The role of concrete in life cycle greenhouse gas emissions of US buildings and pavements

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Concrete is a critical component of deep decarbonization efforts because of both the scale of the industry and because of how its use impacts the building, transportation, and industrial sectors. We use a bottom-up model of current and future building and pavement stocks and construction in the United States to contextualize the role of concrete in greenhouse gas (GHG) reductions strategies under projected and ambitious scenarios, including embodied and use phases of the structures' life cycle. We show that projected improvements in the building sector result in a reduction of 49% of GHG emissions in 2050 relative to 2016 levels, whereas ambitious improvements result in a 57% reduction in 2050, which is 22.5 Gt cumulative saving. The pavements sector shows a larger difference between the two scenarios with a 14% reduction of GHG emissions for projected improvements and a 65% reduction under the ambitious scenario, which is ∼1.35 Gt. This reduction occurs despite the fact that concrete usage in 2050 in the ambitious scenario is over three times that of the projected scenario because of the ways in which concrete lowers use phase emissions. Over 70% of future emissions from new construction are from the use phase.

greenhouse gas emissions | buildings | pavements | concrete | life cycle assessment

Concrete is the most extensively used building material in the world because it possesses a unique combination of attributes—strength, versatility, and durability—for a relatively low cost using raw materials found all over the world. It is used in nearly every element of our built environment including buildings, pavements, bridges, and water and energy systems. This ubiquity in infrastructure has also made concrete use tightly linked to achieving societal sustainability goals. Thacker et al. (1) found that infrastructure, which makes extensive use of concrete, either directly or indirectly influences the attainment of every United Nations Sustainable Development Goal.

On a weight-normalized basis, concrete has a lower carbon and energy footprint than nearly all materials used in the built environment (2). Nevertheless, the cement and concrete sectors are deservedly under scrutiny regarding their environmental footprint because of the sheer scale of production (3). Greenhouse gas (GHG) emissions from the production of cement (the primary driver of GHG emissions for concrete) account for a little over 1% of the total US GHG emissions footprint (4). Thus, the challenge of sustainable development is manifest in microcosm in the use of concrete: accomplishing societal goals while minimizing environmental impacts.

There is no question that we need to reduce the emissions associated with cement and concrete production. However, the mitigation solutions for products made with concrete extends beyond the cement and concrete production value chains. Materials dictate the modes of manufacture and constrain the operational performance of the products into which they are fashioned (5). Concrete is a prime example of this phenomenon. Forming the backbone of large, complex, long-lived systems, changes in the use of concrete can positively or negatively impact the in-use performance and GHG emissions of these systems for decades.

In this systems context, we seek to evaluate the cost and effectiveness of a range of strategies for reducing the GHG footprint of two important systems—buildings and pavements—including both changes in cement and concrete production and changes in system design, maintenance, and operations. Using this comprehensive model, we also evaluate the relative contribution of embodied and operational emissions as these systems undergo significant change and explore whether GHG emissions reductions are possible in these systems even if there is increased use of concrete. Mapping these changes for buildings and pavements is challenging, because the impact of system structure is influenced by local context, the role of extant stock and its evolution, and the long timeframe that needs to be considered. To overcome these challenges, we develop and apply spatially and temporally heterogenous, life cycle models of the buildings and pavements systems. We limit our analysis to the United States because of the extent of data required for modeling. In the United States, these systems account for over 60% of apparent cement usage according to data from the industry and the building, transportation, and industry sectors account for 90% of all GHG emissions (4). As such, changes in the structural components of these systems can provide influential leverage in meeting climate targets.

Significance

Changes to concrete production as well as in building and pavements systems—the largest consumers of concrete—can lead to more than 50% reductions in associated GHG emissions by 2050. Over this period, the operational phase of newly constructed buildings and pavements still generates most GHG emissions unless the electrical grid, heating, and transportation are decarbonized aggressively. Meeting decarbonization targets will require lowering the GHG emissions of concrete production as well as innovative uses to lower building and vehicle fuel consumption. Owing to their low abatement costs, several concrete solutions should be prioritized in climate change policies. More than one-third of the embodied impacts of building and pavement construction can be offset by implementing concrete solutions.

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Literature Review

There is an extensive literature on approaches to mitigate the embodied emissions of cement and concrete production (2, 3, 6–9). Most mitigation approaches involve making cement with lower GHG emissions or making concrete with less cement. Concrete GHG emissions can be lowered through the use of cement substitutes such as low-carbon cements [blended cements or alternative cement binders (10)] or supplementary cementitious materials (such as fly ash or granulated blast furnace slag) (3) or through active use of captured carbon to produce synthetic limestone aggregates or cure concrete (11).

While embodied emissions of concrete are important, life cycle assessments of infrastructure systems built using concrete have shown that in most cases they are much smaller than emissions that occur during the use or operational phase of the structure. In most buildings, the energy consumption over the building's life dominates the total life cycle environmental impact, representing 80 to 90% in many cases (12–15). Similarly, in most pavements, the excess fuel consumption in vehicles caused by pavement–vehicle interaction (excess energy dissipation due to pavement roughness or deflection) is much larger than the embodied impacts of paving materials. Depending on the context (i.e., the traffic and location), roughness and deflection-induced excess fuel consumption contribute 23–78% of the life cycle GHG emissions of pavements (16). Including the reflectivity impact of pavements on the climate in the use phase can increase the use phase contribution to ∼90% of the total GHG impacts (17). Thus, the ways in which we design and maintain structures that use concrete can have much larger impacts than the impact of materials. All of these studies have explored existing buildings or pavements operated under conditions that exist today. Significant changes are expected in the carbon intensity of energy used for the operation of buildings and transportation systems. While this is expected to increase the importance of embodied emissions to future mitigation efforts, the literature does not provide quantification of this trend.

Although several studies have evaluated the whole life cycle impacts of pavements (16, 18, 19) and buildings (20, 21), proposed solutions usually fall into a few categories. Analyses of pavement systems focus on material flows (22, 23) or optimizing budgets and treatment schedules to minimize vehicle fuel consumption and the associated life cycle GHG emissions (24, 25). Similarly, building system analyses concentrate on material quantities or energy consumption (26–30). Thus, there is a disconnect between analyses of embodied GHG reductions for concrete that focus on materials and do not put those reductions in the context of the full life cycle for the structures in which they are used, nor the system of buildings and pavements.

We contextualize the role of concrete in greenhouse gas reductions in the US building and pavement sectors. This includes the potential impacts and costs of reducing the embodied impacts of concrete along with changes in the design and maintenance of structures that use concrete throughout their entire life cycle. We explore whether total life cycle emissions can decrease even with increased usage of concrete due to functional requirements or opportunities to lower use phase emissions. To a limited extent, we examine other actions that can be used to lower GHG emissions in US building and pavement systems. This allows us to evaluate concrete GHG reductions in the context of the systems and frame those opportunities based on cost and GHG reduction potential.

The models applied in this work consider geographic heterogeneity (at a US state level) in the demographics of the current stock of buildings and pavements, local climate, prevailing construction codes, norms for system maintenance, and, in the case of pavements, available public budgets for infrastructure. Using this information, we identify a range of approaches that can be applied to bring emissions from these systems to less than 50% of current levels and how embodied and operational emissions reductions strategies compare.

Approach

System Attributes and Strategies for Scenarios. Our analysis of building and pavement systems in the United States is based on attributes of those systems (e.g., material or energy use) and strategies that may be used to lower GHG emissions. We estimate GHG reduction potential for the strategies from 2016 to 2050 using two scenarios: projected and ambitious improvements. Table 1 summarizes the building and pavement system attributes and strategies under the two scenarios. Strategies are framed in terms of technical targets (e.g., percentage of renewables in the grid) and timing of adoption of those targets, which in some instances varies regionally. The "projected improvement scenario" is intended to reflect a future where current trends to improve system attributes will continue. For buildings, this includes continued decarbonization of the electrical grid and increases in energy efficiency requirements in building and appliance codes. These energy efficiency improvements include increased thermal insulation where concrete can play a role. For pavements, this includes continued improvement in vehicle fuel economy. For both systems, the projected improvement scenario evolves toward the use of net zero emissions concrete (portland cement–based and asphalt-based) through the use of lower-carbon constituents (including recycled content), carbon capture in cement production, and use of captured carbon to produce aggregates and cure concrete. The "ambitious improvement scenario" is intended to reflect a future where more aggressive actions to lower GHG emissions are taken. In all cases, ambitious strategies are limited to technologies that exist today, but have not been adopted at meaningful scale. Building ambitious strategies are similar to the projected actions but with earlier timing of adopting technical targets. Pavements ambitious strategies are primarily tied to an increase in funding for pavement maintenance and repair. This increase in funding is important because, unlike buildings, there are few current policies explicitly intended to improve infrastructure GHG emissions. As such, for the projected improvement scenario we assume that there is no change over time in the pavement system's stiffness, reflectivity, or types of maintenance, rehabilitation, and reconstruction actions (referred to as MRR). The increase in available budget in the pavement ambitious strategy allows for more extensive application of all pavement-related improvements, so there is more of an interdependency among these ambitious strategies. Details on the technical targets and timing of pavement and building sector by region are in *SI Appendix*, section 2, including *SI Appendix*, Tables S1 and S2, along with justification for why the strategies and targets were chosen.

Modeling Approach and Data Sources. We used a bottom-up approach shown in Fig. 1 to model the characteristics of individual reference buildings and pavements and then scale up the results to regional networks and ultimately the entire country using temporally and spatially varying data. To capture spatial variation in building codes, construction practices, structural performance, climate, and energy demand, reference designs and practices were developed for climatic regions across the United States. For buildings, six reference designs (representing the two most common building materials used in residential [single and multifamily] and commercial buildings) were developed for each of the 14 climate zones described by the US Department of Energy (DOE). For pavements, several reference designs and operating schedules were estimated for four pavement types for each of the four climatic regions described by the US Department of Transportation. In both cases, states were assigned to their appropriate region and the prevalence of reference designs was modeled using state-level data. Several models were used to

Table 1. Attributes of concrete production and building and pavement systems for projected and ambitious GHG reduction strategies

Attribute definition	Projected improvement scenario	Ambitious improvement scenario
Concrete (for both buildings and pavements)		
Alternative binders	40% clinker replacement by 2050	50% clinker replacement by 2050
Particle packing	No implementation	Improve the binder intensity
Design optimization	No implementation	19% reduction in concrete consumption per unit area
Reuse of concrete elements	No implementation	0.1-m^3 reuse per cubic meter concrete
End-of-life carbon uptake	Base on the alternative binders' scenario and 2-y spreading	Increasing the spreading period of 3 y
CCS	100% of the average tech by 2050	100% of the best performing tech by 2050
CCU	No utilization	Use of industrial sources of alkalinity by 2050
Building specific		
Energy codes (appliances, lighting, HVAC, insulation)	100% IECC 2015 adoption in 2025. 100% energy efficient adoption in 2045	100% IECC 2015 adoption in 2025. 100% energy efficient adoption in 2035
Electricity grid	Grid decarbonization following the US EIA projection until 2050	Grid decarbonization following the US EIA projection for New York state
Pavement specific		
Asphalt	35% RAP and 100% WMA by 2050, no implementation of recycled binder	50% RAP, 100% WMA, 50% GTR, and waste oil by 2050
Smoothness	Equivalent to required budget for keeping surface roughness constant	20% increase in the currently projected budget
Concrete overlay	Only used in regions where it is already in place	Inclusion of concrete overlay action for all regions
Reflectivity	Average network aged albedo values: concrete = 0.25; asphalt = 0.1	Use reflective coating/binder to reach average network albedo = 0.3
Stiffness	Current stiffness values existing in the national road network	Increase the stiffness to the 95th percentile of the current range
Vehicle fuel efficiency	According to the US Energy Outlook forecast	Same as the projected improvement scenario

CCS, carbon capture, sequestration; CCU, carbon capture, utilization; GTR, ground tire rubber; HVAC, heating, ventilation, and air conditioning; IECC, International Energy Conservation Code; RAP, recycled asphalt pavements; US EIA, United States Energy Information Administration; WMA, warm mix asphalt. More details are in *SI Appendix*, Table S1.

establish the associated material, operational energy, and other use phase requirements for each design over the course of the analysis period (2016–2050). The system boundaries of life cycle assessment include a cradle-to-grave scope and incorporates the emissions of materials and energy from the extraction of material until end of life (see Dataset S1 in the *SI Appendix* spreadsheet for the impacts from each component). A dynamic life cycle inventory was developed to capture the geographical and temporal aspects of the technologies and practices in different states to precisely estimate the material, operational energy, and other use phase requirements over the course of the analysis period (2016–2050). The buildings and pavements modeled in the analysis represent ∼60% of the total cement consumption in the United States (31). Details of the methodology along with the input data sources are described in *SI Appendix*, sections 3 and 4, for pavements and buildings, respectively.

Limitations. Our analysis uses projected and ambitious scenarios that include a set of strategies for lowering US GHG reductions. The strategies are intended to represent major points of leverage but are by no means comprehensive. Indeed, other design-focused strategies could be considered including design for longer life, increased hazard resistance, smaller size, adaptability, and recycling or reuse. Furthermore, there are other actions that could be taken within the building sector such as retrofits of existing buildings, lowering embodied impacts of other building materials besides concrete, and increasing use of on-site renewables. Increasing recycling of all construction and demolition waste would also be beneficial. Thus, the results of this analysis should not be viewed as precise since we do not account for numerous sources of uncertainty in data and future trends, or comprehensive since we have not evaluated the potential of all GHG reduction strategies. However, the results still provide valuable insight on the potential of the strategies in both the projected and ambitious scenarios to mitigate GHG emissions in the building and pavement sectors.

Results

Opportunities for GHG Reductions. The original stated goal for the United States in the Paris Agreement was to lower the total anthropogenic GHG emissions from 6.5 Gt in 2017 to a range of 1.7–2.3 Gt in 2050 (32), a reduction of 65–75%. When electric power emissions are allocated to end-use sectors, buildings, transportation, and industry accounted for 2.0, 1.9, and 1.9 Gt of US GHG emissions in 2017, respectively (4). This represents 90% of the 6.5 Gt of US GHG emissions. Thus, achieving GHG

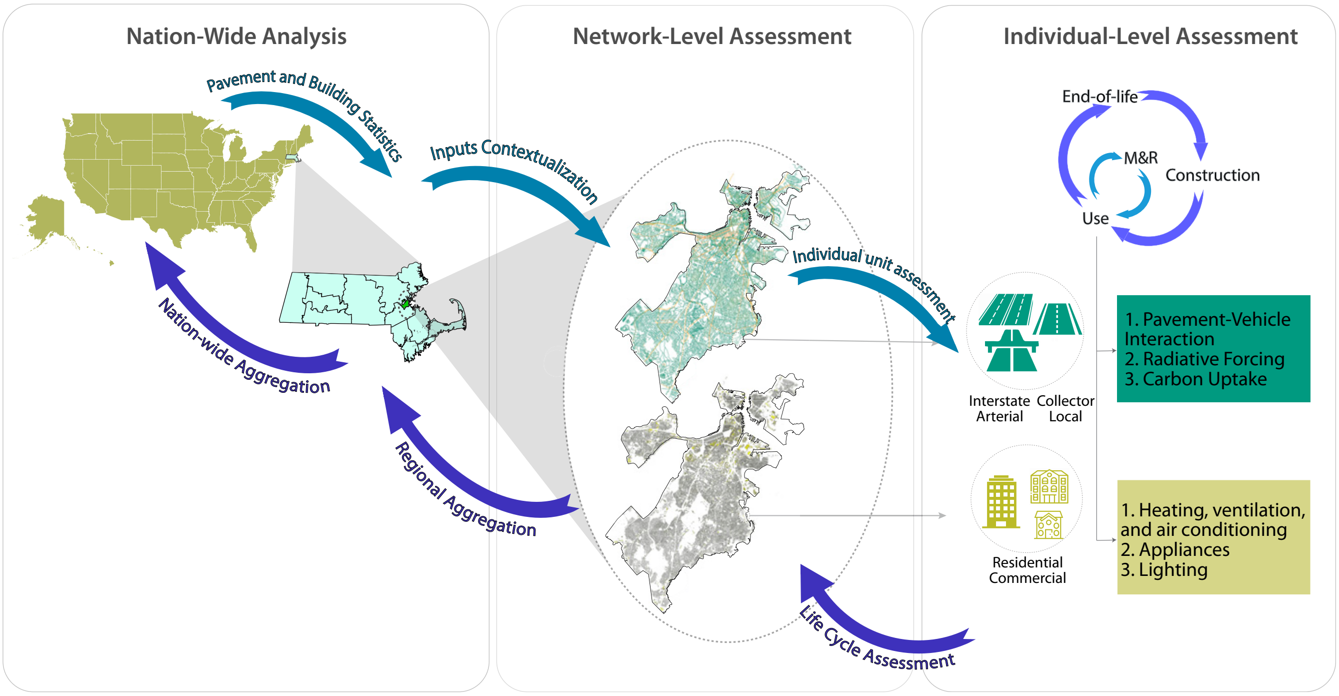

Fig. 1. Summary of the bottom-up approach for investigating the life cycle GHG impact of buildings and pavements in the United States.

reduction targets requires significant contributions from all three of these sectors, and the use of concrete impacts all of them.

Fig. 2 shows the historical and our modeled future GHG emissions for both the buildings and pavement sectors. Historical emissions increase in the 1980s and 1990s due to growth in building stock and the pavement network and vehicle-miles traveled. Emissions peak in the early 2000s and decrease due to building energy efficiency improvements, a lack of pavement network expansion, and vehicle fuel economy improvements.

In the buildings sector, the projected improvement scenario results in a modeled GHG emission of ∼1 Gt in 2050, a reduction of 49% relative to 2016 levels. The ambitious improvements scenario results in a 57% reduction in 2050 down to ∼0.75 Gt GHG. In either scenario, modeled building sector emissions in 2050 are split evenly among residential (single and multifamily) and commercial (all other categories) buildings, with single-family buildings the largest individual category of buildings by far. Both scenarios project nearly identical use of concrete in the

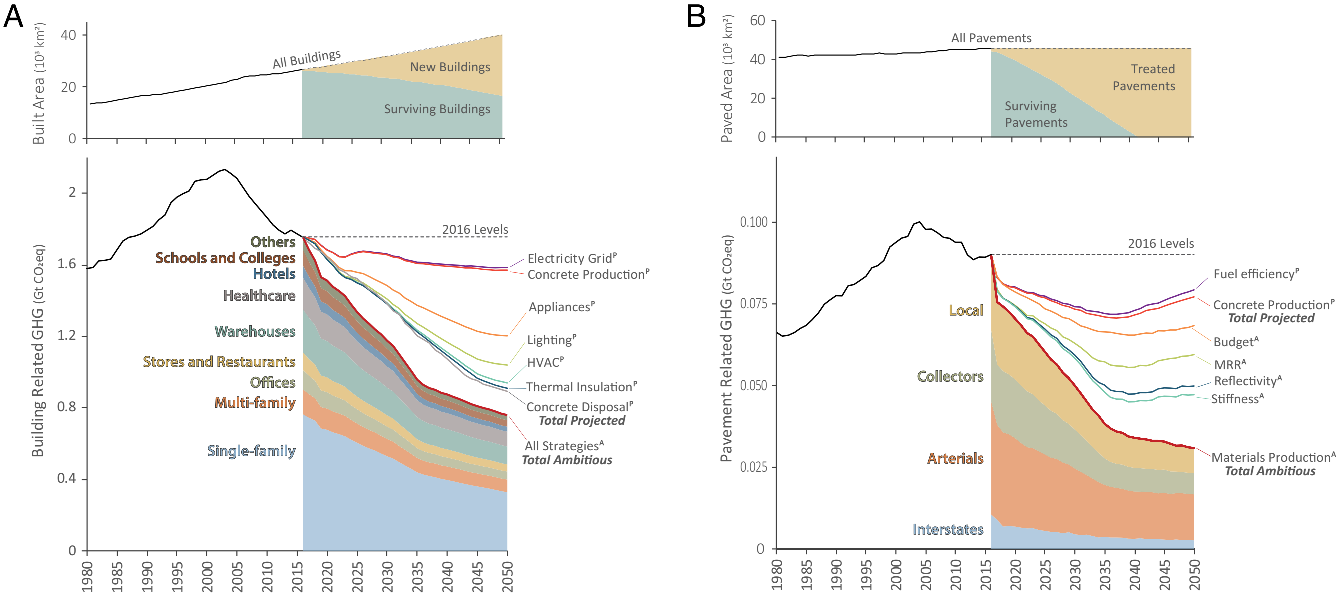

Fig. 2. Built area and historical and future estimated GHG emissions in the (*A*) buildings and (*B*) pavements sectors. Historical emissions are before 2016. The 2016 levels are used as a reference for the reduction of future emissions. Projected and ambitious emissions reductions for the individual attributes listed in Table 1 are plotted (with the exception of buildings ambitious strategies, which are omitted for clarity), with the cumulative total projected and ambitious emissions reduction noted. The ambitious scenario GHG emissions are broken down by building and pavement types.

buildings sector, around 240 Mt (110 Mm^3) in 2050. Energy consumption in the building stock plays a significant role in the sector, which is why the largest opportunities for GHG emission reductions shown in Fig. 2*A* (and the cumulative reduction quantities in Fig. 3*A*) derive from changes to the electricity grid (purple line), appliances (orange line), and lighting (green line). Changes in these three attributes make up over 85% of the 22.5 Gt of the cumulative GHG reductions projected over 34 y under the ambitious improvements scenario (Fig. 3*A*). In this analysis, heating, ventilation, and air conditioning (HVAC) improvements, enhanced thermal insulation, and concrete production only affect new construction, so opportunities for reduction are more limited. Although the ambitious scenario considers changes to important system attributes such as electricity grid decarbonization and more intensive adoption of energy efficiency codes, its 2050 results represent only an additional 10% reduction in GHG emissions from 2016 levels. Unfortunately, this change is not enough to reach the 65% reduction target. This suggests that the sector will have to look to other solutions or possibly much more aggressive changes to these attributes to reach the goal.

The pavements sector is estimated to have a 14% reduction of GHG emissions in 2050 relative to 2016 levels under the projected improvement scenario. Our modeling projects the use of 9.5 Mt (4 Mm^3) of concrete in 2050. For the ambitious scenario, we project both a much more intensive use of concrete (28.2 Mt or 11.9 Mm^3) and a much larger reduction of GHG emissions (Fig. 2*B*).

Pavement sector emissions reductions under the projected scenario are relatively modest because there are few current efforts to systematically improve pavement network GHG intensity. Reductions within the projected improvement scenario are nearly evenly split between expected improvements in vehicle fuel economy and reduced materials production impacts, including increased concrete carbon uptake (Figs. 2*B* and 3*B*). The projected improvement scenario exhibits minimum emissions around 2037, a behavior in contrast to all of the other analyses. This occurs because of projected vehicle fleet characteristics, which are an important determinant of pavement system emissions. Current US DOE projections assume fleet fuel efficiency improves until the late 2030s. Beyond this time, fleet emissions increase while at the same time vehicle-kilometers traveled continue to grow.

The ambitious improvement scenario makes it clear that there are significant opportunities for reductions when there are changes to all pavement system attributes. This indicates there is urgency for action to shift behaviors in the pavement sector to embrace the strategies in the ambitious scenario. Increasing budget is particularly important, leading to more than one-quarter of the reductions seen in the ambitious improvement scenario, because it enables increased maintenance, rehabilitation, and reconstruction activities, which increase smoothness and lower excess fuel consumption. Notably, for the pavements system, the materials and carbon uptake category, including the use of concrete, represents the largest opportunity for reduction of GHG emissions. Materials changes account for more than one-third of the reductions seen in the ambitious scenario, leading to a cumulative reduction of nearly 0.3 Gt over the modeled time horizon (seventh bar in Fig. 3*B*). A relatively small but significant reduction of 76 Mt CO_2 can be obtained from implementing strategies to elevate the carbon uptake of concrete pavements during the use and end-of-life phases of the life cycle, with more than 81% of that reduction stemming from stockpiling the demolished concrete temporarily. The remaining 19% of the reduction comes from the uptake increase during the use phase owing to the relatively large exposed surface area of concrete pavements.

GHG Abatement Costs. The costs of implementing GHG mitigation strategies under the ambitious scenario are shown in the abatement curves in Fig. 4. Both sectors have negative abatement costs for the use of by-products and recycled content (low-carbon binders and reclaimed asphalt) because they are generally lower cost than virgin materials. More ambitious strategies around decarbonizing the electrical grid, improving fuel economy, and capturing carbon and using it in concrete require more investments to make them feasible. For the building sector, several strategies lead to reductions in energy consumption, which decreases user costs and result in negative abatement costs.

Estimating abatement costs for pavements is difficult because there is not a clear way to allocate budget increase costs across the strategies. In particular, smoothness is not depicted in Fig. 4*B* because its estimated cost is over $1,000/$tCO_2$eq due to the fact that its cost is based entirely on an action (rehabilitation or reconstruction) that is motivated by more than simply GHG mitigation. As such, the abatement costs should be viewed as an incremental abatement cost assuming that sufficient budget is available to treat the pavement surface, which would result in a smoother pavement. Investment in concrete overlays have long-term benefits over the life of the pavement in the instances for which they are appropriate, but discounting of the benefits makes the abatement cost slightly positive. Improvements in stiffness and reflectivity to asphalt pavements will be accomplished through the

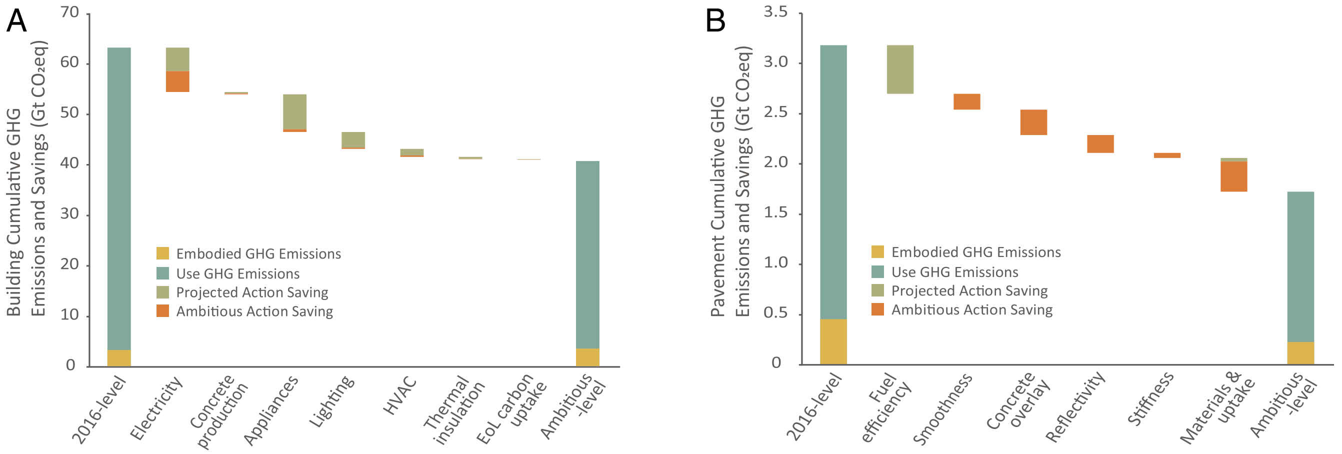

Fig. 3. Cumulative 2016–2050 GHG emission reductions under the ambitious scenario for (*A*) buildings and (*B*) pavements. Reductions for each category are broken down into projected and ambitious scenario contributions (ambitious builds off of projected). The 2016 level assumes that emissions do not change from 2016 levels over the entire 34-y period.

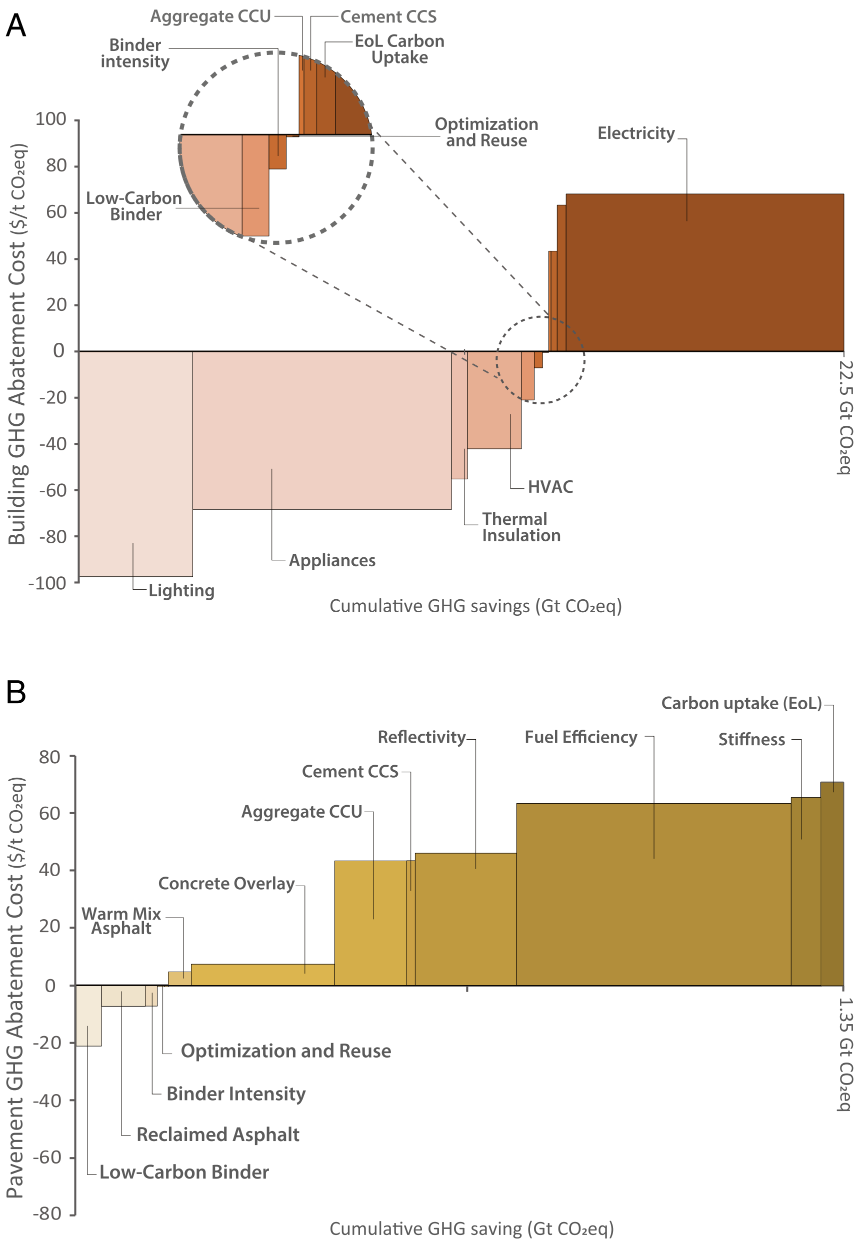

Fig. 4. GHG abatement cost for ambitious strategy over 34 y for (*A*) buildings and (*B*) pavements. CCUS, carbon capture, utilization, and sequestration. The pavement strategy smoothness is not depicted because of the difficulty of estimating an abatement cost that is separate from the budget increase for pavement maintenance and repair. The *x* axis quantifies GHG abatement potential for the strategy in CO$_2$ equivalents. The cumulative GHG abatement across all strategies is shown at the end of the *x* axis.

use of mechanisms such as added synthetic fibers and surface coatings, which are not necessary for concrete due to its higher stiffness and reflectivity. The temporary stockpiling associated with the end-of-life carbon uptake has a moderate abatement cost among building abatement levers but is the costliest option, although essential for achieving net-zero embodied carbon pavements.

Embodied and Use Phase GHG Emissions for New Construction. Although the existing stock of pavements and buildings have a significant influence on life cycle GHG emissions, it is important to evaluate the embodied and use phase trade-offs of new construction since it is often easier to influence. As discussed previously, it has been well established in the literature that for existing buildings, life cycle emissions are caused primarily by use phase activities (33, 34). The literature on pavement use phase is smaller, but recent papers show a similar trend with use phase activities accounting for over half of life cycle emissions (18, 35). More recently, several publications have suggested that this dominance of use phase relative to embodied emissions will invert imminently (36–38). The following analysis explores this using simulation results.

As shown in the *Inset* figures in Fig. 5 *A* and *B*, less than 30% of the cumulative life cycle emissions of new pavements and buildings constructed after 2017 are estimated to come from the embodied phase (in this figure, use phase emissions are solely from buildings and pavements constructed after 2017). In both sectors, it is noteworthy that embodied emissions are relatively flat in the projected scenario and gradually decrease in the ambitious cases. This is the result of competing mechanisms of

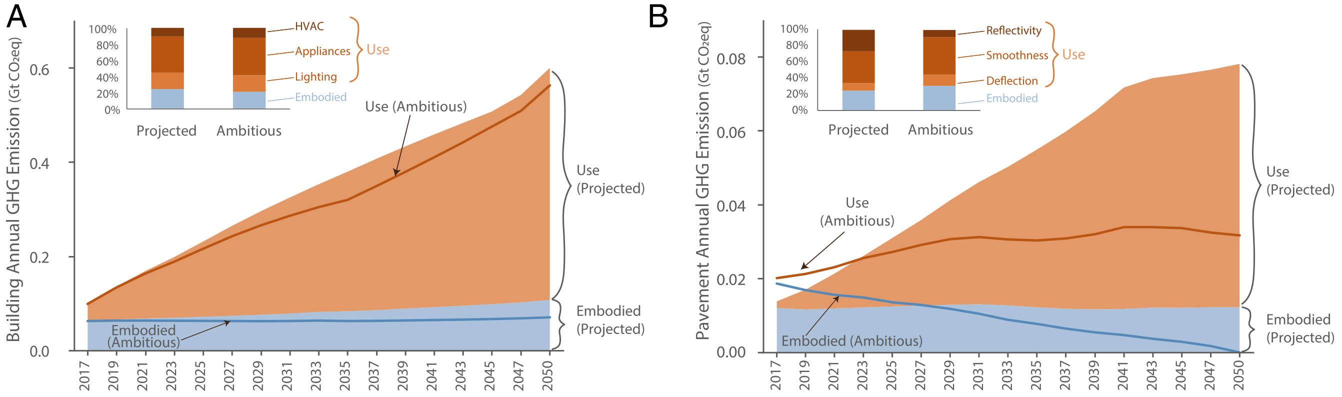

Fig. 5. Annual embodied and use phase GHG emissions for (*A*) new buildings and (*B*) treated pavement area. *Insets* show the breakdown of cumulative emissions over the entire time period.

increasing construction, increasing materials use to improve energy efficiency, and decreasing impact of concrete from use of low-carbon strategies.

For the buildings sector, use phase strategies will lower overall energy consumption and GHG emissions in the sector, but from a life cycle perspective operational energy will still drive emissions from new construction through 2050. For new construction, the projected and ambitious strategies do not lead to notable differences in net emissions.

In the pavement sector, Fig. 5*B* shows that use phase emissions can be held relatively flat in the ambitious scenario despite traffic growth and an expansion of treated pavement area. This is in stark contrast to the projected scenario, which reiterates the critical importance of increased pavement network budget to enable use phase reductions. The solutions for achieving net-zero asphalt and concrete mixtures result in net-zero emissions in 2050 in the ambitious scenario. Because of this, the share of cumulative embodied impacts in the ambitious scenario drops to 24% from 30% in the projected scenario.

The Case of Net Zero Operational Impacts in 2050. Although results of the ambitious scenario represent more aggressive decarbonization than current Energy Information Administration (EIA) forecasts, recent policy discussions suggest that the United States may invest in strategies to even more rapidly decarbonize energy use in buildings and transportation with a goal of achieving net zero emissions by 2050 (39). Details of those plans are not currently available. As such, to understand the implications of more rapid decarbonization we explore a range of decarbonization cases and characterize how these cases would alter the relative importance of operational and embodied emissions. Before doing so, however, it is useful to quantify how the materials changes modeled here alter the embodied emissions of these two systems.

For context, we show how much concrete can contribute to embodied GHG reductions under the ambitious scenario when there is net-zero energy and only concrete impacts are reduced. Fig. 6*A* compares embodied emissions of buildings and pavements in 2050 with net-zero energy for buildings and transportation for a no-change case (left-most bar) and the ambitious scenario with only concrete strategies used. The no-change case assumes technologies and practices at the start of the simulation in 2016 are the same in 2050 as a means of comparison. These results show that aggressive implementation of concrete decarbonization strategies could lead to a savings of 50 Mt CO_2eq (35% of the no change value) in 2050. The majority of concrete savings (green stacked bar chart in Fig. 6*A*) come from cement and concrete production activities (65% offset by alternative binders, carbon capture, utilization, and sequestration [CCUS], and binder intensity). The second largest contributor to savings derives from the inherent properties of concrete (e.g., lighter surface color and lower deterioration rate and therefore lower M&R compared to the 2016 level). This accounts for 10 Mt

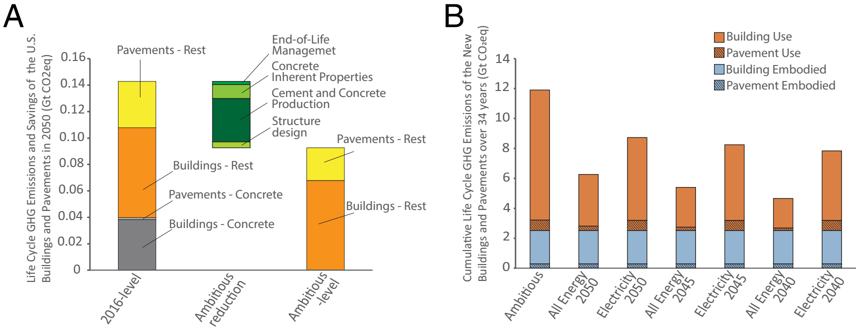

Fig. 6. (*A*) Life cycle GHG emissions of US buildings and pavements in 2050 with a net-zero operational impact and the concrete ambitious scenario reductions only. The 2016 level is a no-change baseline for comparison. The 2016-level impacts from concrete are shown in gray, with impacts from all other materials labeled as "Rest"; orange for buildings and yellow for pavements. The green bar indicates the source of concrete reductions in the ambitious scenario; all other embodied impacts ("Rest") remain the same. Net-zero impacts in 2050 means building energy, transportation vehicle energy, and concrete production and transportation energy are all zero; only material impacts remain the same. (*B*) Cumulative life cycle GHG emissions of newly constructed US buildings and pavements during the 2017–2050 period under different electricity and energy scenarios. The year indicates when the electricity and/or energy sources for heating and ground transportation become net zero.

CO_2eq saving (21% of total saving) and points to the importance of concrete use in certain contexts such as high-traffic roads.

Fig. 6*B* compares cumulative embodied and operational emissions (from the start of the simulation in 2017–2050) for newly constructed buildings and pavements under a range of scenarios. These scenarios represent progressively more aggressive decarbonization of the energy system. As noted previously, under the ambitious scenario (left-most bar), embodied emissions represent less than 30% of total emissions. Each pair of scenarios represent total decarbonization of the electrical grid (labeled Electricity) or the electrical grid and all sources of energy used for heating and ground transportation (labeled All Energy) by a specified year. We see that embodied emissions do not represent the majority of total emissions unless all energy sources are decarbonized by 2045. There is no scenario where embodied emissions represent more than 50% if only the grid is decarbonized. As such, it is clear that use phase emissions will continue to dominate the building and pavement stocks, even under very ambitious net zero targets.

Discussion

This analysis has provided insight on the potential role of concrete in US GHG reductions, which is important given its status as the most used construction material and its relevance to building, transportation, and industrial sector GHG emissions. Our results demonstrate that continuing current trends in the building sector (e.g., grid decarbonization and stringent building energy codes) would be expected to reap substantial benefits with per annum sector emissions dropping nearly 50% by 2050 even with a continued intensive use of concrete (240 Mt in 2050). Unfortunately, even more aggressive adoption of GHG reduction strategies (our ambitious scenario), does not seem to be sufficient to meet stated Paris targets (modeled sector emissions drop by 57%, short of the 65–75% reduction target). Additional measures such as further grid decarbonization or extensive refurbishment of the existing building stock will be needed. For pavements, the story is almost completely inverted. Current trends, including the use of 9.5 Mt of concrete, would lead to only modest reductions (14%) in per-annum emissions by 2050. Clearly, more significant intervention is required in pavements in the form of increased paving budgets, which increase pavement quality and durability, while enabling numerous GHG reductions such as increased pavement reflectivity and stiffness. Implementing these strategies (our ambitious scenario) appears to allow the pavement sector to reach Paris targets (modeled sector emissions drop by 65%, reaching the edge the of 65–75% target) even while making use of 28.2 Mt of concrete (nearly three times the level in the projected improvement scenario).

It is well established that within current and historic buildings and pavements, the use phase produces far more emissions than the embodied emissions associated with construction. This analysis makes plain that use phase emissions will continue to dominate the life cycle GHG emissions of buildings and pavements, unless both the electrical grid and energy sources used for building heating and transportation are decarbonized by 2040, which is much more rapidly that currently published projections. As such, even the achievement of concrete with net-zero embodied impacts is insufficient to achieve GHG reduction targets required for minimizing the worst effects of climate change. However, this work has shown that concrete and other construction materials can play a significant role by enabling reductions in the use phase by improving building energy efficiency, decreasing vehicle excess fuel consumption on pavements, and increasing radiative cooling through higher albedo surfaces. To meet deep decarbonization goals, we will need to pursue both embodied and use phase GHG reduction strategies. In particular, we will need to continue the push for reducing energy consumption of vehicles and building equipment while decarbonizing the electrical grid.

While the abatement cost estimates demonstrate that there are some strategies we should pursue immediately because of their cost savings, particularly in the use of waste materials and energy-efficiency improvements, investments will be required to meet the highest reduction levels. In particular, the costs associated with CCUS pathways and constraints in the supply of some low-carbon binders mean that the cost effectiveness of embodied GHG reduction for concrete remains a challenge. The cost of capturing carbon in the cement industry is among the highest of all industries (40), and the production of synthetic aggregates requires a significant scale-up effort (41). Hence, it is critical that these embodied impact reduction strategies receive government support in much the same way that renewable energy technologies have been supported. The key difference is that we have shown that when applied wisely this will lead to both embodied and use phase GHG reductions. Such investments will move us closer to the goal of sustainable development where society has the built environment necessary for equitable opportunities while mitigating the impacts of climate change.

Data Availability. Life cycle assessment inventory data and spreadsheet datasets have been deposited in OSF (https://osf.io/HR9JB/).

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