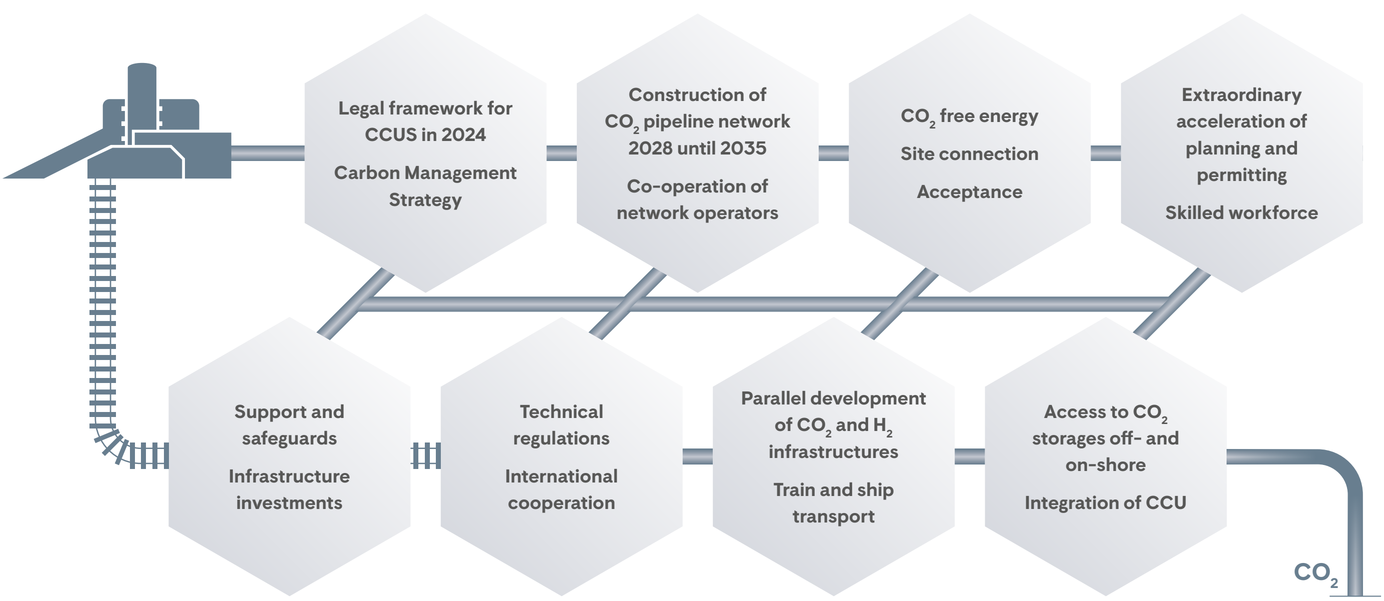
Even if a direct comparison of transport costs must be made on a site-specific basis, this study currently expects costs in the range of EUR 35 to 60 per t CO_2 for transport by rail for distances of more than 500 km, including the infrastructure for loading and unloading[10)]. The costs can also be lower for shorter transport distances.

Energy requirements of CO_2 capture
CO_2 capture is associated with an enormous demand for renewable energy. Based on the modelling, the annual electricity demand in the cement and lime industries will increase to almost four times the current level (from 4.7 TWh to around 17 TWh in 2045). The thermal energy demand per year in the three sectors will increase by almost 100,000 TJ or 20% compared to 2021[11)] (Table 1).

In addition, the demand for electrical energy must be secured with base load-capable generation capacity, as continuous operation of the CO_2 capture system must be guaranteed.

In this respect, the success of decarbonisation depends to a large extent on whether the capacities for renewable energies are expanded significantly faster than before and whether the locations with CO_2 capture are connected to reinforced electricity grids in good time.

Figure 8: Prerequisites and fields of action



Source: VDZ

9) Costs for the connection to the transmission grid are not included. The figures relate to onshore pipeline transport in Germany.
10) This does not include the conditioning of CO_2 for rail transport at the departure and destination stations.
11) CO_2 capture in cement and lime works begins at high initial CO_2 concentrations in the flue gas (≥ 20%). As a result, the high energy requirement shown here in relation to the amount of CO_2 captured is still significantly lower than for capturing the same amount from the air (Direct Air Capture). Furthermore, some of the additional thermal energy required by waste incineration plants and cement works can be covered by waste heat.

Legal framework and fields of action

Key prerequisites for carbon capture in the cement, lime and waste incineration sectors and the necessary development of a CO_2 infrastructure are social and political support and, above all, an appropriate legal basis (Figure 8). The Carbon Management Strategy planned at federal level is an important first step in this regard, setting the political guidelines for the use of CCUS in Germany[12)]. Building on this, the existing legal framework for the authorisation of plants for CO_2 capture, pipeline-connected and cross-border CO_2 transport, as well as for CO_2 utilisation and (interim) storage must be adapted or expanded as early as 2024[13)].

The new legal framework must also focus on the urgently needed acceleration of planning and authorisation procedures. To this end, it is necessary that suitable regulations for the expansion of a hydrogen economy are also transferred to CO_2 transport. Above all, an overriding public interest for CCSU projects and the included infrastructure has to be inshrined in law (with regard to climate protection).

It will be crucial to push ahead with the expansion of the CO_2 network, not only from north to south, but also simultaneously in various regions with large CO_2 clusters, and to increasingly parallelise it with the expansion of the hydrogen core network. This is the only way to connect the relevant industrial regions to a CO_2 infrastructure in good time in order to achieve the climate targets and maintain their competitiveness.

Another prerequisite for the rapid expansion of the CO_2 grid is that the network operators in Germany and beyond are able to cooperate with each other on planning in a timely manner. It is important to weigh up whether network development planning, as with natural gas or electricity, is conducive to rapid infrastructure expansion and therefore necessary. However, an early start to pipeline expansion should not be linked to such a prerequisite. It will also be crucial that technical standards and regulations for grid, transport and storage operations can be applied across national borders thus enabling European carbon management.

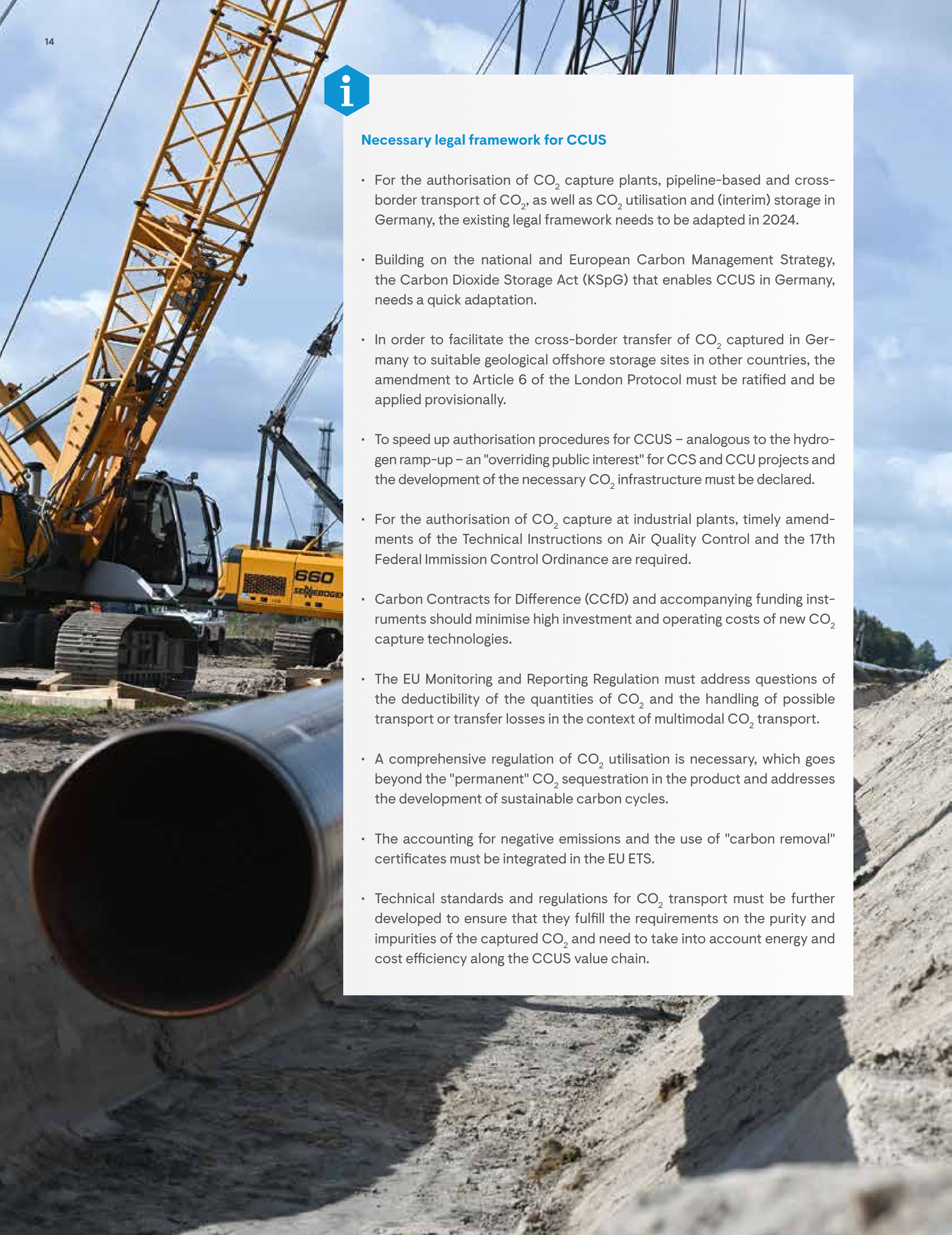
As with the core network to transport hydrogen, investment risks must be hedged in an early phase with a small number of CO_2 network users, and costs for the leased CO_2 transport must be regulated in a similar way to hydrogen. The aim should be to achieve distance-independent grid charges, as otherwise locations with longer transport routes would be at a competitive disadvantage. It will also be important to ensure non-discriminatory grid access for CO_2 sources and potential users.

By developing its own CO_2 storage infrastructure – as is planned with the amendment to the Carbon Dioxide Storage Act – Germany can fulfil its climate policy responsibility and reduce the costs of CO_2 storage. In addition, this would minimise Germany's apparent one-sided dependence on partner countries and strengthen its strategic sovereignty in climate protection. At the same time, a competitive CO_2 infrastructure will become a key location factor in the future for industries with high unavoidable CO_2 emissions.

Decarbonisation poses unprecedented challenges for industry in Germany. This also applies to the cement, lime and waste incineration sectors, where climate neutrality can only be achieved if the unavoidable amounts of CO_2 are captured and the CO_2 is then stored or utilised. The operators of the plants will not be able to accomplish this task alone. Rather, a concerted effort from politics, industry, science and civil society is required. This involves recognising CO_2 capture for unavoidable CO_2 emissions and the rapid development of an infrastructure for the transport and storage or utilisation of the corresponding CO_2. The transformation can succeed, but time is pressing.

12) At the end of February 2024, the Federal Ministry for Economic Affairs and Climate Protection in Germany presented the key points of a national Carbon Management Strategy. This envisages the use of CCUS primarily in the cement, lime and waste incineration sectors.

13) The German Federal Ministry of Economics' proposal to create a Carbon Dioxide Storage and Transport Act at the end of February 2024 points in the right direction.



Necessary legal framework for CCUS

- For the authorisation of CO_2 capture plants, pipeline-based and cross-border transport of CO_2, as well as CO_2 utilisation and (interim) storage in Germany, the existing legal framework needs to be adapted in 2024.
- Building on the national and European Carbon Management Strategy, the Carbon Dioxide Storage Act (KSpG) that enables CCUS in Germany, needs a quick adaptation.
- In order to facilitate the cross-border transfer of CO_2 captured in Germany to suitable geological offshore storage sites in other countries, the amendment to Article 6 of the London Protocol must be ratified and be applied provisionally.
- To speed up authorisation procedures for CCUS – analogous to the hydrogen ramp-up – an "overriding public interest" for CCS and CCU projects and the development of the necessary CO_2 infrastructure must be declared.
- For the authorisation of CO_2 capture at industrial plants, timely amendments of the Technical Instructions on Air Quality Control and the 17th Federal Immission Control Ordinance are required.
- Carbon Contracts for Difference (CCfD) and accompanying funding instruments should minimise high investment and operating costs of new CO_2 capture technologies.
- The EU Monitoring and Reporting Regulation must address questions of the deductibility of the quantities of CO_2 and the handling of possible transport or transfer losses in the context of multimodal CO_2 transport.
- A comprehensive regulation of CO_2 utilisation is necessary, which goes beyond the "permanent" CO_2 sequestration in the product and addresses the development of sustainable carbon cycles.
- The accounting for negative emissions and the use of "carbon removal" certificates must be integrated in the EU ETS.
- Technical standards and regulations for CO_2 transport must be further developed to ensure that they fulfill the requirements on the purity and impurities of the captured CO_2 and need to take into account energy and cost efficiency along the CCUS value chain.

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