



# CO<sub>2</sub> Utilization and Market Size Projection for CO<sub>2</sub>-treated Construction Materials

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Achieving a net climate benefit requires that captured CO<sub>2</sub> (from stack emissions, directly from air or any other source) does not return to the atmosphere. There are several negative-emissions technologies that will meet this criterion. First, underground storage, possibly coupled with mineralization underground, creates essentially permanent removal. Second, CO<sub>2</sub> can be mineralized above ground into benign solid materials that can be left in the environment. Third, construction materials such as concrete, aggregates, and wall boards can be made with the use of CO<sub>2</sub>. From a climate point of view the lifetime of those materials can be considered permanent. While structures (buildings, roads, etc.) will not last permanently, the mineralized CO<sub>2</sub> in the underlying raw materials will. The latter negative emissions technology category has the added benefit of creating revenue from the sale of the products and thus providing financial incentives for deployment. The potential CO<sub>2</sub> utilization amount and market size for mineral-based construction materials is projected from today to 2050 and is discussed in context of the total addressable market for respective products. A range of scenarios for growth are considered and discussed. CO<sub>2</sub> utilization between 1.0 and 10.8 gigatons per year is projected with a market valuation reaching 0.8–1 trillion USD/year by 2050.

**Keywords:** construction materials, carbon capture and utilization, concrete, aggregates, CO<sub>2</sub> removal, market size and growth

## INTRODUCTION

Construction, or more broadly, construction materials offer a unique opportunity for innovation in the context of necessary action to address climate change as well as productivity and quality of workplace in the construction industry. The combined impact of construction (11%) and operation (28%) of the built infrastructure is responsible for nearly 40% of total greenhouse gas activity (World Green Building Council, 2019) and therefore substantial progress must be made in this sector to achieve a net-zero carbon economy (Hansen et al., 2022). Concrete, as one of the dominating construction materials contributes 5–8% of the global CO<sub>2</sub> emissions from the production of cement alone (International Energy Agency, 2018). Changes to cement and concrete production and use can therefore have a profound impact on emissions and society (Strunge et al., 2022a). In addition, the construction industry, worldwide, suffers from a substantial shortage of available labor forces. Therefore, the development and instruction of new construction materials offers the opportunity to implement new construction methods to address this shortage. This includes the use of automation, such as 3D-printing of concrete to speed up construction that

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can be enhanced with tailor-made CO<sub>2</sub>-treated materials. The urgency to address this problem is exacerbated by the projected growth rate for new housing estimating that the equivalent of one New York City will be built every month until 2060 (Gates, 2021).

Achieving a net-zero scenario requires reducing CO<sub>2</sub> emissions to the minimum possible, and offsetting the remaining emissions with capture and storage, and targeted use of CO<sub>2</sub> to manufacture materials. Broadly, carbon dioxide capture, utilization, and storage (CCUS) are actions that are deemed necessary by the Intergovernmental Panel on Climate Change (Masson-Delmotte et al., 2018) and the International Energy Agency (International Energy Agency, 2020). How to integrate these efforts with overall emission reducing progress is a large-scale challenge (Fankhauser et al., 2021). Accepting the premise that CO<sub>2</sub> must be captured, the opportunity to use that CO<sub>2</sub> as a non-fossil carbon-source to make products creates market-driven approaches that will reduce the cost of achieving a net-zero future. A 2016 study projected the annual use potential for CO<sub>2</sub> of about 4 gigatons/year with a revenue volume of \$1 trillion in 2030, if suitable policy support would be put into action (CO<sub>2</sub> Sciences, 2016). Preference should thus be given to technologies that can utilize CO<sub>2</sub> for useful, revenue-generating carbon dioxide capture and utilization (CCU) products. However, given the volume of negative emissions needed, use in products alone will not be sufficient to supplant the need for underground storage of CO<sub>2</sub>.

Potential products can be categorized into two groups. The first category includes products that cannot be made without carbon and for which no non-carbon alternatives exist, e.g., many chemicals, solvents, fuels, detergents. The second category includes those products that currently are not made with carbon, e.g., CO<sub>2</sub>-cured concrete and carbonated aggregates. Especially the latter offers unique options to incorporate large quantities of CO<sub>2</sub> (Woodall et al., 2019) in uses that are entirely new, and the duration of CO<sub>2</sub> removal could be considered as permanent. It is useful in this context to define two tracks for CO<sub>2</sub>-treated materials.

TRACK 1 materials remove CO<sub>2</sub> for more than 100 years and include construction materials (concrete, aggregates) and additionally, mineralization efforts that are frequently discussed in the context of carbon dioxide capture and storage (CCS) should also be considered here as a valuable resource for building materials. None of these materials have traditionally been made with CO<sub>2</sub> and therefore they provide an attractive opportunity for CO<sub>2</sub> removal with lifetimes in excess of 100 years and the potential to constitute negative emissions technologies. Additionally, new materials, such as carbon fibers and carbon-ceramics could reach such lifetimes.

TRACK 2 materials remove CO<sub>2</sub> for less than 100 years but produce products that require carbon contents and in general will have a shorter timescale than Track 1 technologies before releasing CO<sub>2</sub> back into the atmosphere. Their climate benefit stems from avoided CO<sub>2</sub> emissions by replacing fossil carbon with captured CO<sub>2</sub> in a circular fashion.

Track 1 products are an attractive opportunity with substantial deployment capabilities that can achieve an important positive climate impact (Ravikumar et al., 2021a,b). Recent data

on market size and CO<sub>2</sub> utilization potential are discussed in this perspectives paper.

## MARKET SIZE AND PENETRATION FOR CO<sub>2</sub>-TREATED AGGREGATES AND CONCRETE

Aggregate use in construction is abundant in the form of components in concrete, fillers for roads, asphalt, and much more. In 2020, the global market size for aggregates was estimated as 45 billion metric tons using several sources (Carey, 2018; Aggregates Business, 2019; LafargeHolcim, 2020) and, with an assumed compound annual growth rate (CAGR) of 3.3% by 2050, the annual needs for aggregates would rise to 119 billion metric tons. The CAGR value was determined as an industry average of historical data from CRH, Cemex, Holcim, and Vulcan.

Concrete use is typically estimated based on cement production volume (5.2 billion metric tons in 2020) and in 2020 amounted to about 25 billion metric tons. For the purpose of this perspective, only precast concrete is considered further due to its much higher level of CO<sub>2</sub> use for curing compared to ready-mix concrete, even though it currently only accounts for approximately 30% of the total concrete market (Henrion et al., 2021a). The global precast concrete market in 2020 was 7 billion metric tons and is expected to rise at a CAGR of 5.2% to 32 billion metric tons in 2050. This CAGR is an average of published industry data from CRH, Forterra, Holcim, the National Precast Concrete Association, and reports (Grandview Research, 2021).

A key question will be what fraction of these total addressable markets can be covered with the CO<sub>2</sub>-treated alternative materials? Addressing this question in detail is beyond the scope of this perspective and would have to include factors that concern the resulting material properties (Vance et al., 2013; Mehdipour et al., 2019; Rahmouni et al., 2019; Zhang et al., 2019), necessary certifications (American Concrete Institute, 2020), the local (!) availability of suitable raw materials including CO<sub>2</sub> (National Academies of Sciences and Medicine, 2018, 2019; Woodall et al., 2019; Strunge et al., 2022b), public acceptance (Arning et al., 2021), supporting policy (Di Filippo et al., 2019; Henrion et al., 2021b), and of course cost (CO<sub>2</sub> Sciences, 2016).

Consideration of the above-mentioned factors will be necessary to determine the potential deployment rates for a specific application in a particular region. This perspective examines the potential from a macro- or global level to determine upper bounds for CO<sub>2</sub>-treated aggregates and concrete use.

Carbonation of minerals or waste materials can consume between 0.087 and 0.440 tons of CO<sub>2</sub> per ton of aggregate depending on the starting raw material, conversion process, and resulting product material (Woodall et al., 2019). As a starting point, for 2020, the global amount of suitable waste materials was estimated to about 6.6 gigatons per year (Carey, 2018; Hepburn et al., 2019) while the global annual production of alkaline minerals (wollastonite, olivine, serpentinite) was at 16.2 million metric tons (U.S. Geological Survey, 2022). That then determines the range of potential CO<sub>2</sub> use when multiplied by an assumed market penetration for carbonated aggregates. For

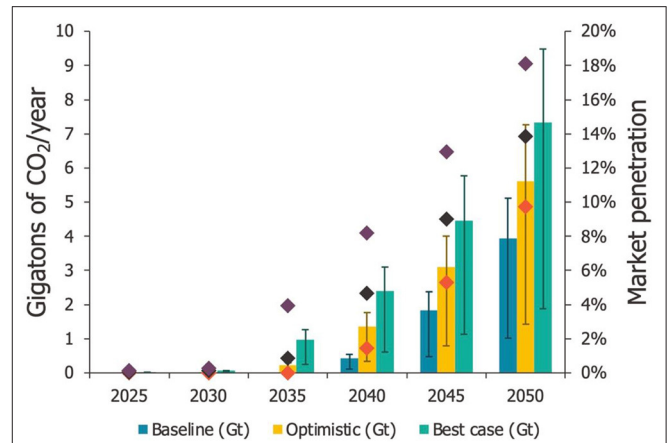
precast concrete, CO<sub>2</sub> utilization estimates range from 0.001 to 0.085 tons per ton of concrete (Zhang and Shao, 2016; Henrion et al., 2021b) but we use a more conservative upper bound of 0.05 tons for the projections. It is noted that while there are indications that CO<sub>2</sub> curing might not affect the natural ability of concrete to further take up CO<sub>2</sub> over its lifetime, this is an ongoing debate for research (Zhang and Shao, 2016).

It will be important, though, to assess the increase in market penetration over time. The market share will be critically dependent on the cost of the CO<sub>2</sub>-treated product. The production cost of the CO<sub>2</sub>-treated product will depend, in part, on the cost of CO<sub>2</sub>. High capture cost, especially when CO<sub>2</sub> is captured from air, will make market competitiveness sensitively linked to a (potential) price on carbon. A price on carbon is a tax or financial penalty for emitting CO<sub>2</sub>. It must be noted, though, that such a price could also be deployed in the form of incentives, such as tax rebates. However, it has been demonstrated that the use of solid waste materials and CO<sub>2</sub> emissions to manufacture building materials can be cost competitive in some regions today due to the cost of waste disposal (Carey, 2018). In general, though, establishing a CO<sub>2</sub>-utilization industry will require policy support in some form and overall, a comprehensive assessment of policy instruments should be researched.

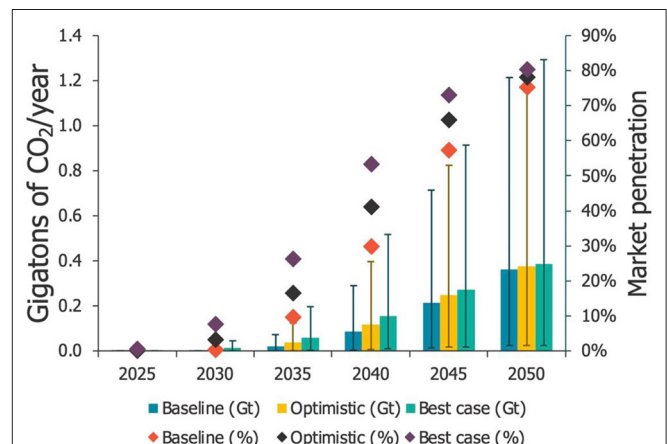
An analysis of the impact of a carbon price resulted in three scenario solutions. For each scenario, the price of carbon is subtracted from the cost of carbonate product and that will result in cost tipping points in the future, enabling increased market penetration. All three scenarios start with a carbon price of USD10/metric ton in 2020 and that is projected to rise to USD100/metric ton as projected by the Carbon Disclosure Project (Carbon Disclosure Project, 2022). The analysis is based on World Bank (World Bank, 2022) data showing that 75% of existing carbon pricing is less than USD10/metric ton. An annual increase of USD2/metric ton was used for a “Baseline” scenario. It is noted that increases in carbon pricing will of course be regionally specific but are assumed to reach USD50/metric ton by 2040. A USD2.5/metric ton annual increase for an “Optimistic” scenario will reach the lower threshold of Carbon Disclosure Project’s analysis of required carbon pricing to meet the targets set by the Paris Agreement in 2015 (Carbon Disclosure Project, 2022). Fastest growth would be achieved in a “Best case” scenario where the carbon price would increase by USD4/metric ton annually, reflecting the higher threshold of the Carbon Disclosure Project analysis.

In 2020, the global average price for aggregates was 10 USD per metric ton, triangulated from various sources (CRH, 2020; LafargeHolcim, 2020; Chinese Aggregates Association, 2022), and is assumed to grow at an annual rate of 1.5% while CO<sub>2</sub>-treated aggregates were priced at 50 USD, based on interviews of producers and in line with Hepburn et al. (Hepburn et al., 2019). Prices for precast concrete were 19 USD per metric ton in 2020 and are assumed to increase at 1.1% annually (based on historical price changes), while the price of CO<sub>2</sub>-cured precast concrete was 26 USD per metric ton.

Market penetration projections by Lux Research Inc. (Lux Research, 2022) were based on a qualitative assessment of



**FIGURE 1** | Global CO<sub>2</sub> utilization potential for aggregates. Error bars reflect the range of CO<sub>2</sub> utilization in the low CO<sub>2</sub> uptake scenario of 0.087 tCO<sub>2</sub>/metric ton of aggregates and high CO<sub>2</sub> uptake scenario of 0.44 tCO<sub>2</sub>/metric ton of aggregates. Note: 2016 Study refers to (CO<sub>2</sub> Sciences, 2016). The diamond symbols indicate the projected market penetration.



**FIGURE 2** | Global CO<sub>2</sub> utilization potential for precast concrete. Error bars reflect the range of CO<sub>2</sub> utilization in the low CO<sub>2</sub> uptake scenario of 0.001 tCO<sub>2</sub>/metric ton of concrete and high CO<sub>2</sub> uptake scenario of 0.05 tCO<sub>2</sub>/metric ton of precast concrete. Note: 2016 Study refers to (CO<sub>2</sub> Sciences, 2016). The diamond symbols indicate the projected market penetration.

competing technologies and industry willingness to adopt. Competing technologies included the possible availability of non-CCU, but low-carbon or zero-carbon technologies for the same or a similar product. Willingness to adopt was based on consideration of the CCU product’s sustainability, performance advantages, and other benefits potentially offsetting a higher cost.

CO<sub>2</sub> use for aggregates could reach between 1.0 and 9.5 gigatons per year in 2050 as shown in **Figure 1** while capturing 18% of the total aggregates market with a revenue generation of USD 182 USD 337 billion.

For precast concrete curing, the projected CO<sub>2</sub> use is <0.1 gigaton per year by 2030 in the best case but will rise to 0.05–1.3 gigatons/year in 2050 as shown in **Figure 2** with a market size that could reach USD 623–USD 666 billion by 2050.

## DISCUSSION

Six years after the publication of CO<sub>2</sub> Sciences' "Global Roadmap for Implementing CO<sub>2</sub> Utilization" (CO<sub>2</sub> Sciences, 2016), the awareness of and the interest in the climate and economic potential of using CO<sub>2</sub> to make products has increased substantially. Especially carbonation of minerals and alkaline waste materials is now an attractive option for permanent carbon dioxide removal from the atmosphere. When coupled with the use of the resulting carbonates as construction materials a large-scale market can be served, and the cost of removal is more easily offset with the revenue from the sale of the materials. The global construction market is growing fast and therefore it is now important to deploy as much CO<sub>2</sub>-treated aggregates and CO<sub>2</sub>-cured concrete as possible to reduce the amount of "embodied carbon" in buildings and other infrastructure (the amount of CO<sub>2</sub> generated in the construction of buildings). Permanently incorporating CO<sub>2</sub> into building materials could help to offset CO<sub>2</sub> emissions occurring elsewhere in the construction process.

It must be emphasized strongly that the data presented above are global data that do not include the granularity of a localized analysis for CO<sub>2</sub> use potential. Preparation and transport of large volumes of heavy raw materials and products in general should discourage transport beyond local distances for environmental and cost reasons. This is particularly true of products such as aggregates and concrete that have low profit margins. The projections for CO<sub>2</sub> utilization in construction materials do highlight that efforts on technology development and policies to support their deployment are meaningful in the context of climate stabilization, even if only a fraction of the global potential comes to market. For example, if only 10% of the 2050 aggregates market is served with CO<sub>2</sub>-treated aggregates, the amount of CO<sub>2</sub> utilization can reach 1.1–5.3 gigatons per year. The IEA projects that in 2050, 5.3 gigatons of CO<sub>2</sub> would have to be

captured and stored while only 0.37 gigatons would be utilized (Table 2.1 in International Energy Agency, 2020). CCU therefore can take on a bigger, and more cost effective, role to reach a net-zero carbon economy. To materialize this amount, it will be important to identify local opportunities to find optimum deployment options in terms of maximum amount of CO<sub>2</sub> removed and positive revenue. Related analyses and plans must factor in local communities needs and constraints in land use and job creation. Lastly, it also must be ensured that the technologies that are intended to use CO<sub>2</sub> to produce construction materials have been designed and analyzed appropriately to ensure a true net-benefit of the CO<sub>2</sub> use (Ravikumar et al., 2021b).

## DATA AVAILABILITY STATEMENT

The data analyzed in this study is subject to the following licenses/restrictions: The data is part of a more comprehensive project that will be made available once it is completed. Requests to access these datasets should be directed to vsick@umich.edu.

## AUTHOR CONTRIBUTIONS

VS led the concept and writing of the paper and integrated contributions from the co-authors. GS and FM equally contributed to the data generation, analysis, and interpretation, and co-edited the manuscript. All authors contributed to the article and approved the submitted version.

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