

## Article

# The German Cement Industry as a CO<sub>2</sub> Source for Other Industries

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**Abstract:** Cement production is responsible for about eight percent of global CO<sub>2</sub> emissions. A potential use for CO<sub>2</sub> is the production of synthetic fuels through power-to-X (PtX) processes. For this purpose, a potential analysis is performed in which the possibilities for CO<sub>2</sub> avoidance and CO<sub>2</sub> capture and utilization (CCU) in the cement manufacturing process are evaluated. Based on the potential analysis, three scenarios for the development of the German cement industry until 2050 are developed and displayed in geo-referenced form, yielding potential locations for PtX plants. Results show that it is unlikely that cement can be fully replaced by alternative construction methods or new types of binders from today's perspective. Measures to reduce CO<sub>2</sub> emissions in cement production are limited, especially due to the restricted possibilities to replace limestone as feedstock. In an intermediate scenario, CO<sub>2</sub> emissions in cement production decrease by 35% until 2050 compared to the average value from the 2014–2018 reference period. For CCU to be introduced at cement plants, the additional costs must be compensated, either through revenues from CO<sub>2</sub> certificates or economic and regulatory incentives.

**Keywords:** cement production; carbon emissions; carbon capture and utilization; power-to-X; synthetic fuels



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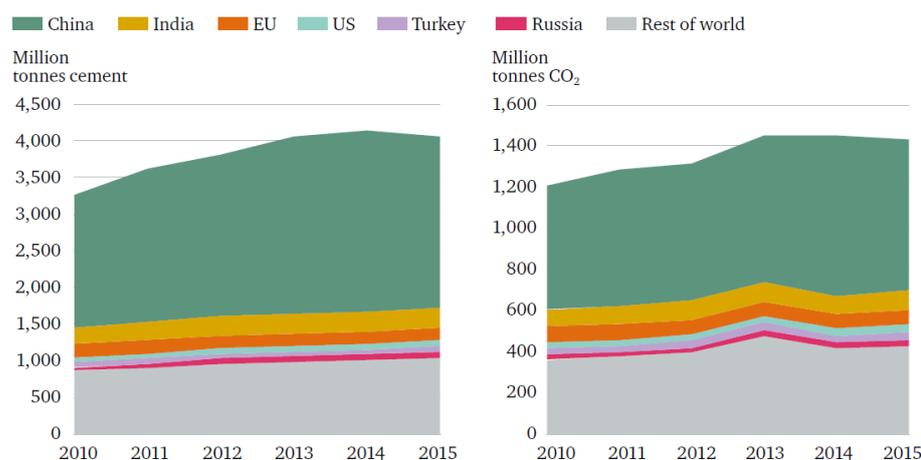
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## 1. Introduction

Cement is an essential raw material for the production of concrete, the world's second most consumed material [1]. Due to its high energy demand and inherent chemical processes, large amounts of carbon dioxide (CO<sub>2</sub>) are released during the cement production process: per kg of cement, 0.59 kg CO<sub>2</sub> are emitted on average [2]. Global cement production has increased strongly in recent years and is today the third largest source of man-made CO<sub>2</sub> emissions after the burning of fossil fuels and land use change [3]: more than 4 billion tons of cement are produced each year, accounting for about 8% of global CO<sub>2</sub> emissions [4]. On average, over half a ton of cement is produced per person per year globally [5].

Figure 1 shows global cement production and the CO<sub>2</sub> emissions released in the process for the years 2010–2015. The largest cement producer, China, is followed by India and the European Union (EU). The proportionality between production volume and emissions shows that cement production is generally CO<sub>2</sub>-intensive, regardless of the country of manufacture.

With 34 million tons in 2018, Germany is the EU's leading cement producer and the twelfth-largest producer globally [7]. The German cement industry is responsible for approximately 20 million tons of CO<sub>2</sub> annually or 17% of industrial CO<sub>2</sub> emissions in 2019 [8]; this illustrates that emission reductions in the cement industry can make a significant contribution to Germany's greenhouse gas reduction targets.



**Figure 1.** Cement production and cement-related CO<sub>2</sub> emissions from 2010 to 2015 [6].

Carbon capture and utilization (CCU) is a potential way to deal with the CO<sub>2</sub> produced during cement production. In contrast to carbon capture and storage (CCS), where CO<sub>2</sub> is stored in underground reservoirs, CCU uses the captured CO<sub>2</sub> as a raw material for a subsequent process. One potential use is the production of synthetic fuels (e-fuels) by means of a power-to-X (PtX) process in which electricity from renewable energy sources is used to split water (H<sub>2</sub>O) into hydrogen (H<sub>2</sub>) and oxygen (O<sub>2</sub>). The hydrogen and CO<sub>2</sub> are then mixed in a synthesis plant and converted into hydrocarbons, which can be used as fuels after further processing [9]. Although the CO<sub>2</sub> captured from the cement production process is ultimately released into the atmosphere when the synthetic fuel is burned, net CO<sub>2</sub> emissions are still reduced, as CO<sub>2</sub> stemming from cement production replaces emissions that would otherwise have occurred by burning a fossil fuel-based alternative which can now remain unused. As an example, the replacement of one liter of gasoline with a synthetic equivalent reduces net CO<sub>2</sub> emissions by 2.3 kg, since specific gasoline emissions amount to about 2.3 kg CO<sub>2</sub>/L.

The Center for Solar Energy and Hydrogen Research Baden-Württemberg (in short ZSW) has been researching PtX technologies for several years. In addition to technical solutions, framework conditions for development and market introduction are investigated. In this context, ZSW is searching for potential CO<sub>2</sub> sources for e-fuels. With the help of a CO<sub>2</sub> potential atlas, potential locations for PtX plants are to be identified, as the availability of CO<sub>2</sub> is a key location factor for the production of synthetic fuels. Specifically, a geographically located database of existing CO<sub>2</sub> sources is to be created, in which geo-referenced information such as geo-coordinates, addresses, postal codes, etc. will be provided with additional information such as volume potentials, gas qualities and supply fluctuations [10].

### 1.1. CO<sub>2</sub> Demand for Synthetic Fuels

In terms of vehicle efficiency, battery-electric and fuel-cell vehicles have major advantages over combustion engines powered by synthetic fuels for cars and light-duty trucks [11]. However, there are few alternatives to synthetic fuels for the decarbonization of international air and sea transport [11], and synthetic fuels offer advantages over battery-electric vehicles in trucks or other heavier commercial vehicles. Due to their good storage capability, e-fuels could also help to compensate for fluctuations in the generation of renewable energies and thus contribute to the stability of the energy supply [12].

According to a survey by LBST and dena, more than 70% of the final energy demand of all transport modes in the EU will be met by e-fuels in 2050, even in a strongly battery-electrified transport scenario, with the largest share of these e-fuels being required for air, sea and road freight transport [13]. Agora Verkehrswende et al. determined a 2050 CO<sub>2</sub> demand of 50 to 300 million tons per year for the supply of raw materials to the chemical

industry in the EU, and a similar demand is assumed for the application in fuels, resulting in a total EU demand of up to 670 million tons of CO<sub>2</sub> per year [14]. Since Germany accounts for 21% of the EU's gross domestic product (GDP) in 2019 [15], and taking GDP as a benchmark, this would result in a potential CO<sub>2</sub> demand of up to 140 million tons per year for Germany in 2050.

### 1.2. Approaches to Reduce Cement Demand

This chapter examines how the future cement demand might develop. Unless otherwise specified, the term *cement* refers to cements based on Portland cement clinker.

One approach to reducing cement demand is concrete recycling. In the case of fresh concrete recycling, excess concrete or mortar residues that have not yet hardened and are produced during the washing of the transport vehicles like concrete mixer trucks are washed out. In this process, the aggregate and the residual water produced are reused as concrete starting materials. The reuse of hardened concrete from demolition measures is referred to as hardened concrete recycling. The demolition concrete is crushed and recycled as concrete chippings, e.g., in the production of fresh concrete. New cement is indispensable for fresh concrete, but the amount of cement can be reduced because of the concrete chippings that contain a cement stone component [16]. However, concrete recycling has its limits and 95% of recycled concrete ends in lower-value uses such as road and landfill construction [17]. Carbon fiber concretes, which function without steel reinforcements and require less concrete due to their strength and corrosion resistance, are another option for reducing cement demand [18]. However, the slimming of structural components alone can only save cement to a limited extent.

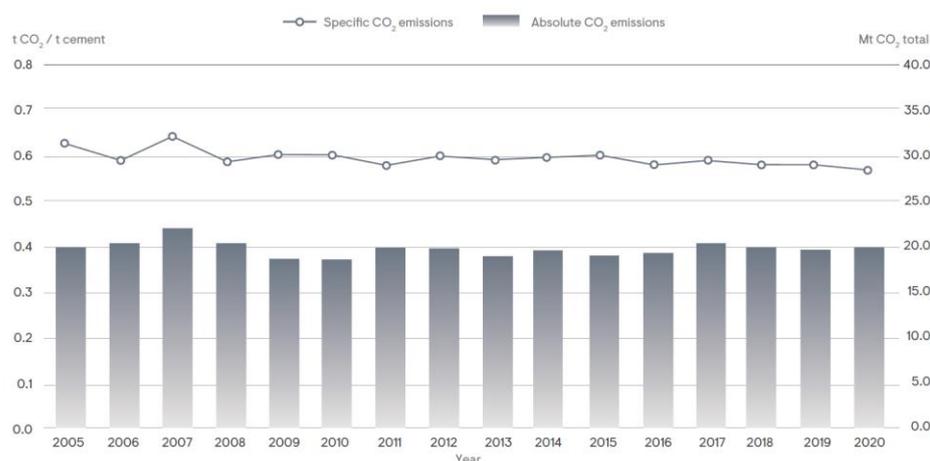
Concrete in building construction could be replaced by lower-emission materials such as bricks or wood. According to a study by Yale University, concrete could be replaced by wood on a large scale. The scenarios range from a "business-as-usual" scenario, in which new buildings continue to be constructed almost exclusively of concrete and steel, to a model in which most countries switch to primarily wood-based construction methods and 90% of all new buildings in 2050 are made of wood [19]. The study refers only to mid-rise urban buildings. For high-rise buildings, roads, bridges and tunnels, concrete remains difficult to replace.

Furthermore, low-carbon cements, also known as "green cements," are being developed. Geopolymers are expected to save 80% to 90% of CO<sub>2</sub> emissions compared to Portland cement. In that process, carbonizable calcium silicate clinkers as well as magnesium oxides from magnesium silicates harden using CO<sub>2</sub> instead of water, which allows them to absorb more CO<sub>2</sub> than is produced in the manufacturing process. However, such approaches still face resistance from consumers and regulators as current standards and building codes as well as protocols for testing cement binders are based on the use of Portland cement [5]. Since regulatory barriers are not insurmountable, it is mainly technical barriers that prevent a breakthrough of alternative cements, which is illustrated by the example of the above-mentioned geopolymers. According to InformationsZentrum Beton, they are resistant to inorganic and organic acids, but do not meet certain durability criteria and the alkaline constituents make their use on construction sites difficult for environmental and health reasons. Due to the limited availability of the raw materials involved, there are also restrictions to mass production [20].

### 1.3. CO<sub>2</sub> Reduction Measures during Cement Production

Cement production generates both chemically and energy-related CO<sub>2</sub> emissions. Limestone is the main raw material for cement, accounting for 75% of the raw materials used in the German cement industry [21]. The chemically-related emissions stem from the decarbonation of the limestone and are responsible for about 60% of cement-related CO<sub>2</sub> emissions. The energy-related emissions stem from direct fuel combustion and indirectly from the generation of required electricity [22].

According to Verein Deutscher Zementwerke (VDZ), not only energy efficiency improvements in cement production but also the use of alternative fuels is increasingly reaching its limits in Germany. Although the share of alternative raw materials and fuels has increased in recent years, specific and total CO<sub>2</sub> emissions have remained almost constant [23]. This can be seen in Figure 2 for the German cement industry.



**Figure 2.** Direct CO<sub>2</sub> emissions from the German cement industry (raw material and energy-related CO<sub>2</sub> emissions excluding electricity generation) [22].

In this context, it must be considered that, although the use of alternative fuels contributes to the conservation of resources, the combustion of organic materials such as used tires, waste oil, animal meal, plastic waste, etc. also releases CO<sub>2</sub>. Since these emissions would also have been produced if the material had been used as a fuel, e.g., in waste incineration plants, at least no additional emissions are produced using fossil fuels in the cement industry.

Another reason for specific CO<sub>2</sub> emissions not falling further is the limited possibilities for replacing limestone as a raw material. The quality of cement decreases with a lowering of the clinker factor. Portland cement is the burnt component of cement responsible for hardening with the addition of water. There are restrictions in the usability especially for composite cements, pozzolanic cements and blast furnace cements, as well as for some subgroups of Portland composite cements. The differences in quality result in poorer corrosion protection of the reinforcement as well as lower resistance to frost, chemicals, and mechanical wear [24].

#### 1.4. CO<sub>2</sub> Separation, Storage and/or Usage

According to VDZ, complete decarbonization of the cement industry is only possible by capturing the emitted CO<sub>2</sub> [23]. The technologies available for this purpose or currently being researched and developed are briefly explained.

In post-combustion processes, the CO<sub>2</sub> is separated from the flue gas stream. Through chemical processes, the CO<sub>2</sub> (approx. 14–33% of the flue gas volumes from cement production) is absorbed with the aid of amine-based, ammonia-containing or alkali-containing solutions. The loaded solvent is regenerated by a temperature and/or pressure change, whereupon it can be returned to the cycle. In contrast to a steam power plant, a separate steam process is required for regeneration in cement plants. Amine scrubbing with the aid of monoethanolamines (MEA) is already used on a large scale in industrial processes, e.g., for ammonia production or natural gas processing [25].

A second-generation post-combustion process that is particularly promising for the cement industry is carbonate looping, also known as calcium looping. In this process, the CO<sub>2</sub> from the exhaust gas is absorbed with the aid of calcium oxide (CaO) in a fluidized bed reactor (carbonator), producing calcium carbonate (CaCO<sub>3</sub>). In the second vortex chamber,

the calcium carbonate-bound CO<sub>2</sub> is expelled at high temperatures to produce burnt lime and gaseous CO<sub>2</sub>. The expelled CO<sub>2</sub> is discharged for compression and storage, and the regenerated CaO is returned to the carbonator [26,27]. As the circulation continues in the two interconnected swirl chambers, the sorbent CaO is sintered, making it less able to absorb CO<sub>2</sub>. To counteract this, a continuous flow of CaO must be supplied [27]. Since the burnt lime can be reused for clinker production, the process can be integrated into the manufacturing process in the cement industry. It is thus not a post-combustion process in the proper sense.

During the oxyfuel process, pure oxygen is used instead of air for the combustion of carbonaceous fuels, resulting in a high CO<sub>2</sub> content in the flue gas [25]. Combustion with pure oxygen and, if necessary, with gas recirculation, is integrated into the cement production process, thus allowing high CO<sub>2</sub> concentrations of up to 80% by volume [28]. After flue gas cleaning and scrubbing, the carbon dioxide/steam mixture can be boiled out, leaving almost exclusively CO<sub>2</sub> [25].

In the *Cleanker* research project, a combination of oxyfuel and calcium looping processes is to be tested in a demonstration plant, with the aim of capturing more than 90% of the fuel- and material-related CO<sub>2</sub> emissions, while the increase in electrical energy demand should remain below 20%, the increase in cement production costs less than 25 euros per ton of cement, and the cost of CO<sub>2</sub> capture less than 30 euros per ton of CO<sub>2</sub> [29]. Given the current cost of CO<sub>2</sub> certificates, if successful, this process could thus be economically feasible in the nearer future.

Assuming substantial cost degressions can be achieved, direct air capture (DAC) could make CO<sub>2</sub> capture at cement plants obsolete, at least regarding the extraction of CO<sub>2</sub> as a raw material. Unlike CO<sub>2</sub> from cement production, the use of air-derived CO<sub>2</sub> for synthetic fuels is CO<sub>2</sub> neutral, provided the energy requirements for DAC are met from renewable energy sources. Information on the cost of DAC varies widely: currently, it is 540 euros/t<sub>CO2</sub> according to DAC plant producers Carbon Engineering and Climeworks, and 45 euros/t<sub>CO2</sub> for Global Thermostat [30]. For 2050, costs of 38 to 71 euro/t<sub>CO2</sub> are predicted [30].

Since the CO<sub>2</sub> concentration in air is about 250 to 300 times lower than in exhaust gases [30], energy requirements and costs for DAC will remain higher than for CO<sub>2</sub> capture at stationary emitters. Because of this, CO<sub>2</sub> capture from flue gases is likely to stay competitive by 2050, if unavoidable sources of CO<sub>2</sub> emissions persist.

## 2. Materials and Methods

### 2.1. Data Sources Used

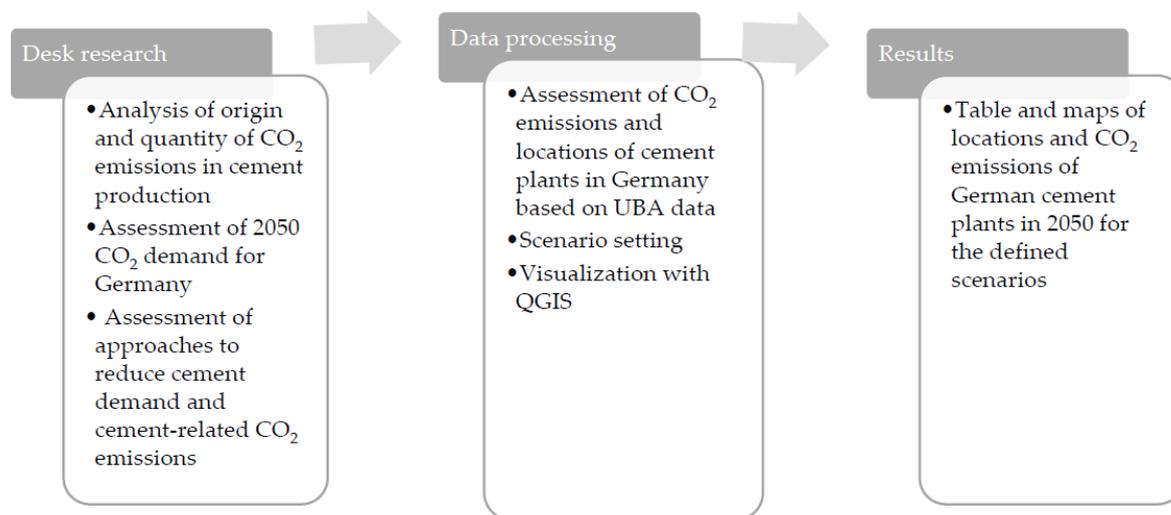
For above-mentioned PtX-CCU approaches to work, CO<sub>2</sub> sources are required that are likely to continue to provide CO<sub>2</sub> for at least the coming decades [10]. For this reason, a potential analysis of the cement industry as a CO<sub>2</sub> source is carried out with regard to 2050. The previous chapter outlined the potential demand for CO<sub>2</sub> as a raw material, approaches for reducing cement demand and measures for reducing CO<sub>2</sub> emissions in cement production as well as the required processes for CO<sub>2</sub> capture in cement plants.

For this, three scenarios were created for CO<sub>2</sub> emissions in the German cement industry in 2050 to reflect different potential evolutions of cement demand and regulatory frameworks. Up-front emission reductions through carbon capture and storage are not considered here, as the amount of CO<sub>2</sub> available for PtX processes is to be determined.

The data on actual CO<sub>2</sub> emissions from German cement plants originate from the German Federal Environment Agency (in German Umweltbundesamt, UBA); pollutants from industrial plants are to be reported to UBA and documented in the Pollutant Release and Transfer Register (PRTR). In addition to emissions, the data include postal codes, addresses and geo-coordinates of cement plants.

To obtain geo-referenced data for the three scenarios, the CO<sub>2</sub> emissions and locations of the German cement plants were documented in a first step. Average emission values per plant from 2014 to 2018 are used as a base. To visualize the results and provide an overview

of the cement plant locations as well as their associated CO<sub>2</sub> emissions, all three scenarios are displayed on a map of Germany using QGIS. Figure 3 summarizes the materials and methods used.



**Figure 3.** Methodical approach: three scenarios on future CO<sub>2</sub> emissions from cement plants and their locations are derived from a desk research on current cement-related emissions, 2050 cement demand, and available CO<sub>2</sub> emission reduction measures in the cement industry.

## 2.2. Scenario Setting

The first scenario (“status quo”) for CO<sub>2</sub> emissions in the German cement industry in 2050 assumes that cement demand remains constant. Blast furnace slag and fly ash can only be substituted to a limited extent, so that the clinker–cement factor in 2050 could remain at similar levels to today (around 71%). This assumption is in line with the findings of Hoenig et al., who assume a maximum reduction of the clinker share to 67% [31]. The energy emissions could decrease if hydrogen was used instead of the fuels currently in use. However, it is possible that, for economic reasons, alternative fuels such as used tires, etc. will continue to be used. Alternatively, emissions could also remain constant if the energy-related CO<sub>2</sub> reduction is offset by increased production volumes, e.g., due to an increase in exports. For this scenario, the average CO<sub>2</sub> emissions from 2014 to 2018 are assumed to be constant until 2050.

The second scenario (“strong decline”) is based on a study by UBA, according to which raw material-related CO<sub>2</sub> emissions from cement production can be reduced by 70% by 2050 compared to 2010, and energy-related emissions are reduced to zero. This reduction is to be achieved solely through new production processes and products; carbon capture and storage were not considered in this study, in line with our assumption as outlined in the previous chapter. The direct CO<sub>2</sub> emissions in 2010 used as a baseline by UBA were only slightly lower than those of the following years (cf. Figure 2). Therefore, the average values for the years 2014 to 2018 are kept as baseline for the scenario *Strong Decline* and reduced by 70%, in line with the UBA study.

The third scenario (“medium decline”) lies in between the first two scenarios, if only part of the UBA predictions for scenario 2 apply. According to the *German Federal Institute for Research on Building, Urban Affairs and Spatial Development* (BBSR), construction activity in 2050 might be about 45% lower than currently due to demographic change in Germany [32]. Alternatively, cement demand could remain stable (cf. scenario 1) and specific CO<sub>2</sub> emissions could decrease, but not as much as in scenario 2. In both cases, a 35% decrease in emissions compared to the 2014 to 2018 average is conceivable.

### 3. Results

Table 1 summarizes the three scenarios. Regarding the potential CO<sub>2</sub> demand in 2050, even in the first scenario, only a small part (15%) of the predicted demand could be met.

**Table 1.** Scenario overview.

	Scenario 1—Status Quo	Scenario 2—Strong Decline	Scenario 3—Medium Decline
Decline until 2050	-	70%	35%
Key assumption	Cement demand and clinker-cement factor remain constant	Alternative production processes and products	Less strongly reduced cement demand or CO <sub>2</sub> emissions
2050 CO <sub>2</sub> emissions [t/a]	21 million	6 million	14 million
Coverage of 2050 CO <sub>2</sub> demand *	15%	5%	10%

\* CO<sub>2</sub> demand of 140 million tons per year in Germany assumed (cf. Section 1.1).

Figure 4 shows the locations of Germany's cement plants and the associated amounts of CO<sub>2</sub> for the three scenarios. A distribution of plants across much of Germany is to be noted. In scenario 1, only three of the 34 plants emit less than 250,000 tons of CO<sub>2</sub> per year, while most plants have annual CO<sub>2</sub> emissions from 0.5 to 0.75 million tons, with the average being 0.62 million tons per year. The cement plant with the lowest CO<sub>2</sub> emissions emits on average of 171,000 t/a, while the plant with the highest CO<sub>2</sub> emissions reaches 1.45 million t/a.

A strong decline of the emissions in the second scenario can be noted in Figure 4. The smallest plant produces 51,000 t/a, the largest 435,000 t/a. Due to the strong reduction of CO<sub>2</sub> emissions, only seven plants still achieve values of 250,000–500,000 t/a, while all others emit less than 250,000 t/a. The average value lies at 185,000 tons per year. In scenario 3, only the Rüdersdorf plant close to Berlin (0.94 million tons) achieves a value above 0.75 million tons per year, while the plant with the lowest CO<sub>2</sub> emissions emits 111,000 t/a. In the Medium Decline scenario, most of the cement plants are found in the 250,000 to 500,000 t/a range, with an average value of 400,000 t/a.

The three scenarios deliberately scale down CO<sub>2</sub> emissions at cement plants proportionally and thus ignore potential losses of financial competitiveness of smaller plants from installing costly CCU technologies. If these factors are included, smaller cement plants that lack economies of scale might close, leading to a concentration of CO<sub>2</sub> emissions at larger plants that might to some extent stabilize CO<sub>2</sub> emissions at these plants.

If Germany achieves today's commitments to GHG emission reduction goals, namely the exit from coal-fired power generation by 2038 and a switch towards steel and chemicals production based on green hydrogen or synthetic fuels, cement plants will thus be among the single largest remaining CO<sub>2</sub> emitters in Germany even in the most advanced reduction scenario. This yields advantages in capturing CO<sub>2</sub>, compared to remaining other emissions sources, which will be more dispersed.

In case CO<sub>2</sub> utilization and/or capture or DAC are not viable at some cement plants, its emissions would need to be offset by other carbon sinks. In an all-renewable world, afforestation is a remaining option. German forests store on average 6 tons of CO<sub>2</sub> per hectare, meaning that the plant with lowest CO<sub>2</sub> emissions (110,000 t CO<sub>2</sub> p.a.) in the Strong Decline scenario requires about 18,000 ha or 180 km<sup>2</sup> of forest, while the average plant in scenario 3, Medium Decline, (400,000 t CO<sub>2</sub> p.a.), requires 670 km<sup>2</sup> or about twice the surface of Munich, Germany's third-largest city.

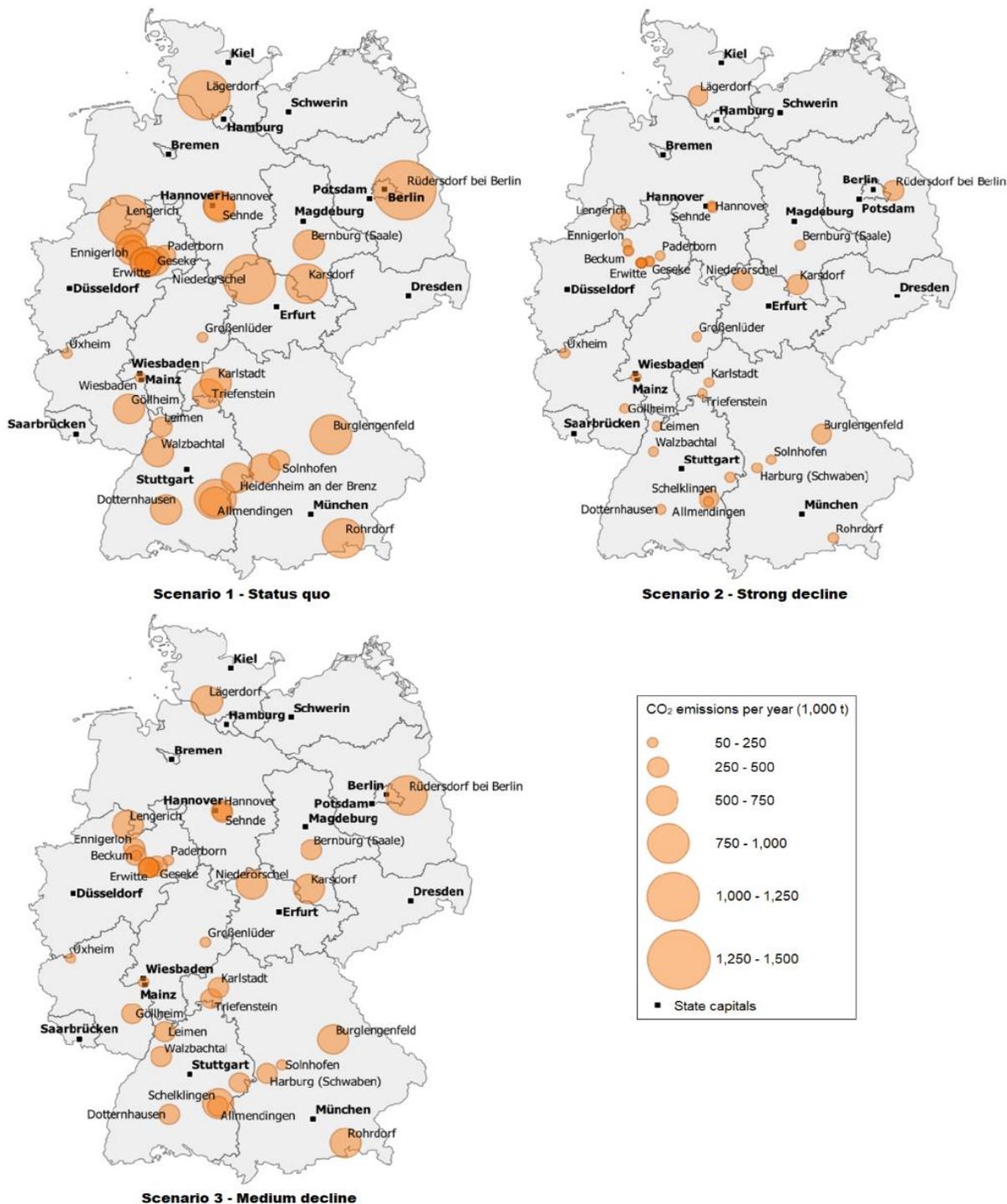


Figure 4. Scenarios for CO<sub>2</sub> emissions of cement plants in Germany in 2050.

#### 4. Discussion

From today’s perspective, the cement industry is suitable as a CO<sub>2</sub> source for the production of synthetic fuels in 2050. However, since it is estimated that measures required for CO<sub>2</sub> capture and utilization (CCU) result in an increase of production costs by about 25 euros per ton of cement (cf. Section 1.4), policymakers must provide a European regulatory framework that creates incentives for CO<sub>2</sub> capture in order to avoid relocations to nearby countries. At the same time, CCU must be further developed for use on an

industrial scale to improve cost-effectiveness. Of the three scenarios presented, the second, *Strong Decline*, is difficult to imagine from today's perspective: a reduction in CO<sub>2</sub> emissions of this magnitude requires technological breakthroughs in alternative binders that is not yet obvious—a development as projected in scenarios 1 and/or 3 thus seems more likely. An increase in CO<sub>2</sub> emissions from cement production until 2050 in Germany is, however, equally unlikely due to demographic change or Germany's ambitions to achieve climate neutrality by this date.

Of the collocated CO<sub>2</sub> demand of up to 140 million tons per year in Germany in 2050, the cement industry can theoretically cover up to 21 million tons, or about 15% in the most conservative scenario. While this is a substantial contribution, other sources of non-avoidable CO<sub>2</sub> emissions and, most importantly in a climate-neutral setting, DAC-based approaches need to be applied to satisfy Germany's 2050 CO<sub>2</sub> demand.

Given its low value per ton, cement production is generally likely to remain close to population centers, so even a strong technological shift in CO<sub>2</sub> management as indicated in scenario 2 will not lead to a stronger concentration of production facilities per se in Germany in order to counteract additional costs with economies of scale. This argument would be supported by efforts to reduce transport-related CO<sub>2</sub> emissions.

On the other hand, it is likely that existing chemical plants and refineries will play a pivotal role in the production of synthetic fuels. Cement plants that are close to such facilities or to pipeline infrastructures that can be repurposed to transport CO<sub>2</sub> might thus have a competitive advantage in putting "their" CO<sub>2</sub> to further use. As an example, the Rüdersdorf plant close to Berlin is about 100 km from the Schwedt refinery that today supplies large parts of northeastern Germany with oil derivatives. Similarly, the Leimen and Walzbachtal plants are close to South Germany's largest refinery in Karlsruhe.

In the long term, however, only final products storing CO<sub>2</sub> permanently or produced from zero-emissions energy can be compatible with the Paris Agreement's goal of reaching net-zero CO<sub>2</sub> emissions by 2050 [33]. Hence, a pure CCU approach to cement-related CO<sub>2</sub> emissions will not suffice to achieve net-zero emissions in Germany by 2045. Cement plants will thus need to directly sequester and store or compensate through other activities such as DAC the CO<sub>2</sub> that cannot be put to use economically, while the CO<sub>2</sub> from cement plants used in synthetic fuels would ultimately also be required to be captured from the environment in a carbon capture, utilization and storage (CCUS) process chain.

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