Science
AAAS

Building materials could store more than 16 billion tonnes of CO_2 annually

Elisabeth Van Roijen, Sabbie A. Miller, Steven J. Davis

Science

Accepted November 5, 2024
Published January 10, 2025

Building materials could store over 15 gigatons of CO_2 annually

Authors: Elisabeth Van Roijen[1]*, Sabbie A. Miller[1], Steven J. Davis[2]

Affiliations:

[1] Department of Civil and Environmental Engineering, University of California, Davis, CA

[2] Department of Earth System Science, Stanford University, Stanford, CA

* Corresponding author. Email: evanroijen@ucdavis.edu

Abstract: Achieving net-zero greenhouse gas (GHG) emissions likely entails not only lowering emissions but also deploying carbon dioxide removal (CDR) technologies. Here, we explore the annual potential to store CO_2 in building materials. We find that fully replacing conventional building materials with CO_2-storing alternatives in new infrastructure could as much as 16.6 ± 2.8 Gt of CO_2 each year—roughly 50% of anthropogenic CO_2 emissions in 2021. The total storage potential is far more sensitive to the scale of materials used than the quantity of carbon stored per unit mass of materials. Moreover, the carbon storage reservoir of building materials will grow in proportion to demand for such materials, which could reduce demand for more costly or environmentally risky geological, terrestrial, or ocean storage.

One-Sentence Summary: Building materials represent an opportunity to store many gigatonnes of CO_2 per year.

Main Text:

Limiting the rise of global mean temperatures and stabilizing Earth's climate will require achieving net-zero emissions of long-lived greenhouse gases (GHGs) or balancing out anthropogenic CO_2 emissions with an equivalent amount of GHG removal. (*1*). While decarbonization efforts are critical and must be scaled urgently, ongoing (residual) emissions from difficult-to-decarbonize sources (*2*, *3*) will likely need to be balanced by direct removal of carbon dioxide (CO_2) or other GHGs from the atmosphere and subsequent storage in geological, terrestrial, or ocean reservoirs or products. (hereinafter "CDR") (*4*). In comparison, carbon capture and storage (CCS) of CO_2 emissions from point sources only contribute to CDR if the captured CO_2 was recently in the atmosphere, such as from combustion of biomass. Such CDR would involve separate mechanisms of both capture and storage of atmospheric carbon. As highlighted by the National Academies of Science, Engineering, and Medicine, value-added products are a promising option for storing large quantities of carbon (*5*). In particular, building materials offer two characteristics that make them well-suited to act as a storage reservoir: (i) their quantity – the cumulative mass of infrastructure materials produced from 1900 to 2015 was nearly as high as that of all human food, animal feed, and energy resources combined (*6*); and (ii) their longevity – structural materials typically remain in use for decades, which can contribute to their sequestering GHGs long enough time horizon to provide climate benefits (*7*). These two factors combine to make this enormous human-made mass of materials an immense opportunity to store GHGs (*8*). Further, CCS technologies require the construction of pipelines and other infrastructure to ensure stable underground storage of CO_2, which may pose risks to the environment and human wellbeing (*9*). Therefore, engineering building materials to act as a CDR method may be a logical first step given the large mass of materials already consumed in the built environment if similar performance can be attained, thus eliminating the need to develop and scale other carbon storage systems.

. In recent years, the production of building materials has resulted in an estimated 3.5-11 Gt of CO_2e or 10-23 % of global GHG emissions (*11–13*). Recent studies have explored the application of emerging technologies to alter the composition and manufacturing methods of structural materials to facilitate uptake of CO_2 or CH_4 by the materials or their constituents, and thereby reversing some or most of the process emissions (*16*). For example some studies have examined the potential for timber buildings to act as a global carbon sink (*17–19*), while other studies have considered the contribution of alternative cements and the impacts of concrete carbonation at end-of-life on the carbon uptake potential of concrete (*20*, *21*). Here, we examine the global potential to store carbon in some of the most common building materials: concrete, brick, asphalt, plastic, and wood. We do not examine alloys because they have very specific functional tolerances and a limited ability to store carbon. Alternatively, decarbonization strategies for steel may include the use of green hydrogen for direct-reduced iron steel production (*10*). We calculated annual storage potential of building materials assuming 2016 levels of consumption (the most recent year with available data for all materials), all carbon within materials (stoichiometric or measured) originated from the atmosphere, and the storage is effectively permanent (details are provided in 15). Our estimates are based on the extent to which conventional inputs could be substituted by alternatives that either contain biogenic carbon (e.g., recently removed from the atmosphere via photosynthesis) (*22*, *23*) or contain key minerals (e.g., recently formed carbonate minerals that may solidify with the use of concentrated sources of CO_2) (*24*). We assume these building materials have negligible use-phase emissions and we assume these materials are likely landfilled at end-of-life resulting in minimal GHG emissions (*25*). However, we note that future research could consider use phase emissions and uptake such as the emissions associated with the demolition process of building materials, which in some cases could be substantial (*26*), as well as emissions associated with burning or anaerobic decomposition of wood. We highlight companies with pilot-scale demonstrations of these materials, which have shown substantially lower carbon footprints, and in some cases net-removal of carbon from the atmosphere, compared to conventional materials. Further, given the uncertainty around the energy demand and GHG emissions associated with these alternative materials, we determine the total allowable emissions that would still result in achieving net carbon removal.

Results

The carbon storage potential of our built environment

We determined the relevant capture mechanisms and magnitude of carbon storage per unit of different building materials (Fig. 1). While bio-based plastics resulted in the highest storage potential per kg of material, they contribute the least to total potential due to the relatively small production quantities compared to all other building materials. Inversely, aggregates in concrete have one of the lowest storage potentials (<1 kg CO_2/kg); yet, due to the substantial scale of global demand, they present the largest total potential. Considering these tradeoffs, areas ripe for rapid market penetration and potential for mass scaling could lead to more substantial climate benefits than driving the greatest degree of uptake for any individual material-based carbon storage option.

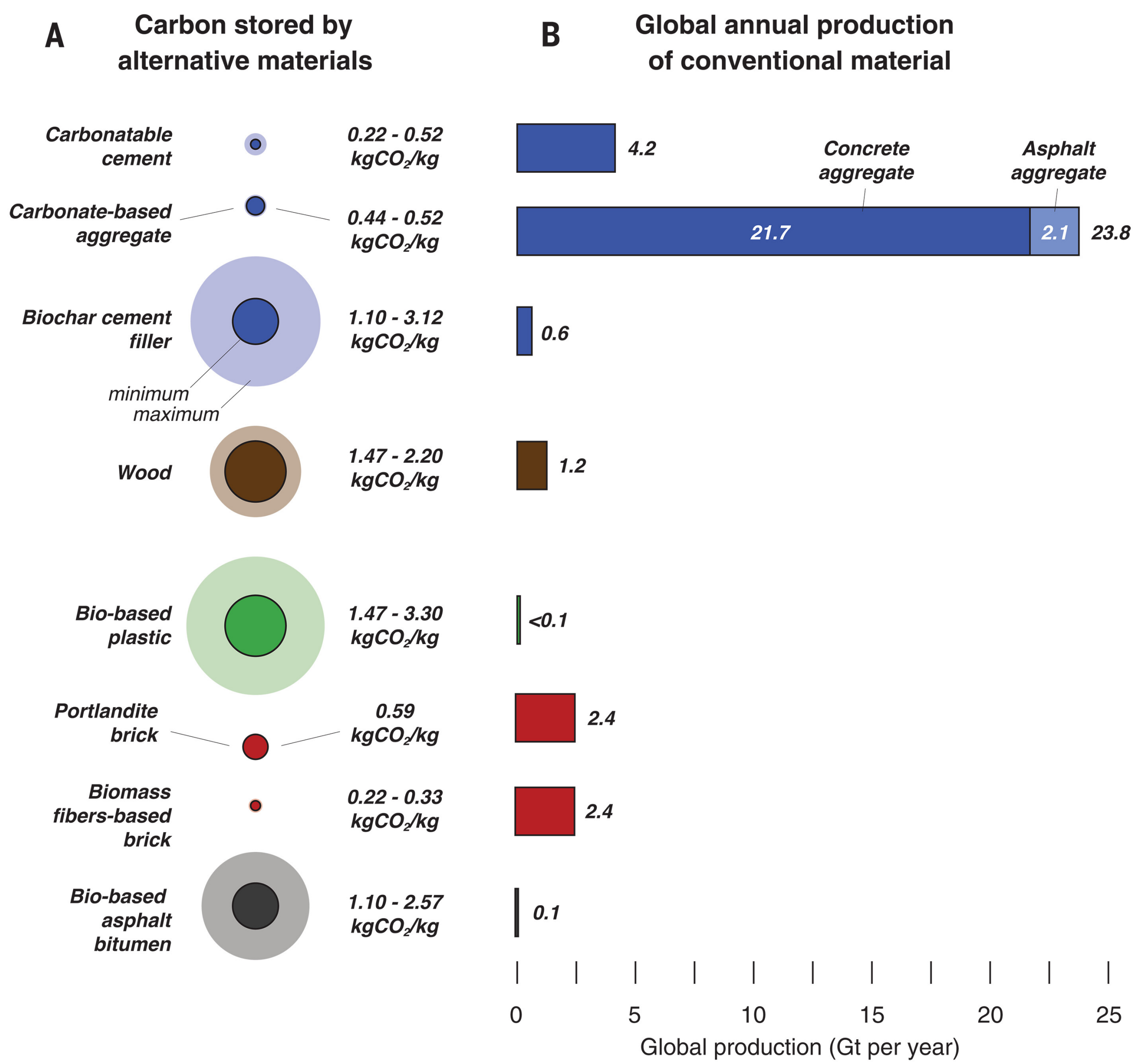

Figure 1 The potential to store carbon in building materials varies considerably depending on the carbon density of alternative materials (kg CO_2 per kg material, A) and the scale at which conventional materials are being used (B).

These building materials have the capacity to store up to 16.6 ± 2.8 Gt of CO_2 (**Table 1**), which is equivalent to roughly 50% of CO_2 emitted from all anthropogenic sources in 2021 (*27*). We can attribute most of this storage, 11.5 ± 1 Gt of CO_2 to aggregates used in concrete and asphalt pavement. This notable capacity for fixed carbon is driven by the large mass of aggregates used in these two materials, which outweigh the other materials by three-fold. We considered different permutations for CO_2 storage in cement, but we found that the combination of a magnesium-oxide based cement, synthesized from forsterite (Mg_2SiO_4) and carbonated, with 15 wt% biochar as filler results in the highest level of CO_2 capture (~ 0.9 kg of CO_2 absorbed per kg of cementing binder), resulting in a total potential storage of 2.6 ± 1.1 Gt CO_2. Bricks were the next most impactful material for CO_2 storage, and by assuming a biomass fiber carbon content of 0.6 kg C/kg, the global production of bricks can result in roughly 0.8 Gt of CO_2 storage. This quantity of storage is equivalent to 1/3 of the mass of bricks produced, despite fibers comprising only 15 wt% of the brick. Additionally, with appropriate raw materials, mineral carbonation of portlandite ($Ca(OH)_2$) in bricks can lead to an additional 1.2 Gt of fixed CO_2. If the market and appropriate forestry practices can support increasing wood consumption by 20%, this change leads to absorption of an additional 0.45 ± 0.09 Gt of CO_2. We note that this potential is heavily dependent on forest management techniques and emissions associated with harvesting, transporting and manufacturing of wood products as well as emissions associated with fire or decay of biomass residues (*28*, *29*). We can attribute an additional degree of CO_2 storage (<5%) to bio-based plastic and asphalt binder, with the low storage potential resulting from relatively low consumption (less than 0.2 Gt).

Table 1. Summary of the global carbon dioxide removal potential of the materials examined based on 2016 global production values. Chemical-derived emissions for traditional materials are presented as well for reference.

Material	**Global material production (Gt)**	**Global chemical-related emissions (Gt CO_2)**	**Global carbon dioxide storage potential (Gt CO_2)**
Concrete aggregate	21.7	0	-10.5 ± 1
Asphalt aggregate	2.1	0	-1.0 ± 0.09
Cement	4.2	1.7	-1.3 ± 0.5
Cement filler	0.6	0	-1.3 ± 0.6
Brick	2.4	0	-1.6 ± 0.3
Wood	1.2	-2.3	-0.5 ± 0.9
Asphalt bitumen	0.1	0	-0.2 ± 0.1
Plastic	0.1	0.1	-0.2 ± 0.06
Total	**32.4**	**-0.5**	**16.6** ± 2.8

Because of the wide range of materials that could store carbon and the amount of carbon per unit mass of those materials, we tested the sensitivity of estimated storage potential to different modeling assumptions and the levels of implementation related to different materials **(Fig 2).** Our results reinforce the conclusion that the single largest driver of carbon stored and emissions reduced is the mass of materials consumed, with aggregate and cement for concrete production having the highest consumption (**Fig 2A** and **2B**, respectively), followed by brick and asphalt aggregate. Higher assumed carbon content also drives greater storage, but this parameter is outweighed by material demand in terms of total potential.

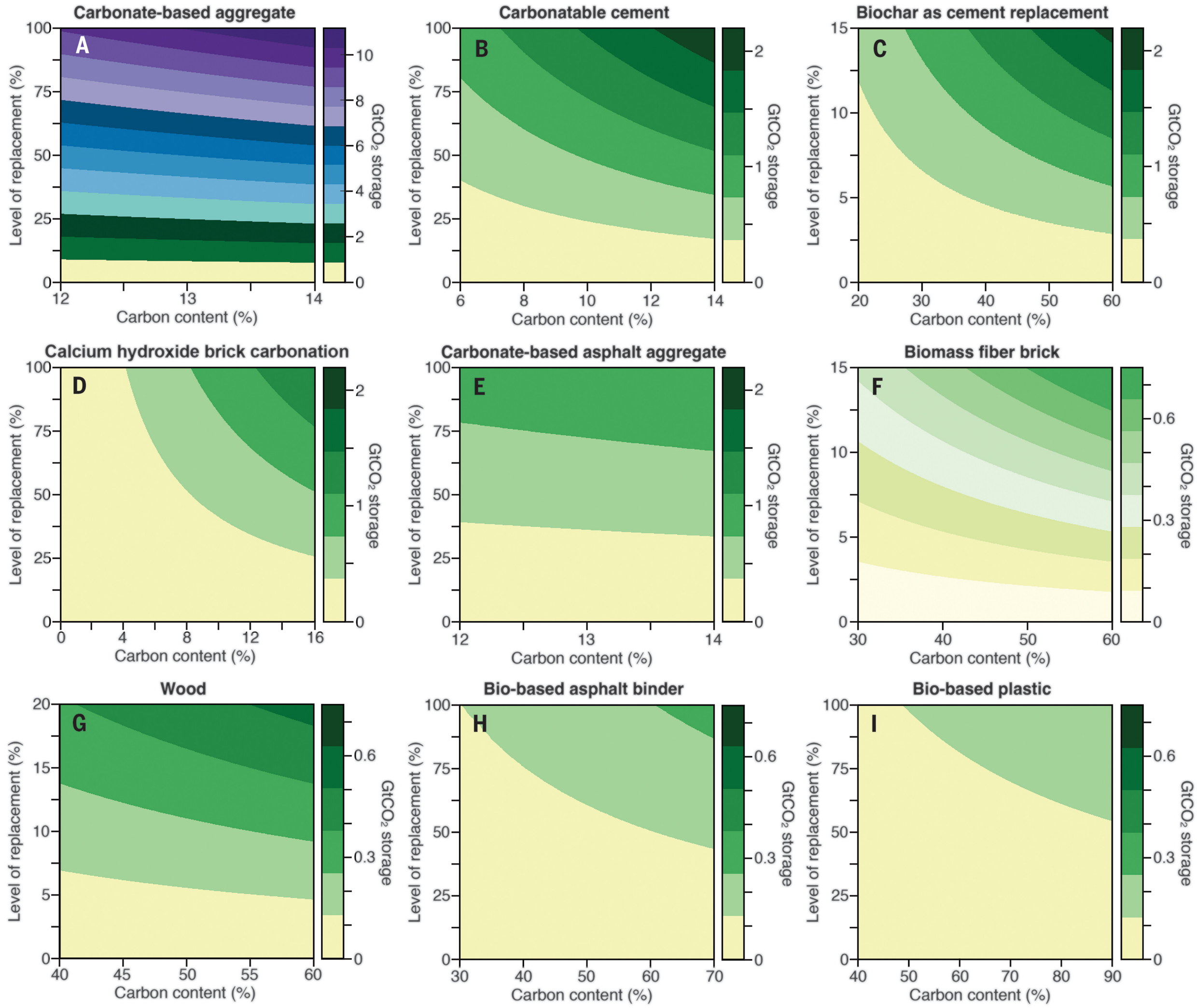

Figure 2 Sensitivity of the theoretical carbon storage potential for each material to carbon content and level of implementation.

Resource availability assessment

Considering that the large material demand for construction is the primary driver in storage potential, we conduct a preliminary assessment of resource availability to realize the described carbon storage potential. We did not include carbonatable cements (i.e., cements that solidify through carbon mineralization instead of hydration) and bricks in our assessment because robust production pathways for these materials have not currently been identified. For carbon mineralization pathways of aggregate, we considered various Ca and Mg-rich industrial waste materials (namely, red mud, blast furnace slag, steel slag, mine tailings, cement kiln dust, biomass ash, lignite ash and coal ash) and end-of-life concrete as potential feedstocks. Based on their annual production and elemental composition, we found that roughly 2 Gt of carbonate-based aggregate can be produced, offering 1 Gt of CO_2 storage. However, it is important to note that future supplies of such resources may change. For example, the availability of blast furnace slag may decrease as the transition to direct-reduced iron continues (*30*). While there are abundant natural resources capable of contributing 10,000 to 1,000,000 Gt of carbon sequestration through carbonation (e.g. olivine, basalt, serpentine, etc.)(*31*), these minerals are difficult to access, and an energy-efficient carbonation process has yet to be identified on a large scale (*32*). Therefore, further exploration into the use of these natural resources is needed. Substitutions of 15 wt% of bricks with biomass fibers, all asphalt bitumen with bio-oil, and all plastics with bio-based plastics requires only using 5% of the annual agricultural residue (i.e., biomass resources from agricultural cultivation that are not directly used for human food). Using biochar as a filler to replace 15 wt% of cement would utilize another 24% of agricultural residues. Implementing all biomass strategies we considered would still leave 71% of agricultural byproducts available for other applications. A potential side benefit of using biochar is that the process of producing it via pyrolysis could co-produce valuable byproducts, such as syngas and bio-oil. However, the current production and use of biochar is very limited. Roughly 0.4 Mt of biochar was produced in 2021, whereas the carbon storage we model would demand 600 Mt (*33*). In scaling-up biochar production to that degree, it would be critical to ensure such chars remove atmospheric carbon on net and also consistently meet any physical requirements for safe use. Our estimates of resource demand are based on an assumption of a 1:1 carbon replacement ratio, where the carbon content of biomass is efficiently converted to the carbon content of building materials. Any inefficiencies that result in material waste would increase material demand (see the sensitivity analysis in data S6).

In addition to the quantity of feedstock resources available, it is important to note the geographical areas where current building materials are produced compared to where these alternative technologies have the potential to be scaled up. The minerals required for carbonatable cement production or carbonate-based aggregates are available in large quantities but are often located deep beneath the Earth’s surface, making them difficult to access. Therefore, regions with easier access to mineral deposits, such as through surface exposed continental flood basalts and brine from salt lakes or sea water, could be ideal locations for the scale up of these new technologies (*34*). Given that future cement and concrete demand is expected to grow in regions of Southeast Asia and Africa (*35*), relevant flood basalt areas and salt lakes that in these regions may be leveraged (*36*). Furthermore, Europe has a large potential for supplying necessary minerals for the carbonation of cement and concrete, due to the higher potential for removing aging infrastructure, paired with five commercially active mines and 107 other locations compatible for mining silicate rocks. Agricultural residues such as wheat and rice straw are largely produced in Asia, while the United States (US) is the largest producer of corn straw (*37*) and Brazil is the largest producer of sugarcane bagasse (*38*).These biomass residues could be converted to be biochar and leveraged for use in cement composites, which is currently largely produced in China, India, and the US (*39*). Alternatively, these residues could be integrated in brick production which is largely produced in US, China and India (*40*), or used to create plastics, roughly 70% of which are produced in Asia and the US (*41*).

Contribution to CDR targets in mitigation scenarios

According to the IPCC AR6, to stay below 1.5°C and 2°C targets by 2100, a cumulative maximum of 1133 Gt and 1049 Gt of CO_2 would need to be removed by CDR technologies, respectively (*1*). These CDR requirements reflect efforts to offset the most difficult-to-abate GHG emissions (and to compensate for any emissions overshoot); such CDR is needed in addition to rapid decarbonization strategies such as transition to low-carbon or zero-carbon energy systems, reducing non-CO_2 emissions, and reducing energy and material demands through improved efficiency (*42*). Given that building materials such as concrete and plastics are considered difficult-to-abate industry emissions, we also include the CDR values that are necessary assuming that net-zero emissions are achieved (hereafter referred to as net-negative CDR targets). In other words, these CDR targets reflect the amount of CO2 that would need to be stored, assuming that traditional concrete and plastics (and other difficult-to-abate sources of emissions) are replaced with low-carbon (net-zero) emitting technologies or are off-set by CCS technologies. Although increases in global population and affluence are likely to drive an increase in materials production (*43*), we make a conservative estimate that the overall quantities of different building materials remain at 2016 levels (with the exception of wood, for which we consider a moderate increase of 20% to stay within future projections of wood harvest from sustainable forestry practices amounting to 0.4 to 1.75 Gt C in 2050). Given these levels of material demand, a full transition to carbon-storing alternatives by 2025, 2050, or 2075 would accommodate at least 1380, 920, and 460 Gt of CO_2 to be removed by 2100, respectively (**Fig 3**). This quantity of storage exceeds the amount of net-negative CDR required by 1.5 and 2°C targets. Exceeding this amount of carbon storage is important because the techniques for production of these carbon-storing materials may require more energy than traditional production. For example, the production of carbonatable cements may require more energy than Ordinary Portland Cement due to added steps associated with mining, processing magnesium or calcium oxides, as well as sourcing CO_2 for the carbonation process (*44*). Thus, while we did not model energy-related emissions for new technologies, our calculations suggest that some energy-related emissions associated with the production of these carbon storing materials could still occur without inhibiting the ability to achieve desired emissions reduction targets.

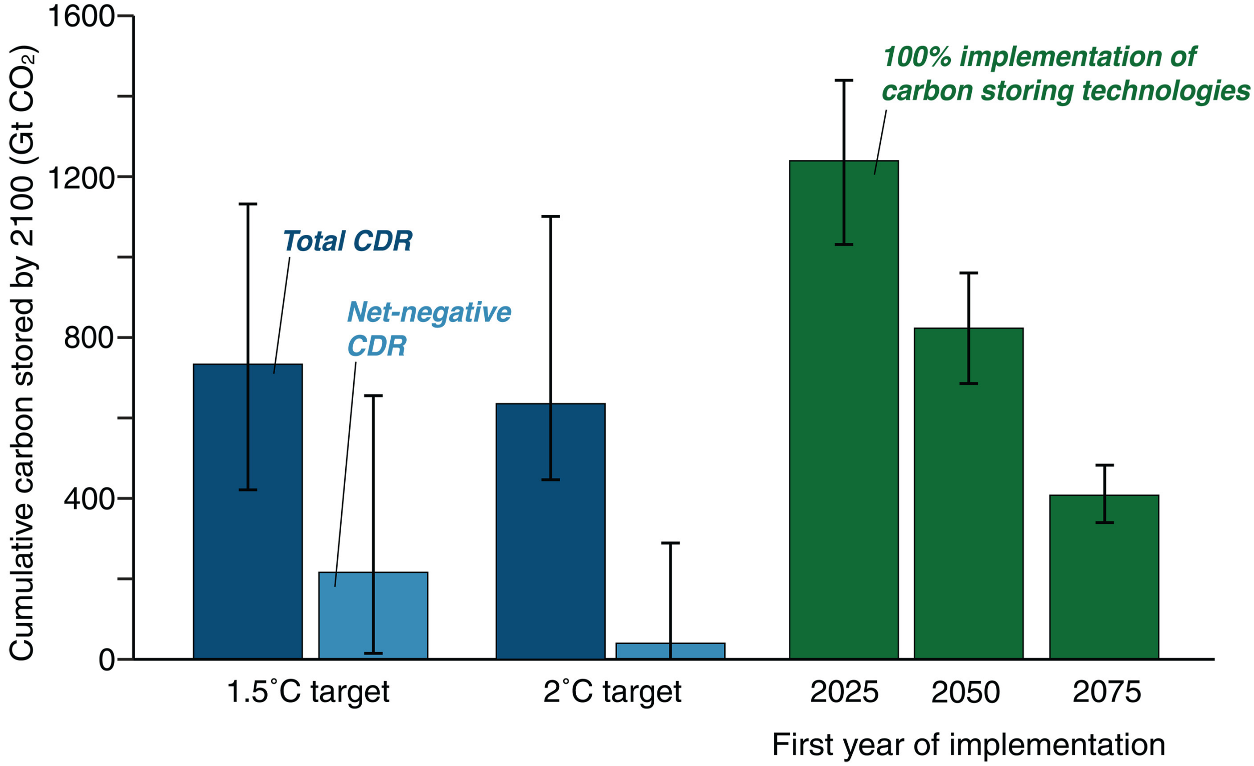

Figure 3. Cumulative CO_2 removals by 2100 as a function of the year of implementation of carbon storing technologies. Cumulative carbon storage is compared with the IPCC targets of gross CDR (dark blue) and net-negative CDR (light blue) for staying below 1.5C and 2C with no overshoot, assuming full implementation of the technologies presented herein. The error bars represent the minimum and maximum values for carbon dioxide storage.

In addition to energy-related emissions, feedstock resource constraints may also be a limiting factor to achieving the levels of storage required by CDR in mitigation scenarios. Therefore, we conducted an additional assessment to analyze the potential for using only currently available resources: namely, replacing roughly 10% of aggregate with carbonate-based aggregate, substituting 15% of brick with biomass fiber, fully transitioning to bio-based plastic production, utilizing bio-oil based asphalt binder, and replacing 6-15% of cement with biochar filler. We found that fully implementing these technologies by 2045 and 2090 would be sufficient to store 30 and 35% of gross CDR required in median 1.5° and 2°C scenarios, respectively (**Table 2**).

Table 2. Assessment of resource availability constraints on the ability to meet IPCC climate change targets of 1.5 and 2°C.

Global warming target with limited or no overshoot	Cumulative CDR by 2100 (Gt CO_2) (min, max)		Take-off year required to achieve cumulative CDR target: Scenario 1: Using all currently available resources (min, max)	Take-off year required to achieve cumulative CDR target: Scenario 2: Using all currently available resources but not counting increase in wood consumption (min, max)
1.5°C	Total CDR	740 (420, 1133)	1916 (1995, 1818)	1910 (1992, 1809)
	Net-negative CDR	220 (20, 660)	2045 (2095, 1935)	2043 (2094, 1930)

2°C	Total CDR	630 (442, 1049)	1941 (1990, 1839)	1936 (1986, 1830)
	Net-negative CDR	40 (0, 290)	2090 (n/a, 2027)	2089 (n/a, 2025)

Although these feedstock resources are technically available to be stored in buildings, it is crucial to recognize that they may also be in demand for other applications such as energy production or animal feed. As an example, our estimates assume biochar is produced by char-maximizing slow pyrolysis rather than processes like gasification which produce less char and more energy. Similarly, insofar as mineral wastes such as blast furnace slag are used as supplementary cementitious materials (SCMs), they will not be available for use as carbonate-based aggregate. Furthermore, shifts in demands of feedstock resources may result in unintended consequences (e.g. indirect land-use change impacts resulting from increased biomass consumption). Therefore, efforts to derive sustainable cultivation practices and materials production pathways, proper accounting of GHG fluxes and other environmental impacts beyond climate damages must be continuously addressed.

Given that the largest driver for the magnitude of carbon that can be stored in building materials is the mass of materials consumed, estimates regarding future consumption of these materials can have a substantial impact on results. Policy incentives aimed at mitigating GHG emissions or other environmental impacts could increase recycling or re-use rates of building materials or reduce material intensity of construction by changing specifications and design, thereby lowering demand. For example, studies have shown that improvements in material efficiency strategies for buildings could reduce future demand by nearly 26% (*45*). Yet simultaneously, projected population growth could increase material consumption; for example, recent estimates have projected a 23% growth in cement consumption(*35*). Material consumption might also be affected by changes in feedstock costs, crude oil prices (for plastics and asphalt), economies of scale in manufacturing, and product innovation. For example, various policies have been introduced that could increase the demand of bio-based materials such as the European Green Deal Industrial Plan (*46*). Therefore, we conduct an additional sensitivity analysis in this work to examine the effects of changes in future consumption of materials on storage potential. Namely, we consider a +/- 20% change in demand by 2100 for all materials and find that total annual storage could range from 13.2 to nearly 20 Gt of CO_2 by 2100. Further, if all technologies were implemented by 2050, cumulative storage achieved by 2100 would change by +/- 14% as a result of changes in material demand. In addition, we conduct a sensitivity specifically for plastics, which have been experiencing an alarming growth rate in production over the past few decades and are anticipated to triple in production by 2100 (*47*). This sensitivity analysis for plastics suggests that the contribution of plastics to total carbon stored could increase from less than 1% to close to 5%, resulting in an additional 0.6 Gt of annual carbon storage potential by 2100 (see Supplementary Data Sheets 4 and 8 for full results).

Discussion

If all the alternatives we considered were applied simultaneously, the built environment could store 13.8 to 19.3 Gt of CO_2 each year, assuming minimum and maximum carbon contents, respectively. Meanwhile, emissions from the production of these materials amounted to approximately 3 Gt of CO_2 in 2016 (or 1.8 Gt of CO_2 excluding energy-related emissions), so the combined mitigation opportunity of avoiding process emissions and storing carbon is >20 Gt CO_2. Further, assuming a constant rate of material consumption, we find that over 1200 Gt of CO_2 could be stored in the built environment by 2100 if all storage options were used in 2025, while the production of building materials under a business-as-usual approach would result in 136.8 Gt of cumulative CO_2 emissions based on process-based emissions alone.

Many of the carbon-storing building materials we consider have the potential to be cost-competitive with the conventional materials they replace, due to the low cost of feedstocks needed (such as mineral waste or biomass residues). As a result, an increasing number of companies are beginning to produce materials with CO_2-storing capabilities, suggesting there is market demand.

Companies working to reduce the carbon footprint of concrete have primarily focused on producing both low-carbon binding agents and synthetic aggregates. But some companies are working on the types of alternative cements we modelled here. For example, Solidia Technologies and Caron Upcycling UCLA are proposing pathways to sequester CO_2 in cement via carbon mineralization, reporting up to 70% lower CO_2 emissions than conventional concrete (*48*, *49*). Meanwhile, BluePlanet and O.C.O Technology (formerly called Carbon8) aim to produce synthetic carbonate aggregates using alkaline rock and industrial wastes combined with CO_2 waste streams to create carbon-negative building materials (*50*, *51*).

Bio-based plastics have been around since the early 20th century, but only account for roughly 1% of total annual plastic production, 48% of which is used in short-term packaging applications (*52*). However, the bio-based plastic market is expected to expand to more durable applications like construction, driven by policy changes and the shift towards a circular bioeconomy. Braskem and Biovyn are companies producing bio-based polyvinyl chloride (PVC) and polyethylene (PE) (*53*, *54*). To limit land-use impacts, companies like Dow and Mango Materials are using waste biomass and methane as feedstocks (*55*, *56*). Further, despite the impacts of agricultural processes, these bio-based alternatives have the potential to be carbon-negative with the use of renewable energy (*57*).

Brick manufacturers have the potential to produce carbonate-based or biomass-based bricks that capture CO_2 by utilizing waste materials. Orbix, for instance, uses carbon mineralization of calcium in steel slag combined with CO_2 to create calcium carbonate-based bricks which has been claimed to reduce the carbon footprint by 600 kg CO_2/tonne (*58*, *59*). Bio Fiber Industries is using hemp as a feedstock to make building materials such as bricks. Just Biofiber is combining the two technologies, biomass (such as hemp curd) and mineralization of lime, to produce what they are proposing will be carbon-negative building blocks (*60*).

Although the use of bio-oil in asphalt as a replacement for petroleum-based bitumen is not widely commercialized, Avello Bioenergy is exploring the economic feasibility and carbon sequestration potential of their patented bioasphalt binder (*61*). Similarly, in 2021 Avantium, a chemical company in the Netherlands, partnered with an infrastructure company Roelof, to develop the first major roadway made from lignin-based bioasphalt (*62*). These bio-based asphalt alternatives have been suggested to reduce GHG emissions by 30-60% compared to typical petroleum-based asphalt (*63*).

Despite recent advances in industry, there are still a number of roadblocks for achieving the theoretical carbon storage quantities we determined. Many of the companies mentioned remain at the prototype or pilot stages of production. The barrier to large-scale production could be in part due to competitive pricing of conventional building materials and the lack of established value chains necessary for widespread implementation of these alternative technologies. For example, carbon mineralization pathways require highly concentrated CO_2 gas and feedstocks rich in MgO or CaO. However, CO_2 sources from direct air capture are currently hindered due to high costs (*64*). While not CDR, industry stakeholders could examine the potential for leveraging flue-gas sources and industries generating alkaline-rich waste streams, such as steel manufacturing, to make the process economically viable (*65*). This carbon utilization would not offer the necessary benefits of CDR, but could provide a means to store carbon while limiting need for geologic reserves. Similarly, while biomass-to-polymer conversion routes have reached technological maturity, bio-based plastic manufacturers struggle to scale production due insufficient access to biomass residues required to meet market demands for plastic.

In addition to barriers associated with costs and feedstock availability, another obstacle for the upscaling of the carbon storage technologies presented herein is the risk-averse nature of the building industry as a result of the potential liabilities associated with material failure (*66*). A change in material composition runs a high likelihood of altering material performance. A loss in performance could pose a safety risk if not accounted for in design, and if addressed in design, it could lead to an increased volume of material to carry the same loads and/or more frequent replacement, which in turn could contribute to environmental impacts (*67*). While in theory improved performance can have an inverse effect, there are hindrances to adoption. For example, despite promising research indicating comparable or superior performance of carbonation-cured building materials, they have not yet been incorporated into relevant building codes and standards, making it difficult to commercialize on a large-scale (*65*). Therefore, implementing performance-based codes that allow for changes in concrete composition, while meeting safety requirements, is likely needed to help achieve large-scale carbon storage in building materials. Further, despite many bio-based plastics having identical chemical structures and therefore material properties to their fossil-based counter parts, the use of bio-based plastics in construction is extremely limited (*68*). However, it is important to note that long-term durability studies (and some initial performance indicators, such as constructability characteristics) have not yet been conducted for some of the carbon-storing materials presented herein, such as carbonatable cements or the high use of biochar noted as a filler in cement composites. Therefore, in cases where a loss of desired performance may be expected, research to systematically quantify durability characteristics and investigation into methods that can overcome limitations may be warranted (e.g., the use of galvanization to mitigate against steel corrosion). Further, in this study, it is assumed that the CO_2 is durably stored in these materials for many decades. However, if any of this CO_2 is released either through the degradation of the material (e.g. in the case of wood), or the disposal of material, it would be important to consider the timing of emissions uptake and release in order to more accurately determine the CDR potential (*26*).

Given projected increases in demand for infrastructure materials (*69*), valorizing carbon in the form of long-lived materials could be an area supported through policy mechanisms. The urgency of mitigating climate damages has led to emissions-reduction pledges and regulatory frameworks in many regions and countries, including for industrial materials production (e.g., California's recent bill to reach net-zero emissions from the cement industry by 2045 (*70*)). Strategies to store carbon in building materials are particularly relevant for policymakers as these materials are predominantly from regionally available resources, and some proposed pathways to decarbonization can drive local resource scarcities (*71*) and/or lead to increased health burdens on local populations (*72*). However, they can simultaneously stimulate local economies and create jobs. For the implementation of robust incentives and policies to drive CDR, performance-based metrics for product standards and comparisons must be developed to support the inclusion of carbon-storing building materials. However, the use of such building materials may be initially more suitable for non- or low-load-bearing applications (e.g., insulation, flooring, pavements), which by weight are a substantial fraction of the built environment. Therefore, policymakers could focus on strategies to increase the use of carbon-storing materials presented herein with high technology readiness levels (e.g. bio-based plastics, biomass bricks, and wood) for such applications where risks associated with a change in performance may be more limited.

References and Notes

1. United Nations Environment programme, Climate Change 2023: Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. 35–115 (2023).
2. S. J. Davis, N. S. Lewis, M. Shaner, S. Aggarwal, D. Arent, I. L. Azevedo, S. M. Benson, T. Bradley, J. Brouwer, Y.-M. Chiang, C. T. M. Clack, A. Cohen, S. Doig, J. Edmonds, P. Fennell, C. B. Field, B. Hannegan, B.-M. Hodge, M. I. Hoffert, E. Ingersoll, P. Jaramillo, K. S. Lackner, K. J. Mach, M. Mastrandrea, J. Ogden, P. F. Peterson, D. L. Sanchez, D. Sperling, J. Stagner, J. E. Trancik, C.-J. Yang, K. Caldeira, Net-zero emissions energy systems. *Science (1979)* **360**, eaas9793 (2018).
3. G. Luderer, Z. Vrontisi, C. Bertram, O. Y. Edelenbosch, R. C. Pietzcker, J. Rogelj, H. S. De Boer, L. Drouet, J. Emmerling, O. Fricko, S. Fujimori, P. Havlík, G. Iyer, K. Keramidas, A. Kitous, M. Pehl, V. Krey, K. Riahi, B. Saveyn, M. Tavoni, D. P. Van Vuuren, E. Kriegler, Residual fossil CO2 emissions in 1.5-2 °c pathways. *Nat Clim Chang* **8**, 626–633 (2018).
4. J. Rissman, C. Bataille, E. Masanet, N. Aden, W. R. Morrow, N. Zhou, N. Elliott, R. Dell, N. Heeren, B. Huckestein, J. Cresko, S. A. Miller, J. Roy, P. Fennell, B. Cremmins, T. Koch Blank, D. Hone, E. D. Williams, S. de la Rue du Can, B. Sisson, M. Williams, J. Katzenberger, D. Burtraw, G. Sethi, H. Ping, D. Danielson, H. Lu, T. Lorber, J. Dinkel, J. Helseth, Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070. *Appl Energy* **266**, 114848 (2020).
5. National Academies of Sciences Engineering and Medicine, "Gaseous Carbon Waste Streams Utilization: Status and Research Needs" (Washington D.C., 2019); https://doi.org/10.17226/25232.
6. F. Krausmann, C. Lauk, W. Haas, D. Wiedenhofer, From resource extraction to outflows of wastes and emissions: The socioeconomic metabolism of the global economy, 1900–2015. *Global Environmental Change* **52**, 131–140 (2018).
7. S. A. Miller, E. Van Roijen, P. R. Cunningham, A. Kim, Opportunities and challenges for engineering construction materials as carbon sinks. *RILEM Technical Letters* **6**, 105–118 (2021).
8. ARPA-E, U.S. Department of Energy Announces $45 Million in Carbon Storage Technologies for Building Materials, *Advanced Research Projects Agency - Energy* (2021).
9. D. Rojas-Rueda, K. McAuliffe, E. Morales-Zamora, Addressing Health Equity in the Context of Carbon Capture, Utilization, and Sequestration Technologies. Springer Science and Business Media Deutschland GmbH [Preprint] (2024). https://doi.org/10.1007/s40572-024-00447-6.
10. R. Xu, D. Tong, S. J. Davis, X. Qin, J. Cheng, Q. Shi, Y. Liu, C. Chen, L. Yan, X. Yan, H. Wang, D. Zheng, K. He, Q. Zhang, Plant-by-plant decarbonization strategies for the global steel industry. *Nat Clim Chang* **13**, 1067–1074 (2023).
11. A. Mishra, F. Humpenöder, G. Churkina, C. P. O. Reyer, F. Beier, B. L. Bodirsky, H. J. Schellnhuber, H. Lotze-Campen, A. Popp, Land use change and carbon emissions of a transformation to timber cities. *Nat Commun* **13** (2022).
12. E. G. Hertwich, Increased carbon footprint of materials production driven by rise in investments. *Nat Geosci* **14**, 151–155 (2021).
13. Y. C. for E. + A. United Nations Environment ProgrammeUnited Nations Environment Programme, Building Materials and the Climate: Constructing a New Future. United Nations Environment Programme [Preprint].
14. H. Richie, M. Roser, CO2 emissions, *Our World in Data*. https://ourworldindata.org/co2-emissions.
15. E. G. Hertwich, Increased carbon footprint of materials production driven by rise in investments. *Nat Geosci* **14**, 151–155 (2021).
16. S. A. Miller, E. Van Roijen, P. R. Cunningham, A. Kim, Opportunities and challenges for engineering construction materials as carbon sinks. *RILEM Technical Letters* **6**, 105–118 (2021).
17. G. Churkina, A. Organschi, C. P. O. Reyer, A. Ruff, K. Vinke, Z. Liu, B. K. Reck, T. E. Graedel, H. J. Schellnhuber, Buildings as a global carbon sink. *Nat Sustain* **3**, 269–276 (2020).
18. A. Amiri, J. Ottelin, J. Sorvari, S. Junnila, Cities as carbon sinks - Classification of wooden buildings. *Environmental Research Letters* **15** (2020).
19. D. Dzhurko, B. Haacke, A. Haberbosch, L. Köhne, N. König, F. Lode, A. Marx, L. Mühlnickel, N. Neunzig, A. Niemann, H. Polewka, L. Schmidtke, P. L. M. Von der Groeben, K. Wagemann, F. Thoma, C. Bothe, G. Churkina, Future buildings as carbon sinks: Comparative analysis of timber-based building typologies regarding their carbon emissions and storage. *Front Built Environ* **10** (2024).

20. F. Xi, S. J. Davis, P. Ciais, D. Crawford-Brown, D. Guan, C. Pade, T. Shi, M. Syddall, J. Lv, L. Ji, L. Bing, J. Wang, W. Wei, K. H. Yang, B. Lagerblad, I. Galan, C. Andrade, Y. Zhang, Z. Liu, Substantial global carbon uptake by cement carbonation. *Nat Geosci* **9**, 880–883 (2016).
21. N. Lippiatt, T. C. Ling, S. Y. Pan, Towards carbon-neutral construction materials: Carbonation of cement-based materials and the future perspective. Elsevier Ltd [Preprint] (2020). https://doi.org/10.1016/j.jobe.2019.101062.
22. C. C. N. De Oliveira, M. Z. Zotin, P. R. R. Rochedo, A. Szklo, Achieving negative emissions in plastics life cycles through the conversion of biomass feedstock. doi: 10.1002/bbb.2165 (2021).
23. Y. Zhang, M. He, L. Wang, J. Yan, B. Ma, X. Zhu, Y. S. Ok, V. Mechtcherine, D. C. W. Tsang, Biochar as construction materials for achieving carbon neutrality. *Biochar* **4** (2022).
24. S. A. Miller, R. J. Myers, Environmental Impacts of Alternative Cement Binders. *Environ Sci Technol* **54**, 677–686 (2020).
25. M. R. Ponnada, P. Kameswari, Construction and Demolition Waste Management – A Review. **84**, 19–46 (2015).
26. E. Van Roijen, K. Sethares, A. Kendall, S. A. Miller, The climate benefits from cement carbonation are being overestimated. *Nat Commun* **15** (2024).
27. Z. Liu, Z. Deng, S. Davis, P. Ciais, Monitoring global carbon emissions in 2022. *Nat Rev Earth Environ* **4**, 205–206 (2023).
28. T. W. Hudiburg, B. E. Law, W. R. Moomaw, M. E. Harmon, J. E. Stenzel, Meeting GHG reduction targets requires accounting for all forest sector emissions. *Environmental Research Letters* **14** (2019).
29. A. Favero, A. Daigneault, B. Sohngen, "Forests: Carbon sequestration, biomass energy, or both?" (2020); https://www.science.org.
30. P. Cunningham, " A framework for considering resource availability, experimental performance, and environmental impacts to advance alternative mineral admixtures.," thesis, University of California, Davis, Davis, CA (2024).
31. G. Gadikota, Carbon mineralization pathways for carbon capture, storage and utilization. Nature Research [Preprint] (2021). https://doi.org/10.1038/s42004-021-00461-x.
32. M. Mazzotti, J. C. Abanades, R. Allam, K. Lackner, F. Meunier, E. Rubin, J. C. Sanchez, K. Yogo, R. Zevenhoven, "Mineral carbonation and industrial uses of carbon dioxide" (2018).
33. Triton market research, "Global Biochar Market 2022-2028."
34. J. Li, M. Luo, K. Wang, G. Li, G. Zhang, Review of carbon dioxide mineralization of magnesium-containing materials. *Carbon Neutralization* **2**, 574–584 (2023).
35. D. Cheng, D. M. Reiner, F. Yang, C. Cui, J. Meng, Y. Shan, Y. Liu, S. Tao, D. Guan, Projecting future carbon emissions from cement production in developing countries. *Nat Commun* **14** (2023).
36. D. J. Beerling, J. R. Leake, S. P. Long, J. D. Scholes, J. Ton, P. N. Nelson, M. Bird, E. Kantzas, L. L. Taylor, B. Sarkar, M. Kelland, E. DeLucia, I. Kantola, C. Müller, G. Rau, J. Hansen, Farming with crops and rocks to address global climate, food and soil security. *Nat Plants* **4**, 138–147 (2018).
37. M. Saleem, Possibility of utilizing agriculture biomass as a renewable and sustainable future energy source. Elsevier Ltd [Preprint] (2022). https://doi.org/10.1016/j.heliyon.2022.e08905.
38. Food and Agriculture Organization of the United Nations, "Agricultural production statistics 2000–2021" (2022); https://doi.org/10.4060/cc3751en.
39. H. G. van Oss, U. S. G. Survey, "Mineral Commodity Summaries: Cement" (US Geological Survey, 2016).
40. "Mineral Commodity Summaries 2022- Clay" (2022); https://pubs.usgs.gov/periodicals/mcs2022/mcs2022-clays.pdf.
41. Distribution of global plastic materials production in 2022, by region. https://www.statista.com/statistics/281126/global-plastics-production-share-of-various-countries-and-regions/.
42. "Climate Change 2022: Mitigation of Climate Change" (2022); https://www.ipcc.ch/report/ar6/wg3/downloads/report/IPCC_AR6_WGIII_SummaryForPolicymakers.pdf.
43. OECD, Global Material Resources Outlook to 2060. (2019).
44. P. Badjatya, A. H. Akca, D. V. Fraga Alvarez, B. Chang, S. Ma, X. Pang, E. Wang, Q. van Hinsberg, D. V. Esposito, S. Kawashima, Carbon-negative cement manufacturing from seawater-derived magnesium feedstocks. *Proc Natl Acad Sci U S A* **119**, 1–10 (2022).
45. "Material Efficiency in Clean Energy Transitions" (Paris, 2019); https://www.iea.org/reports/material-efficiency-in-clean-energy-transitions.
46. G. Philippidis, R. X. Álvarez, L. Di Lucia, H. G. Hermoso, A. G. Martinez, R. M'barek, A. Moiseyev, C. Panoutsou, E. S. Itoiz, V. Sturm, M. van Leeuwen, W. J. van Zeist, P. J. Verkerk, The development of bio-

based industry in the European Union: A prospective integrated modelling assessment. *Ecological Economics* **219** (2024).
47. P. Stegmann, V. Daioglou, M. Londo, D. P. Van Vuuren, Plastic futures and their CO 2 emissions. *Nature* **612**, 272–276 (2022).
48. Solidia solutions. https://www.solidiatech.com/solutions.html.
49. Carbon Upcycling: closing the carbon cycle. https://carbonupcycling.com/technology/.
50. Blue Plant Permanent Carbon Capture. https://www.blueplanetsystems.com/products.
51. Carbon8 : A circular impact company. https://www.carbon8.co.uk/.
52. "Market update 2020" (2020).
53. INEOS: sustainable PVC for a changing world. https://www.biovyn.co.uk/SUSTAINABLE-PVC/.
54. Braskem: I'm Green Bio-Based. https://www.braskem.com.br/imgreen/bio-based-en.
55. Dow ENGAGE REN Polyolefin Elastomers. https://www.dow.com/en-us/brand/engage-ren.html?cid=WEB:Dow:11925:202204_PSP_EMEAI_NUR_ENGAGE_REN:BPC:EMEAI:na:na:na:na:PressRelease:PSP:NUR:ce43175c-96c5-ec11-a7b6-002248276e2b.
56. Mango Materials: complicated science, simple solutions. https://www.mangomaterials.com/innovation/.
57. E. C. Van Roijen, S. A. Miller, Towards the production of net-negative greenhouse gas emission bio-based plastics from 2nd and 3rd generation feedstocks. *J Clean Prod* **445**, 141203 (2024).
58. Orbix: Carbonation. https://www.orbix.be/en/technologies/carbonation.
59. Carbstone. https://ecodesign.vlaanderen-circulair.be/en/cases/cases-detail/carbstone.
60. JustBioFiber product specifications. https://justbiofiber.com/products/product_specifications/.
61. Avello Bioenergy: Bioasphalt binder. http://www.avellobioenergy.com/en/products/bioasphalt_binder/.
62. E. Vels, Test road with Dutch bio-asphalt seems to withstand the first 6 months successfully, *Innovation Origins* (2021). https://innovationorigins.com/en/test-road-with-dutch-bio-asphalt-seems-to-withstand-the-first-6-months-successfully/.
63. Agro Chemistry, Biobased asphalt with ligng can cut emissions up to 60%. https://www.agro-chemistry.com/news/biobased-asphalt-with-lignin-can-cut-emissions-up-to-60/.
64. "Direct Air Capture 2022: a key technology for net zero" (Paris, 2022); https://www.iea.org/reports/direct-air-capture-2022.
65. N. Li, L. Mo, C. Unluer, Emerging CO2 utilization technologies for construction materials: A review. *Journal of CO2 Utilization* **65**, 102237 (2022).
66. S. A. Miller, G. Habert, R. J. Myers, J. T. Harvey, Achieving net zero greenhouse gas emissions in the cement industry via value chain mitigation strategies. *One Earth* **4**, 1398–1411 (2021).
67. J. A. Olsson, S. A. Miller, M. G. Alexander, Near-term pathways for decarbonizing global concrete production. *Nat Commun* **14** (2023).
68. European Bioplastics, Bioplastics market development update 2023. https://www.european-bioplastics.org/market/.
69. M. Swilling, M. Hajer, T. Baynes, J. Bergesen, F. Labbé, J. K. Musango, A. Ramaswami, B. Robinson, S. Salat, S. Suh, P. Currie, A. Fang, A. Hanson, K. Kruit, M. Reiner, S. Smit, S. Tabory, "The Weight of Cities: Resource Requirements of Future Urbanization" (Nairobi, Kenya, 2018).
70. J. Becker, *SB-596 Greenhouse Gases: Cement Sector: Net-Zero Emissions Strategy.* (Sacramento, CA, 2021).
71. A. Torres, J. Brandt, K. Lear, J. Liu, A looming tragedy of the sand commons. *Science (1979)* **357**, 970–971 (2017).
72. S. A. Miller, F. C. Moore, Climate and health damages from global concrete production. *Nat Clim Chang* **10**, 439–443 (2020).

Acknowledgments: The authors would like to thank A. Horvath and C. Scown for conversations during manuscript preparation.

Funding: This work was supported by the National Science Foundation, grant CBET-2143981 (S.A.M.); the UC Multicampus Research Programs and Initiatives of the University of California, grant M23PL6005 (S.A.M. and S.J.D.). The contents do not represent the official views or policies of the grantor or the State of California.

Author contributions:

Conceptualization: SM

Methodology: SM, EV

Investigation: SM, EV

Visualization: SD, EV, SM

Funding acquisition: SM

Project administration: SM

Supervision: SM

Writing – original draft: SM, EV

Writing – review & editing: EV, SM, SD

Competing interests: Authors declare that they have no competing interests.

Data and materials availability: All data are available in the main text or the supplementary materials.

Supplementary Materials

Materials and Methods

Supplemental Data S1:S7