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Cost-motivated pathways towards near-term decarbonization of the cement industry†

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Cement production facilities contribute over 8% of global carbon dioxide (CO_2) emissions, with approximately 60% of these emissions stemming from process-related activities and the remaining 40% from energy consumption. This unique emission profile means that merely decarbonizing the energy source will be insufficient to achieve net-zero emissions for this sector. Recognizing the hard-to-decarbonize nature of the cement industry, this perspective investigates the costs associated with implementing retrofit decarbonization options at existing cement facilities to expedite emissions reduction. We evaluate the impact of clinker replacement, alternative fuels, point source capture, and direct air capture on both total CO_2 emissions and cement production costs. After validating the emissions and costs for baseline cement production and each decarbonization strategy, we develop dispatch curves (a method to sequentially compare costs and removal capacities across available technologies) to identify the most cost-effective pathways to achieve net-zero emissions. Through this analysis, we reveal that utilizing all four decarbonization strategies is potentially the most cost effective and can facilitate a net-zero future for the cement industry with a 29% increase in cement costs. We also explore deployment strategies and tailored solutions for individual facilities. This work builds on substantial progress in the field by analyzing the combined potential of these sustainable technologies to help the industry meet its decarbonization goals.

Sustainability spotlight

Advancing novel, sustainable technologies for hard-to-decarbonize industries such as cement, steel, and chemicals has been a major research focus in recent years, but to meet global net-zero emission goals by 2050, we need to rapidly decarbonize these sectors. This necessitates that presently available, retrofit technologies are scaled rapidly to abate existing emissions. Consequently, in this work, we investigate the decarbonization potential and costs associated with high TRL technologies available as retrofit alternatives for the cement industry. The findings and methodology presented offer a unique perspective to help existing industrial facilities pursue a cost-optimized combination of approaches to reach their decarbonization goals. This work firmly falls under UN SDGs 9 (industry, innovation, and infrastructure) and 13 (climate action).

1 Introduction

The effects of anthropogenic greenhouse gas emissions are recognized as a major challenge of the 21st century as global energy use and economic growth continue to rise. This growth and development, especially in low- and middle-income countries, often necessitates the deployment of fossil fuels, steel, and cement – each of which are responsible for the release of large quantities of carbon dioxide (CO_2) and other gaseous pollutants that can contribute to accelerated global warming. Cement production is currently responsible for 8% of global CO_2 emissions and, according to the International Energy Agency (IEA), demand for cement is forecasted to increase by 12–23% by 2050 compared to 2018 levels, with significant growth expected in regions such as South Asia and Africa.[1] If conventional processes are used, this increase in demand will also significantly increase CO_2 emissions. Multiple organizations have considered the amount of CO_2 emissions that the cement industry will need to avoid in order to hit specific global temperature rise targets. Specifically, the IEA estimates that to ensure at least a 50% chance of limiting global warming to 2 °C above pre-industrial revolution era average temperatures, CO_2 emissions from cement production must decrease by at least 24% between 2018 and 2050 by introducing alternative fuels to reduce energy emissions.[1,2] Alternatively, the Global Cement and Concrete Association (GCCA) has set a more ambitious, net-

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† Electronic supplementary information (ESI) available: It includes a detailed explanation of the calculations used to calculation CO_2 emissions and costs (both capital and operating) associated with each decarbonization pathway. We also include documentation of the emission factors, heating values, and fuel prices used for the variety of replacement fuel options as well as capital cost estimations for representative cement plants. We also include additional figures to investigate the sensitivity of total cement costs to improvements in PSC and DAC costs. See DOI: **https://doi.org/10.1039/d4su00590b**

zero by 2050 goal in order to limit global warming to 1.5 °C.[3] To meet these goals, significant technological advancements in reducing and/or capturing CO_2 emitted during the cement production process must be implemented.

Currently, 95% of hydraulic cement production in the United States is Ordinary Portland Cement (OPC), which is comprised of a mixture of clinker (a binder made of alite, belite, tricalcium aluminate, and calcium aluminoferrite) and gypsum.[4,5] The production of OPC generally requires the integration of several process units and begins with grinding mixtures of limestone and gypsum rocks for calcination in the kiln, as shown in Fig. 1.[4] To produce the clinker material, the finely ground materials are heated to temperatures as high as 1450 °C, enabling the conversion of limestone to lime ($CaCO_3 \xrightarrow{+heat} CaO + CO_2$), releasing process related CO_2 emissions that ultimately make up 60% of all cement emissions.[4,6] The remaining 40% of cement production emissions come from the combustion of either coal or petcoke to heat the kiln.[6–9] Finally, to make OPC after calcination in the kiln, the clinker is cooled and mixed with gypsum to produce the final cement product that is 80–90 wt% clinker.[4,9,10] Given the direct CO_2 emissions released during cement production, it is evident why such an industry can be "hard-to-decarbonize," as identifying alternative, clean fuels can only reduce emissions by a fraction of the total. Despite this, there have been significant strides in decarbonizing the cement industry *via* retrofit technologies that can update OPC manufacturing sites to emit less CO_2. While new cement production pathways that target reduced process emissions have recently seen growth,[11,12] in this perspective, we will focus on how the utilization of high technology readiness level retrofit alternatives can combat emissions from existing cement plants with long remaining lifetimes. These alternatives include fuel mixtures, clinker replacement, and carbon capture technologies (Fig. 1).

One extensively investigated retrofit technology involves replacing carbon intensive coal and petcoke with cleaner fuel alternatives. While in other industries, such as the power sector, coal can be phased out of use due to the availability of renewables and other clean energy sources,[13] the high temperatures required for the calcination of limestone and the importance of the flame temperature in ensuring high quality clinker product has historically limited the shift from coal/petcoke to clean, alternative fuels or electricity.[8,9] In the last several decades, however, the shift from a single, wet kiln (*i.e.*, a kiln that dries, dehydrates, calcines, and sinters/burns the raw materials) to a combination of a pre-calciner with a dry kiln (*i.e.*, a kiln that only performs the sintering/burning process) has reduced the clinker calcination time and nearly halved the energy required at elevated temperatures.[14,15] This allows more time to be spent operating at lower temperatures which can be achieved using alternative fuels.[14,15] Lower carbon content fuels such as natural gas, biomass, and municipal solid waste have been considered as alternatives to reduce CO_2 emissions from cement plants.[9] In industrial applications, biomass-based alternative fuels are often used in mixtures with coal/petcoke, and it is estimated that by 2050, this mixture will comprise of 30% coal, 10% petcoke, and 60% biomass-based fuels.[14] While some cement plants have explored alternative, higher fuel replacement fractions, regulatory requirements and restrictions often limit the extent of replacement. Given the importance of maintaining high quality clinker, monitoring the relevant operating conditions associated with alternative fuels (*i.e.*, a fuel mixture or full replacement by natural gas) has been shown to prevent the loss of clinker quality.[9,16] In order to ensure that the biomass-based fuels are properly pre-treated (*i.e.*, ground to ideal sizes, dried, cleaned, *etc.*) and that appropriate kilns are used to burn the fuel completely, additional capital expenditures must be made to upgrade the fuel choice.[17]

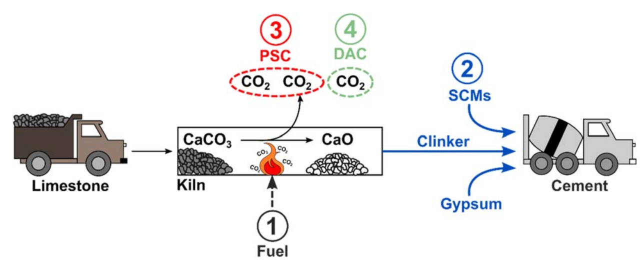

Fig. 1 Schematic of cement production outlining the key process steps and retrofit decarbonization options that are discussed in this work. The CO_2 emissions associated with this process can come from process emissions from the calcination of limestone ($CaCO_3$) to lime (CaO) and fuel consumption. In this work, we consider mitigating these emissions by evaluating the costs of (1) alternative fuels, (2) clinker replacement by supplementary cementing materials (SCMs), (3) point source capture (PSC), and (4) direct air capture (DAC).

Next, given the large fraction of emissions that stem from clinker production (*i.e.*, both process and energy emissions), significant research has been done to investigate the replacement of clinker with alternative supplementary cementing materials (SCMs). SCMs can be used to reduce the total mass of clinker required per ton of cement produced, while still maintaining similar mechanical properties to OPC.[18] Fly ash or blast furnace slag, two of the main SCMs used to date, are byproducts of the combustion of pulverized coal and of steel production, respectively.[10] While over the last 20 years their use in cement has increased (with fly ash utilization approaching 60% in 2021 in the United States), it is anticipated that the combined supply of fly ash and slag will decrease as the carbon-heavy industries attempt to improve their sustainable practices as well.[10,19] Alternatively, calcined clays have been identified as a promising option for the future of SCMs, as they are found in abundance across all sections of the earth's crust.[18,20] Despite their use in India in the 1970s before fly ash was widely available, clay is not used extensively across the world. Specifically, blends of calcined clays, non-calcined limestone, and clinker (LC^3) can reduce clinker content in cement from 80–90% of the total cement mass down to 50%.[18,21] Because large fractions of clinker are replaced by clay that does not emit CO_2 during calcination, the process CO_2 emissions are substantially reduced: prior studies reported that by reducing the clinker content in cement from just 70 to 60% by mass, it is possible to reduce the CO_2 emissions by 13.6% from a fossil fuel baseline.[22] Additionally, current cement facilities can produce LC^3 cement with little alterations to the equipment infrastructure, specifically the kiln.

A third decarbonization technology involves removing and storing CO_2 from the effluent gas streams leaving the cement facility. Given the "hard-to-decarbonize" nature of cement manufacturing, carbon capture, utilization, and storage (CCUS) is anticipated to play a large role in addressing CO_2 emissions associated with cement manufacturing. Gaseous waste streams leaving cement plants have concentrations of 14–33 vol% CO_2, thus it is likely that point source capture (PSC) can be a viable option for reducing up to 90% of the total CO_2 emissions.[23,24] The exact mechanism by which PSC is most efficient and cost-effective might vary by application, as both post-combustion capture and oxy-combustion capture have been proposed for use in cement plants.[25] Because both options have unique advantages and disadvantages, in this investigation, we will treat the carbon capture facility as technology agnostic and simply estimate viable cost ranges for a PSC facility. These costs will outline goals for each technology to optimize the emissions reductions and associated costs.

Finally, net negative CO_2 capture platforms such as direct air capture (DAC) and storage are likely necessary for cement manufacturing, as the high process emissions and lack of alternative methods to produce OPC will make it incredibly difficult to reach net-zero emissions. Thus, in addition to PSC, DAC can help remove CO_2 from the atmosphere without making any changes to the cement plant. To the best of our knowledge, a full analysis comparing the cost of upgrading a cement manufacturing plant to reduce total emissions (*i.e.*, *via* retrofit options) with the cost of simply buying carbon credits generated from proven DAC and storage facilities has yet to be done. Assuming the carbon credits purchased from DAC would be in line with any carbon taxes, this sets an upper limit for the cost at which cement manufacturers will eventually be willing to pay for upgrading to a more sustainable framework.

Growing awareness surrounding the need to decarbonize the cement industry has led to several reviews and perspectives outlining the technological viability of pursuing the above tactics.[4,8,9,20,26,27] Despite this interest, there have been limited publications to inform the most promising and affordable pathways towards decarbonization at scale. It is unlikely that one technology will be the single solution to decarbonizing the cement industry, thus a variety of options will need to be pursued.[6] The deployment of these options will depend on the scale of the cement plant and CO_2 removal, requiring a marginal cost analysis that not only investigates the raw cost of implementing such technologies, but can also prioritize which technology should be pursued first to achieve a baseline level of emissions reduction while limiting the costs to the cement manufacturer. Technoeconomic studies have been done on these individual platforms, but, to the best of our knowledge, further recommendations surrounding optimal pathways to pursue have not been investigated.[25,28–30]

In this perspective, we approach the problem of decarbonizing the cement industry by developing an in-house model to compare the decarbonization potential of each retrofit technology on removing CO_2 emissions in the United States cement industry. We first validate the estimated emissions with prior data and develop a holistic cost analysis of each platform in order to investigate the impacts of implementing a single technology or combining any/all the retrofit options. We use this technoeconomic model to evaluate the optimal sequence for deploying technologies to decarbonize the industry, aiming to minimize the total costs of abatement. The final costs associated with these decarbonization pathways are ultimately compared to inform which combination of technologies can minimize the costs to the manufacturer while achieving emission removal goals. This technoeconomic analysis and discussion provides a basis upon which cement facilities can prioritize currently available technologies to meet near-term decarbonization goals.

2 Methodology

To provide insight to the most viable decarbonization pathways, we consider both the total emissions avoided and the associated retrofitting costs of the decarbonization technologies outlined above. We start by developing an accurate baseline emissions model and describe further calculations of the emissions reductions associated with the decarbonization pathways. Following this, we discuss the approach we take to calculate the costs of implementing the technologies.

2.1. Model validation

To calculate the baseline emissions associated with the cement industry, we assume uniform fuel, clinker fraction, and kiln efficiencies based on average values reported in 2021 in the Getting the Numbers Right (GNR) database for the United States cement industry.[10] While these assumptions oversimplify the nature of the cement industry in the United States, the trends in operating emissions still apply regardless of the absolute values of the above metrics for specific plants. Additionally, we assume that the reported baseline kiln efficiencies and fuel consumption rates apply to a fuel comprised of only coal. Using the reported emissions factor values for coal (an average of the emissions factors for bituminous, subbituminous, and lignite coal) and the U.S. average yearly cement production (ESI Section S1†), we calculate that the U.S. emitted 55.9 Mt CO_2 from cement production in 2021, which agrees well with the 54.2 Mt CO_2 reported in the GNR report.[10] Additional details surrounding our estimation of carbon emissions for both the baseline scenario and the retrofit decarbonization options are included in the ESI Section S1.†

A further validation of the model involves investigating the effects of replacing clinker with alternative SCMs. As mentioned above, when performing a similar investigation of clinker replacement, Fennell *et al.* found that total CO_2 emissions dropped by 13.6% when reducing clinker content from 0.7 to 0.6.[22] Using the framework outlined in the ESI Section S1,† our model predicts that CO_2 emissions will drop from 47 $Mt_{CO_2}\,yr^{-1}$ to 42 $Mt_{CO_2}\,yr^{-1}$ (or a 10.6% drop in emissions) between clinker contents of 0.7 and 0.6, confirming alignment with the prior findings.

2.2. Costing analysis framework

When a technology is upgraded, CO_2 emissions are reduced in accordance with the relationships developed in the ESI Section S1;† however, additional upfront investments may be required, and operating costs may be altered, affecting the overall production costs. Assuming a constant cement production rate per year, we can price the new materials and fuels according to eqn (1).

$$C_{\text{cement}} = C_{\text{CAPEX}} + C_{\text{OPEX,fuel}} + C_{\text{OPEX,rawmaterials}} + C_{\text{capture}} \quad (1)$$

where C_{cement} (\$ t_{cement}^{-1}) is the total cost to produce a single ton of cement, C_{CAPEX} (\$ t_{cement}^{-1}) is the capital cost amortized over the lifetime of the plant, $C_{\text{OPEX,fuel}}$ (\$ t_{cement}^{-1}) is the fuel cost to produce a ton of cement, $C_{\text{OPEX,rawmaterials}}$ (\$ t_{cement}^{-1}) is the raw material cost required to produce a ton of cement, and C_{capture} (\$ t_{cement}^{-1}) is the cost per ton of cement to capture CO_2 over the lifetime of the plant, if relevant. The expressions used to calculate the value of each of these terms are expanded in the ESI, Section S2.†

In this model, we assume (1) additional capital costs associated with implementing the retrofit technologies apply regardless of the marginal amount of CO_2 removed (ESI, Table S2†); (2) we use the heating values of relevant fuels (ESI, Table S1†) to convert between mass and energy based cost estimates; (3) baseline cost of PSC is \$60 $t_{CO_2}^{-1}$ while that of DAC is \$200 $t_{CO_2}^{-1}$;[31–34] (4) PSC can only capture up to 90% of the remaining CO_2 emitted from the cement facility; (5) DAC occurs at an external location and credits must be purchased by the cement manufacturer to achieve 100% CO_2 abatement; and (6) there are no policy initiatives that exist to improve process economics. The baseline costs of PSC are selected from a 2020 article by Feron *et al.* which estimated benchmark PSC costs for amine-based PSC systems.[31] Those of DAC are selected assuming reported, optimistic targets can be achieved at scale.[32–34] Performing PSC at all cement facilities may not be practical/feasible given the different costs associated with CO_2 transportation and/or storage at different geographic locations.[35,36]

Using the above set of assumptions, combined with additional costs reported in a prior analysis (outlined in the ESI, Table S3†),[37] we calculate the baseline costs (*i.e.*, coal only, 90% clinker) to be \$99.9 t_{cement}^{-1}. This establishes an estimate of the costs that may be anticipated; however, the specific production costs of each cement plant will vary, and thus this generalized analysis likely oversimplifies some of the nuances associated with operating each cement plant. Despite this, current cement selling prices in the United States are ~\$132 t_{cement}^{-1}.[38] To estimate the cost of the cement produced in the United States, one can remove the profits that the cement company earns (the cement industry is estimated to have a 10% profit margin)[39] and any additional taxes or operating costs (estimated to be ~\$15 t_{cement}^{-1}).[37] Removing profits and taxes, we achieve an estimated cost of cement production in the United States of ~\$106 t_{cement}^{-1}, well in alignment with our model. Given this, we conclude that we have captured the major production costs that are likely to change with clinker and energy replacements. This suggests that studying the additional costs (\$ t_{cement}^{-1}) incurred beyond the baseline conditions that result from implementing any decarbonization option are representative of the changes to commercial plant total costs. Thus, for the remainder of the discussion, costs presented will be the additional decarbonization costs required beyond the baseline of \$106 t_{cement}^{-1} (*i.e.*, current cost at 0% CO_2 removal).

3 Costing pathways towards decarbonization

Using the above emission and costing frameworks, we first address the costs associated with pursuing each of the decarbonization pathways individually in order to assess their decarbonization potential and understand the rough order of magnitude cost increases that may be expected for each technology. We then consider the benefits of combining decarbonization options by developing an analysis to determine the most cost-effective way to achieve net-zero emissions in the cement industry. We use this analysis to recommend a cost-effective path forward for individual facilities looking to achieve their decarbonization goals. While we focus on a single, representative cement plant here, we note that the cost of implementing these new technologies may vary depending on the specific plant considered.

3.1. Individual decarbonization options

Each of the technologies introduced above can be considered independently, as has often been done by cement plants and researchers in the past.[18,40,41] According to Fig. 2a, we observe that simply replacing clinker with alternative SCMs or exchanging coal with natural gas for the kiln fuel can lower total costs below the current baseline conditions. Previous studies have reported similar trends in clinker replacement costs, but regulatory approval is still needed for use of 50% clinker by mass in all cement applications.[18] On the contrary, the replacement of coal with natural gas has not been studied as extensively. This is because historically, natural gas prices have been much higher than those of solid fuels and natural gas still emits CO_2.[42] Additionally, switching to a gaseous fuel requires adjustments for changes in radiative heat transfer, which can lead to inconsistent production and increased CO_2 emissions.[42] Instead, it is more likely that the fuel mixture discussed previously (30% coal, 10% petcoke, and 60% biomass-based fuels) will be used in the next several decades (*vide supra*), which only has the potential to reduce CO_2 emissions by 16.7% while increasing the costs of cement production by \$3 t_{cement}^{-1}, or 3% from the current baseline cement cost in the United States. Because fuel mixtures are more likely to prevail, we will not explore natural gas as a part of this analysis. When considered in isolation, all options to replace raw materials (*i.e.*, clinker or fuel replacement) cannot achieve large abatement fractions: at most, we predict that only 35% of the CO_2 emissions can be removed by lowering the clinker fraction from 0.90 to 0.50 (or 90% to 50% clinker). While this has the potential to hit the described IEA 24% target for cement by 2050, it will be insufficient for the net-zero by 2050 goal set by the GCCA.[3]

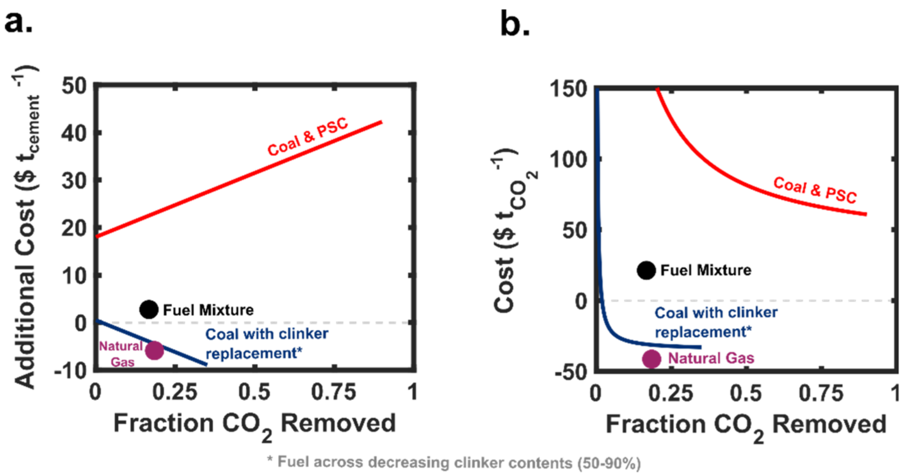

Fig. 2 (a) Additional costs of implementing the decarbonization technology for cement production (\$ t_{cement}^{-1}) beyond the current baseline costs of cement production (\$106 t_{cement}^{-1}). (b) Costs of CO_2 removal (\$ $t_{CO_2}^{-1}$) associated with pursuing clinker replacement, fuel replacement, and/or retrofitting a capture unit onto the plant with varying costs of capture. The costs of capture at the maximum capture fraction of 90% are \$60 $t_{CO_2}^{-1}$, in line with current PSC systems. The fuel alternatives are single data points because the technology can only remove a set amount of CO_2 when the fuel is replaced. On the contrary, the clinker replacement and PSC curves represent the range of decarbonization amounts that can result by varying the amount of clinker replaced or CO_2 captured, respectively. The dashed gray line at \$0 in both figures represents the baseline costs.

Instead of replacing raw materials, capturing any CO_2 emissions *via* PSC (Fig. 2a) can clearly achieve at least 90% removal, depending on the capture fraction of the implemented technology.[43] However, a major limitation of PSC technologies are their large capital and operating costs. Specifically, we note that regardless of the amount of CO_2 removed for PSC, a large capital cost expenditure will elevate the production costs, as indicated by the increase in cost to \$18 t_{cement}^{-1} at 0% removal in Fig. 2a. For PSC costs of \$60 $t_{CO_2}^{-1}$ reported for amine-based post-combustion capture platforms (that can achieve 90% removal), cement costs could rise by \$42 t_{cement}^{-1}, or 40%. Such a large increase in price is likely to be unacceptable for an industry with low margins and, thus, would likely require external motivation to encourage industrial implementation (*i.e.*, policy incentives).

In addition to simply understanding the impact of these decarbonization costs on the cost of cement production (\$ t_{cement}^{-1}), we can also translate the costs into the cost of CO_2 removal (\$ $t_{CO_2}^{-1}$) (Fig. 2b). This allows us to compare cement decarbonization costs to decarbonization technologies implemented in other industries. In Fig. 2b, we observe that, as expected, it is possible to save money by fully implementing alternative SCMs or by replacing coal with natural gas; however, if clinker replacement were only pursued to reduce CO_2 emissions by ≤2%, there would be no cost savings to be had due to both the capital cost investment (ESI, Table S2†) in order to upgrade the flash calciner for clay and the low carbon removal rates. Notably, PSC costs are minimized when the total CO_2 removed is maximized due to the large capital cost that applies across all capture fractions and causes the observed non-linear drop in costs. The nominal cost of PSC that we investigate here (*i.e.*, \$60 $t_{CO_2}^{-1}$) is only achieved when the CO_2 removed achieves its design targets of 90%. At any removal rates below this, the marginal amount of CO_2 avoided is not enough to access the benefits of economies of scale in PSC systems. The cost magnitudes predicted in Fig. 2b align with other decarbonization technologies and projections for the total costs to decarbonize power industries, agriculture, and other industrial sectors (*i.e.*, iron and steel, chemicals).[44]

3.2. Optimizing pathways towards complete decarbonization

It is evident from the above analysis that achieving high CO_2 removal rates *via* CO_2 capture can be quite expensive, thus we choose to further investigate the possibility of implementing a combination of decarbonization platforms that can both achieve 100% CO_2 removal and lower the total costs to the cement manufacturers. To assess this, we consider combining some/all the decarbonization pathways to optimize their deployment and achieve complete decarbonization (*i.e.*, net-zero emissions). We outline 8 different pathways using combinations of clinker replacement with LC^3 SCMs (*i.e.*, lower the clinker content to 50%), coal replacement by a fuel mixture, PSC, and DAC. The introduction of DAC at this point in the investigation allows us to achieve 100% CO_2 avoidance by simply offsetting any emissions that are not covered by the retrofit alternatives introduced in Section 3.1. Each of the pathways are outlined in Table 1.

Given the observations in Fig. 2, while the total cost of cement production (\$ t_{cement}^{-1}) may increase, the marginal cost of CO_2 removal (\$ $t_{CO_2}^{-1}$) is minimized by avoiding as much CO_2 as possible when using a selected method. Thus, for this investigation, we do not consider intermediate values of CO_2 removal (*i.e.*, only 50% clinker fractions are considered when replacing clinker with alternative SCMs and 90% of any remaining CO_2 emissions are always removed *via* PSC). Additionally, we consider each of the scenarios from Table 1 to determine the total costs of decarbonizing *via* the selected

Table 1 Pathways towards complete decarbonization of the cement industry. These options only consider technologies that are currently available for retrofit or carbon credit purchase *via* direct air capture to achieve 100% CO_2 removal. In each scenario, baseline clinker content is 90% while clinker replacement diminishes clinker content to 50%. Baseline fuel is coal while the fuel mixture is 30% coal, 10% petcoke, and 60% biomass-based fuels. When implemented, point source capture removes 90% of any remaining emissions after clinker replacement and fuel mixtures have been implemented (if relevant)

	Technologies implemented in scenario			
Scenario	Clinker replacement	Fuel mixture	Point source capture (PSC)	Direct air capture (DAC)
1				✓
2			✓	✓
3	✓			✓
4	✓		✓	✓
5		✓		✓
6		✓	✓	✓
7	✓	✓		✓
8	✓	✓	✓	✓

method. These investigations allow us to outline the most cost-effective pathways for a cement company to pursue or a regulatory body to recommend when outlining their decarbonization goals, as the pathway chosen will likely depend on the long-term plan for CO_2 removal.

To capture the difference in each of the scenarios, we developed dispatch curves (Fig. 3) for each of the 8 scenarios outlined in Table 1 to inform the most cost-effective pathways towards achieving net-zero emissions in the cement industry. We base this dispatch curve on the costs of CO_2 abatement ($\$ \ t_{CO_2}^{-1}$) to align with prior dispatch curves for industrial decarbonization.[44] As observed previously, clinker removal offers the most benefit to both removing CO_2 while lowering the cement facility costs, thus across each of the scenarios, it is always the first option that should be deployed. After clinker replacement, the fuel mixture replacement is the next most affordable, but it cannot achieve large amounts of CO_2 abatement due to both the CO_2 emissions associated with fuel mixtures and the presence of process emissions. As expected, when PSC is an option and analyzed in terms of the marginal cost of removal ($\$ \ t_{CO_2}^{-1}$), it should be pursued prior to deploying DAC and DAC should serve as a "catch all" for any remaining emissions, as the cost of DAC is comparatively high per ton of CO_2 ($\$200 \ t_{CO_2}^{-1}$).

As previously mentioned, these curves are based on the cost of abatement ($\$ \ t_{CO_2}^{-1}$); however, given the low margins in the cement industry, the direct costs of cement production ($\$ \ t_{cement}^{-1}$) are critical to determine how likely producers are to implement such technologies. By calculating the area under each of the dispatch curves in Fig. 3, we can derive the total costs of cement production, allowing us to compare the final costs that result from each scenario and pick the option that minimizes the total costs for 100% decarbonization (Fig. 4a, 100% removal). From this calculation, we observe that Scenario #8 minimizes the total costs at $\$31 \ t_{cement}^{-1}$ (or a 29% increase from the current cost of cement), with Scenario #4 a close

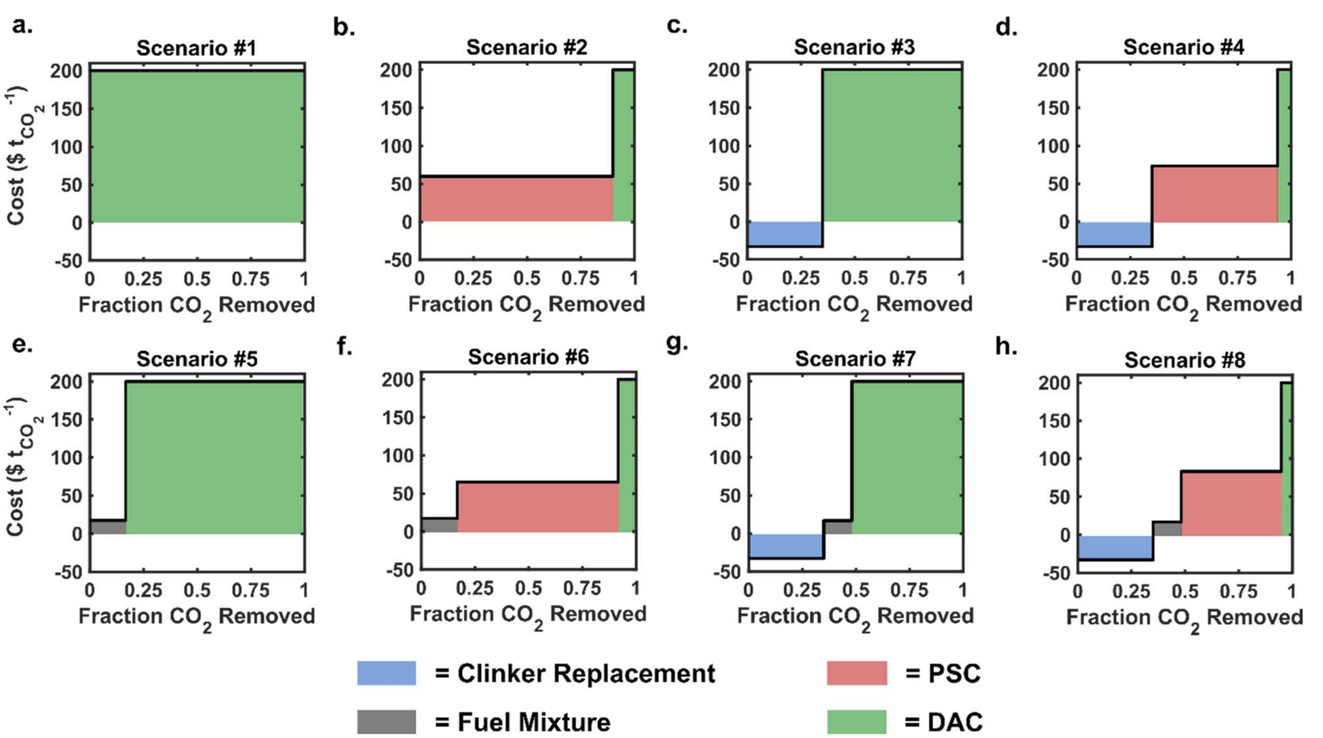

Fig. 3 (a–h) Dispatch curves of technologies for each of the decarbonization pathways outlined in Table 1. The dispatch curves are developed based on the costs of CO_2 removal ($\$ \ t_{CO_2}^{-1}$). The black line indicates the costs associated with decarbonizing *via* the technology associated with the color under/above the curve.

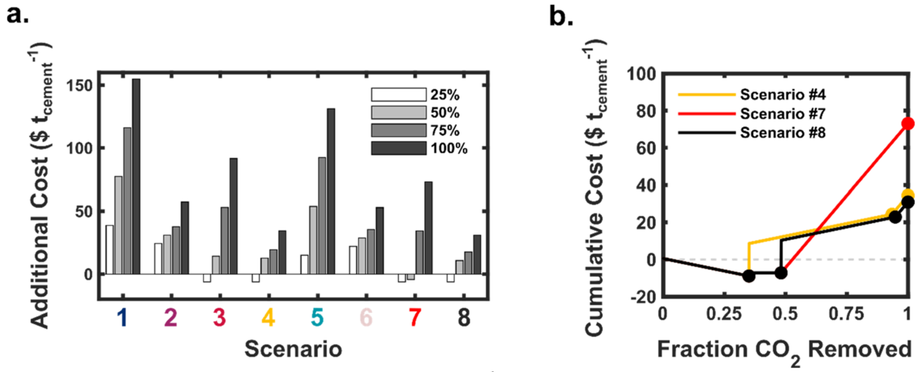

Fig. 4 (a) Additional costs to a cement plant ($ t_{cement}^{-1}) to achieve up to net-zero CO_2 removal assuming PSC = $60 $t_{CO_2}^{-1}$ and DAC = $200 $t_{CO_2}^{-1}$. The costs at 25%, 50%, 75%, and 100% removal are representative of actual costs that will be incurred by the cement manufacturing facility to achieve the desired CO_2 removal. (b) The total additional costs to a cement plant ($ t_{cement}^{-1}) to achieve a fraction of CO_2 removal in Scenarios #4, #7, and #8. The dashed gray line at $0 t_{cement}^{-1} represents the baseline costs.

competitor at $34 t_{cement}^{-1} (or a 32% increase from the current cost of cement), suggesting that pursuing fuel mixture replacement may not be worth it to minimize the total costs.

We performed a brief sensitivity analysis to understand the effects that capture costs might have on the preferred decarbonization pathway by lowering both PSC and DAC costs to $20 $t_{CO_2}^{-1}$ and $100 $t_{CO_2}^{-1}$, respectively (ESI, Fig. S1†). The metric for PSC was selected as the lowest reported cost estimate[45] while that of DAC was chosen because it is a well-known, near-term cost target.[46,47] We observed that at these lower, optimistic cost estimates, the preferred pathway for decarbonization remained the same, but the lowest cost option available for 100% decarbonization (Scenario #8) dropped to only a $7 t_{cement}^{-1} increase from the current cost of cement (or a 7% increase). This brief study reveals that improvements in the costs of carbon capture can make decarbonizing the cement industry much more economically feasible, enabling additional time for non-retrofit alternative cement production technologies (*i.e.*, technologies under development by companies such as Sublime and Brimstone) to develop for later deployment.

Achieving net-zero emissions in the cement industry is an ambitious goal and thus, in case companies want to partially reduce their emissions, we have included the projected costs associated with partially decarbonizing 25%, 50%, or 75% of current emissions (Fig. 4a). The costs associated with intermediate, fractional removal quantities are included in the ESI, Fig. S2.† These analyses reveal an interesting deviation from the prior observations, whereby Scenario 7 becomes more affordable than Scenario 8 if a company is looking to achieve 50% removal. At 50% capture, only a small amount of CO_2 needs to be removed by carbon capture, while the rest is avoided by pursuing clinker and fuel replacement. Because we assume that DAC is implemented offsite without any capital costs to the cement company, it always costs $200 $t_{CO_2}^{-1}$ regardless of the amount of CO_2 captured; however, PSC requires that the capture facility is retrofitted to the cement plant with extensive capital investments. These high capital investments prevent PSC from being affordable at low capture amounts, leading to large increases in the cost of cement production. This trend is further emphasized in Fig. 4b between 0.48 and 0.61 removal fractions, where cement facilities would save significantly by pursuing only DAC and not PSC (*i.e.*, Scenario #7 would be preferred over Scenario #8). Like the sensitivity study we performed previously, we also chose to lower the cost of DAC to $100 $t_{CO_2}^{-1}$ while keeping PSC costs at $60 $t_{CO_2}^{-1}$ to investigate the effects this had on the optimal cost and pathway (ESI, Fig. S3†). While it is unlikely that DAC costs will drop while PSC costs remain constant, it highlights that the favorable range for Scenario #7 over Scenario #8 extends to ~80% removal, making the DAC option more desirable over a wider range of decarbonization amounts. Consequently, if DAC costs are lowered significantly, the difference between installing a PSC facility and only performing DAC may be minimal, allowing the cement facility to avoid new plant construction and further capital expenditures.

4 Conclusions

Considering the "hard-to-decarbonize" nature of the cement industry and the breadth of research dedicated to this challenge, it is clear that initiating decarbonization efforts in the near term is crucial. The perspective presented here identifies a potential pathway forward using technologies that are at higher technology readiness levels compared to the more nascent platforms aimed at eliminating cement process emissions entirely. While there are still significant strides in cement regulation that are required to begin pursuing these retrofit technologies, we show that the breadth of available research supports the transition towards replacing clinker, implementing fuel alternatives, and employing carbon capture technologies to significantly reduce carbon emissions. In this work, we exhibit that it is possible to eliminate carbon emissions with a $31 t_{cement}^{-1} increase in production costs by pursuing a combination of all four decarbonization options. If even more aggressive point source and direct air capture system costs of $20 $t_{CO_2}^{-1}$ and $100 $t_{CO_2}^{-1}$, respectively, are assumed, cement costs may only increase by $7 t_{cement}^{-1}. While the margins are low in the cement industry, we hope that regulatory changes and policy incentives will enable the deployment of the technologies outlined in this work. It is also important to acknowledge that there are potentially other factors for cement companies to consider such as the high capital costs associated with PSC, how easy retrofitting a decarbonization pathway may be in a particular facility, and/or the experience the facility has with altering operating conditions to account for varying system inputs. While the approach presented herein is used to broadly analyze the United States cement industry, it can be adapted to perform similar investigations of other countries and regions. Further, the operating conditions, costs, efficiencies, *etc.* that are associated with operational plants can be considered to improve the model's accuracy for specific applications.

The analysis presented here supports the idea that these pathways can help achieve the decarbonization goals set by the IEA and GCCA, however, we also want to emphasize the need for continued support for new cement manufacturing pathways that avoid CO_2 process emissions. The high emissions rate and costs associated with decarbonizing often make net-zero emissions extremely difficult to envision for the industry, but the search for new technologies that rely on electrical inputs may warrant continued attention. These futuristic goals are important to continue investigating but, in this perspective, we have used an analytical framework to support that it is possible to begin transitioning towards a cleaner industrial platform to prevent the magnitude of cement industry emissions from continuing to contribute to the broader climate issues.

Data availability

The data supporting the findings in this study have been included within the article or as part of the ESI.†

Author contributions

K. M. R.: conceptualization, methodology, validation, formal analysis, investigation, data collection, data analysis, writing (original draft), writing (review and editing), and visualization. F. H. S.: data analysis and writing (review and editing). Z. L. B.: conceptualization, data analysis, and writing (review and editing).

Conflicts of interest

The authors declare no competing financial interest.

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References

1 International Energy Agency; Cement Sustainability Initiative, *Technology Roadmap: Low-Carbon Transition in the Cement Industry*, 2018.
2 Global Cement and Concrete Association, *GCCA Sustainability Guidelines for the Monitoring and Reporting of CO2 Emissions from Cement Manufacturing*, 2019.
3 GCCA. Concrete Future – Roadmap to Net Zero, *Global Cement and Concrete Association*, 2021, 1–48.
4 S. Griffiths, B. K. Sovacool, D. D. Furszyfer Del Rio, A. M. Foley, M. D. Bazilian, J. Kim and J. M. Uratani, Decarbonizing the Cement and Concrete Industry: A Systematic Review of Socio-Technical Systems, Technological Innovations, and Policy Options, *Renewable Sustainable Energy Rev.*, 2023, **180**, 113291, DOI: 10.1016/j.rser.2023.113291.
5 EPA. 11.6 Portland Cement Manufacturing, in *Mineral Products Industry*, 2020.
6 J. Cresko, E. Rightor, A. Carpenter, K. Peretti, N. Elliott, S. Nimbalkar, W. R. Morrow, A. Hasanbeigi, B. Hedman, S. Supekar, C. McMillan, A. Hoffmeister, A. Whitlock, T. Lgogo, J. Walzberg, C. D'Alessandro, S. Anderson, S. Atnoorkar, S. Upsani, P. King, J. Grgich, L. Ovard, R. Foist, A. Conner, M. Meshek, A. Hicks, C. Dollinger and H. Liddell, *Industrial Decarbonization Roadmap*, 2022.
7 O. M. Fadayini, C. Madu, T. T. Oshin, A. A. Obisanya, G. O. Ajiboye, T. O. Ipaye, T. O. Rabiu, J. T. Akintola, S. J. Ajayi and N. A. Kingsley, Energy and Economic Comparison of Different Fuels in Cement Production, in *Cement Industry - Optimization, Characterization and Sustainable Application*, IntechOpen, 2021, DOI: 10.5772/intechopen.96812.
8 A. Rahman, M. G. Rasul, M. M. K. Khan and S. Sharma, Impact of Alternative Fuels on the Cement Manufacturing Plant Performance: An Overview, *Procedia Eng.*, 2013, **56**, 393–400, DOI: 10.1016/j.proeng.2013.03.138.
9 M. S. Imbabi, C. Carrigan and S. McKenna, Trends and Developments in Green Cement and Concrete Technology, *Int. J. Sustainable Built Environ.*, 2012, **1**(2), 194–216, DOI: 10.1016/j.ijsbe.2013.05.001.
10 Global Cement and Concrete Association, *Getting the Numbers Right (GNR)*, 2021.
11 Sublime Systems, https://sublime-systems.com/.
12 Brimstone, https://www.brimstone.com/.
13 U.S. Energy Information Administration, 1. The Electricity Mix in the United States Shifts from Fossil Fuels to Renewables, in *Annual Energy Outlook 2023*, EIA, 2023, pp. 9–13.
14 The European Cement Association, *The Role of Cement in the 2050 Low Carbon Economy*, 2013.
15 H. G. Van Oss and A. C. Padovani, Cement Manufacture and the Environment, Part II: Environmental Challenges and Opportunities, *J. Ind. Ecol.*, 2003, **7**(1), 93–126, DOI: 10.1162/108819803766729212.
16 A. Rahman, M. G. Rasul, M. M. K. Khan and S. Sharma, Recent Development on the Uses of Alternative Fuels in Cement Manufacturing Process, *Fuel*, 2015, **145**, 84–99, DOI: 10.1016/j.fuel.2014.12.029.
17 CSI-ECRA, *CSI/ECRA - Technology Papers 2017 Development of State of the Art Techniques in Cement Manufacturing: Trying to Look Ahead. Technology Papers*, 2017, 190.
18 K. Scrivener, F. Martirena, S. Bishnoi and S. Maity, Calcined Clay Limestone Cements (LC3), *Cem. Concr. Res.*, 2018, **114**, 49–56, DOI: 10.1016/j.cemconres.2017.08.017.

19 D. Perilli, Update on Fly Ash in the US, April 2023; 2023, https://www.globalcement.com/news/item/15657-update-on-fly-ash-in-the-us-april-2023.
20 K. L. Scrivener, Options for the Future of Cement, *Indian Concr. J.*, 2014, **88**(7), 11–21.
21 A. Alujas, R. Fernandez, R. Quintana, K. L. Scrivener and F. Martirena, Pozzolanic Reactivity of Low Grade Kaolinitic Clays: Influence of Calcination Temperature and Impact of Calcination Products on OPC Hydration, *Appl. Clay Sci.*, 2015, **108**, 94–101.
22 P. S. Fennell, S. J. Davis and A. Mohammed, Decarbonizing Cement Production, *Joule*, 2021, **5**(6), 1305–1311, DOI: 10.1016/j.joule.2021.04.011.
23 J. A. Moya, N. Pardo and A. Mercier, The Potential for Improvements in Energy Efficiency and CO2 Emissions in the EU27 Cement Industry and the Relationship with the Capital Budgeting Decision Criteria, *J. Cleaner Prod.*, 2011, **19**(11), 1207–1215, DOI: 10.1016/j.jclepro.2011.03.003.
24 IPCC, *IPCC Special Report on Carbon Dioxide Capture and Storage*, ed. Metz, B., Davidson, O., de Coninck, H., Loos, M. and Meyer, L., 2005.
25 H. Gerbelová, M. Van Der Spek and W. Schakel, Feasibility Assessment of CO2 Capture Retrofitted to an Existing Cement Plant: Post-Combustion *vs.* Oxy-Fuel Combustion Technology, *Energy Procedia*, 2017, **114**, 6141–6149, DOI: 10.1016/j.egypro.2017.03.1751.
26 M. Antunes, R. L. Santos, J. Pereira, P. Rocha, R. B. Horta and R. Colaço, Alternative Clinker Technologies for Reducing Carbon Emissions in Cement Industry: A Critical Review, *Materials*, 2022, **15**(1), 209, DOI: 10.3390/ma15010209.
27 G. Habert, S. A. Miller, V. M. John, J. L. Provis, A. Favier, A. Horvath and K. L. Scrivener, Environmental Impacts and Decarbonization Strategies in the Cement and Concrete Industries, *Nat. Rev. Earth Environ.*, 2020, **1**(11), 559–573, DOI: 10.1038/s43017-020-0093-3.
28 F. Yang, J. C. Meerman and A. P. C. Faaij, Carbon Capture and Biomass in Industry: A Techno-Economic Analysis and Comparison of Negative Emission Options, *Renewable Sustainable Energy Rev.*, 2021, **144**, 111028, DOI: 10.1016/j.rser.2021.111028.
29 A. M. Cormos and C. C. Cormos, Reducing the Carbon Footprint of Cement Industry by Post-Combustion CO2 Capture: Techno-Economic and Environmental Assessment of a CCS Project in Romania, *Chem. Eng. Res. Des.*, 2017, **123**, 230–239, DOI: 10.1016/j.cherd.2017.05.013.
30 D. R. Sakhamuru *Techno-Economic Analysis and Strategic Decarbonization of the Indian Cement Industry*, Massachusetts Institute of Technology, 2022.
31 P. H. M. Feron, A. Cousins, K. Jiang, R. Zhai and M. Garcia, An Update of the Benchmark Post-Combustion CO2-Capture Technology, *Fuel*, 2020, **273**, 117776, DOI: 10.1016/j.fuel.2020.117776.
32 D. Danaci, M. Bui, C. Petit and N. MacDowell, En Route to Zero Emissions for Power and Industry with Amine-Based Post-Combustion Capture, *Environ. Sci. Technol.*, 2021, **55**(15), 10619–10632, DOI: 10.1021/acs.est.0c07261.
33 H. Azarabadi and K. S. Lackner, Postcombustion Capture or Direct Air Capture in Decarbonizing US Natural Gas Power?, *Environ. Sci. Technol.*, 2020, **54**(8), 5102–5111, DOI: 10.1021/acs.est.0c00161.
34 D. W. Keith, G. Holmes, D. St. Angelo and K. Heidel, A Process for Capturing CO2 from the Atmosphere, *Joule*, 2018, **2**(8), 1573–1594, DOI: 10.1016/j.joule.2018.05.006.
35 E. Smith, J. Morris, H. Kheshgi, G. Teletzke, H. Herzog and S. Paltsev, The Cost of CO2 Transport and Storage in Global Integrated Assessment Modeling, *Int. J. Greenhouse Gas Control*, 2021, **109**, 1–76, DOI: 10.1016/j.ijggc.2021.103367.
36 W. J. Schmelz, G. Hochman and K. G. Miller, Total Cost of Carbon Capture and Storage Implemented at a Regional Scale: Northeastern and Midwestern United States, *Interface Focus*, 2020, **10**, 20190065.
37 Thunder Said Energy, Cement Costs and Energy Economics?, 2024, https://thundersaidenergy.com/downloads/cement-costs-and-energy-economics/.
38 IBIS World, https://www.ibisworld.com/us/bed/price-of-cement/190/.
39 S. Baldeira and I. Hovenko, *Building Materials: Industry Profitability and Growth*, Bloomber Professional Services, 2016, https://www.bloomberg.com/professional/insights/commodities/building-materials-industry-profitability-and-growth/.
40 E. Beguedou, S. Narra, E. Afrakoma Armoo, K. Agboka and M. K. Damgou, Alternative Fuels Substitution in Cement Industries for Improved Energy Efficiency and Sustainability, *Energies*, 2023, **16**(8), 3533, DOI: 10.3390/EN16083533.
41 A. Gailani, S. Cooper, S. Allen, A. Pimm, P. Taylor and R. Gross, Assessing the Potential of Decarbonization Options for Industrial Sectors, *Joule*, 2024, 1–28, DOI: 10.1016/j.joule.2024.01.007.
42 S. S. Akhtar, E. Ervin, S. Raza and T. Abbas, From Coal to Natural Gas: Its Impact on Kiln Production, Clinker Quality and Emissions, *IEEE Cem. Ind. Tech. Conf., [Pap.], 15th*, 2013, 1–24, DOI: 10.1109/CITCON.2013.6525276.
43 M. N. Dods, E. J. Kim, J. R. Long and S. C. Weston, Deep CCS: Moving beyond 90% Carbon Dioxide Capture, *Environ. Sci. Technol.*, 2021, **55**(13), 8524–8534, DOI: 10.1021/acs.est.0c07390.
44 M. Della Vigna, Y. Bocharnikova, A. Gandolfi, Q. Marbach, A. Shalaeva and N. Bhandari, *Carbonomics*, 2023, 1–34.
45 U.S. Department of Energy, *Basic Research Needs for Carbon Capture: Beyond 2020*, 2010.
46 The National Academies Press, *Negative Emissions Technologies and Reliable Sequestration*, 2019, pp. 1–496, DOI: 10.17226/25259.
47 U.S. Department of Energy, *Carbon Negative Shot*, 2024, https://www.energy.gov/fecm/carbon-negative-shot.