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

Jeremy Gregory[1,*], Hessam Azarijafari[1], Ehsan Vahidi[1], Fengdi Guo[1], Franz Ulm[1], Randolph Kirchain[2]

[1]Department of Civil and Environmental Engineering, Massachusetts Institute of Technology

[2]Materials Research Laboratory, Massachusetts Institute of Technology

*Corresponding author, jgregory@mit.edu, +1-617-324-5639

Abstract

Concrete is a critical component of deep decarbonization efforts because it 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 US 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 47% of GHG emissions in 2050 relative to 2016 levels, whereas ambitious improvements result in a 56% reduction in 2050, which is 22 Gt cumulative saving. The pavements sector shows a larger difference between the two scenarios with a 20% reduction of GHG emissions for projected improvements and a 68% reduction under the ambitious scenario, which is approximately 1.7 Gt. Over 70% of future emissions from new construction are from the use phase.

1 Introduction

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. found that infrastructure, which makes extensive use of concrete, either directly or indirectly influences the attainment of every United Nations Sustainable Development Goal[1].

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 total footprint of concrete, like any material that constitutes a complex product, extends beyond production. Materials dictate the modes of manufacture and constrain the operational performance of the products into which they are fashioned[5]. Concrete is the 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. 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.

1.1 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 clinker cements) or supplementary cementitious materials (such as fly ash or granulated blast furnace slag) or through active use of captured carbon to produce synthetic limestone aggregates or cure concrete[3].

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 80-90% in many cases[10–13]. 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[14]. Including the reflectivity impact of pavements on the climate in the use phase can increase the use phase impacts to approximately 90% of the total GHG impacts[15]. Thus, the ways in which we design and maintain structures that use concrete can have much larger impacts than the impact of materials.

Analyses of pavement systems focus on material flows[16,17] or optimizing budgets and treatment schedules to minimize vehicle fuel consumption and the associated life cycle GHG emissions [18,19]. Similarly, building system analyses concentrate on material quantities or energy consumption [20–24]. 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 United States 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. 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.

2 Method

2.1 System attributes and strategies for scenarios

Our analysis of building and pavement systems in the US 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., % 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. 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 exists 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 is 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 Section 1.8 and 2.6 of the Supporting Information (SI), respectively.

Table 1. Building and pavement system GHG reduction strategies for system attributes under projected and ambitious improvement scenarios. CCUS = carbon capture, utilization, and sequestration; US EIA = The Unites States Energy Information Administration; IECC = International Energy Conservation Code; HVAC = heating, ventilation, and air conditioning.

Attribute Definition	**Projected Improvement Scenario**	**Ambitious Improvement Scenario**
Buildings		
Concrete Production	GHG emissions in concrete mix production will be reduced by linearly implementing 50% low-carbon binders by 2025 as well as CCUS by 2045, which involves carbon capture for cement plants and utilization of captured carbon for aggregate production.	GHG emissions in concrete mix production will be reduced by linearly implementing 50% low-carbon binders by 2022 as well as CCUS by 2035.
Energy Codes (appliances, lighting, HVAC, insulation)	Adoption of newer energy codes in newly constructed buildings. 100% IECC 2015 adoption in 2025. 100% Energy Efficient adoption in 2045.	Adoption of newer energy codes in newly constructed buildings. 100% IECC 2015 adoption in 2025. 100% Energy Efficient adoption in 2035.
Concrete Disposal	Carbon uptake due to concrete carbonation after the demolition of buildings. Carbonation will be linearly implemented from 0% to 50% by 2050.	Carbon uptake due to concrete carbonation after the demolition of buildings. Carbonation will be linearly implemented from 0% to 100% by 2050.
Electricity Grid	Grid decarbonization following the US EIA projection until 2050.	Grid decarbonization following the US EIA projection for New York (NYLI) which based on a 33% reduction in GHG emissions.
Pavements		
Materials	Asphalt: reclaimed asphalt pavements (50% - current maximum use by states) and warm-mix asphalt (100%) usage[*]. Concrete: carbon capture for cement (100%) and low-carbon binders (50%) [*].	Use low impact binder, recycled asphalt, and CCUS technologies (including synthetic aggregates) to achieve zero-impact mixtures[**].
Smoothness	Equivalent to the required budget for keeping surface roughness values constant (the average annual roughness is constant from 2016-2050).	20% increase in the currently projected budget.
Concrete overlay	According to the regional actions already defined for each zone, some of which already include concrete overlays.	Inclusion of concrete overlay action for asphalt pavement (interstates, arterials, and collectors) in the regional

		treatment actions for regions that do not already have them.
Reflectivity	Average network aged albedo values: Concrete = 0.25, Asphalt = 0.1 (the average reflectivity value of all the segments will stay constant for the 2016-2050 period).	Use reflective coating/binder to reach average network albedo = 0.3[**].
Stiffness	Current stiffness values existing in the national road network (the average reflectivity value of all the segments will stay constant for the 2016-2050 period).	Increase the stiffness to the 95^{th} percentile of the current frequency.
Concrete carbon uptake	Use: the carbon binding capacity of the mixtures will stay at 1.1 (status quo). End-of-Life: the concrete will be recycled or landfilled without carbon uptake.	Use: the carbon binding capacity of the mixtures will increase to 1.3[**]. End-of-Life: concrete rubble will be spread and temporarily stockpiled for 18 months.
Vehicle fuel efficiency	According to the U.S. Energy Outlook forecast.	Same as the projected improvement scenario.

* The strategy was linearly implemented on repaired and reconstructed roads to 2045, and then on all repaired and reconstructed roads thereafter.

** The strategy was linearly implemented on repaired and reconstructed roads to 2035, and then on all repaired and reconstructed roads thereafter.

2.2 Modeling approach and data sources

We used a bottom-up approach shown in Figure 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 multi-family) and commercial buildings) were developed for each of the fourteen 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 establish the associated material, operational energy, and other use phase requirements for each design over the course of the analysis period (2016-2050). 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 approximately 60% of the total cement consumption in the US [25]. Details of the methodology along with the input data sources are described in the SI, section 1 and 2 for buildings and pavements, respectively.

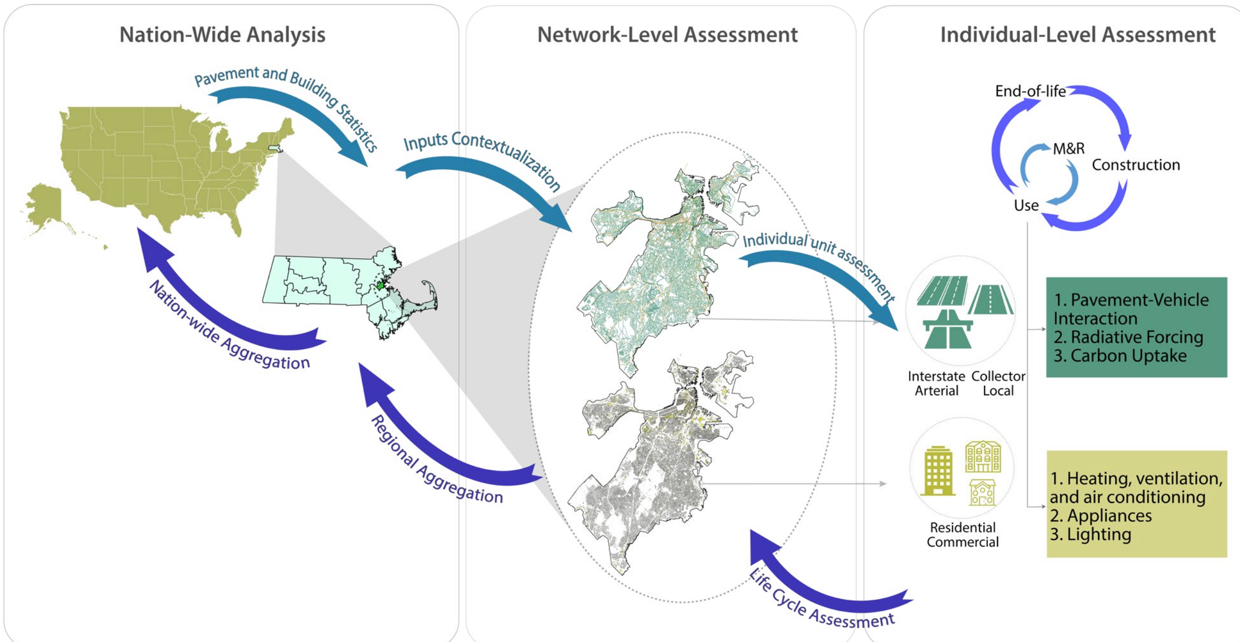


Figure 1. Summary of the bottom-up approach for investigating the life cycle GHG impact of buildings and pavements in the US.

2.3 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 material efficiency, 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.

3 Results

3.1 Opportunities for GHG reductions

The original stated goal for the US 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[26], 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 reduction targets requires significant contributions from all three of these sectors, and the use of concrete impacts all of them.

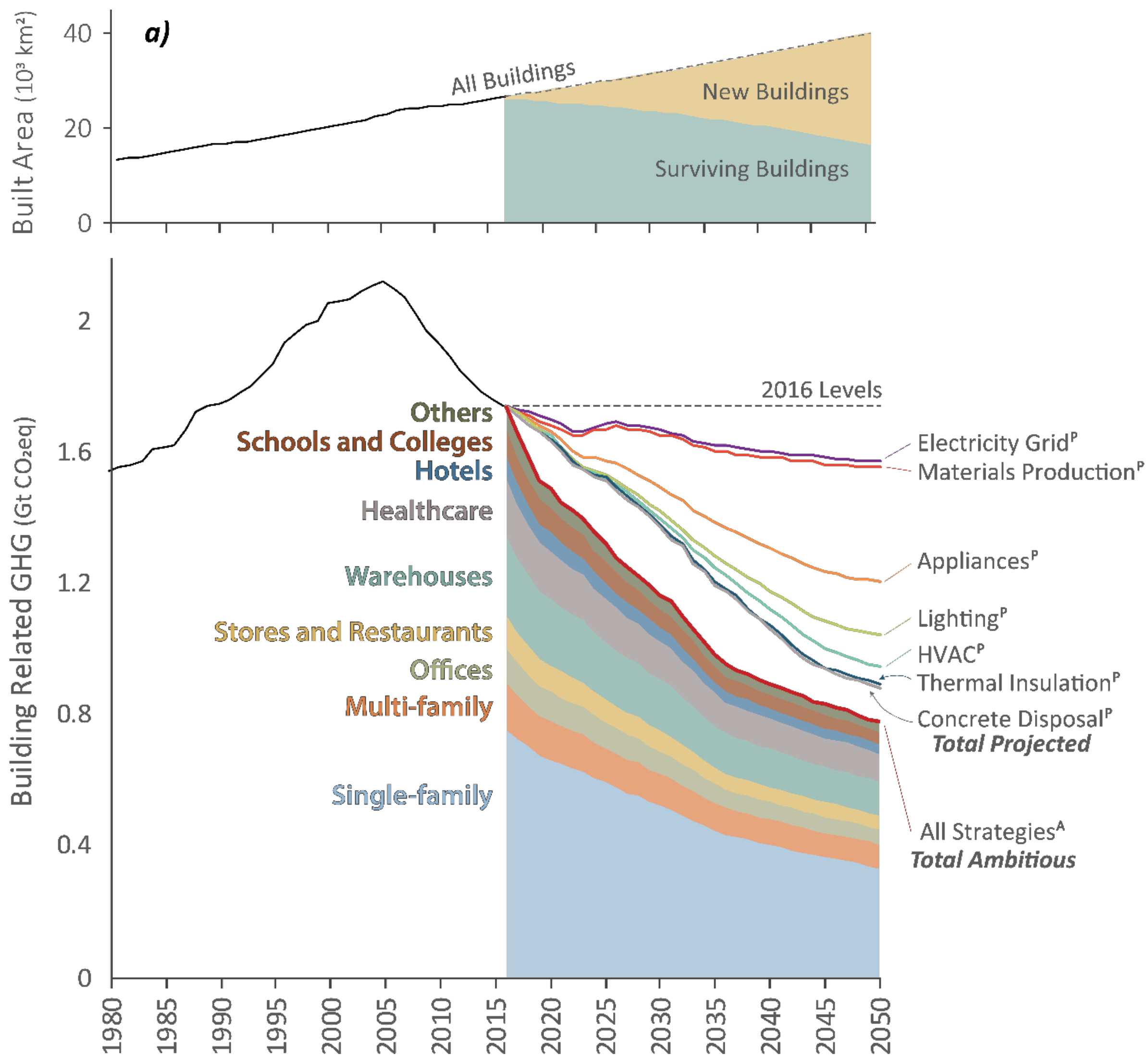
Figure 2 shows the historical and our modeled future GHG emissions for both the buildings and pavement sectors. Historical emissions increase in the 1980s and 90s due to growth in building stock and the pavement network and vehicle-miles traveled. Emissions peak in the early 2000s and decrease due to 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 approximately 1 Gt in 2050, a reduction of 47% relative to 2016 levels. The ambitious improvements scenario results in a 56% reduction in 2050 down to approximately 0.8 Gt GHG. In either scenario, modeled building sector emissions in 2050 are split evenly among residential (single and multi-family) 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 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 Figure 2a (and the cumulative reduction quantities in Figure 3a) 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 Gt of the cumulative GHG reductions projected over 34 years under the Ambitious Improvements scenario (Figure 3a). In this analysis, 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 20% reduction of GHG emissions in 2050 relative to 2016 levels under the projected improvement scenario. Our modeling projects the use of 90,000 t (38,000 m^3) of concrete in 2050. For the ambitious scenario we project both a much more intensive use of concrete (260,000 t or 110,000 m^3) and a much larger reduction of GHG emissions. (See Figure 2b.)

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 (Figure 2b and Figure 3b). The project 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 as vehicle-kilometers traveled continues 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, represent 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 0.6 Gt over the modeled time horizon (seventh bar in Figure 3b). A relatively small but significant reduction of 12.6 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 82% of that reduction stemming from stockpiling the demolished concrete temporarily. The remaining 18% of the reduction comes from the uptake increase during the use phase owing to the relatively large exposed surface area of concrete pavements.



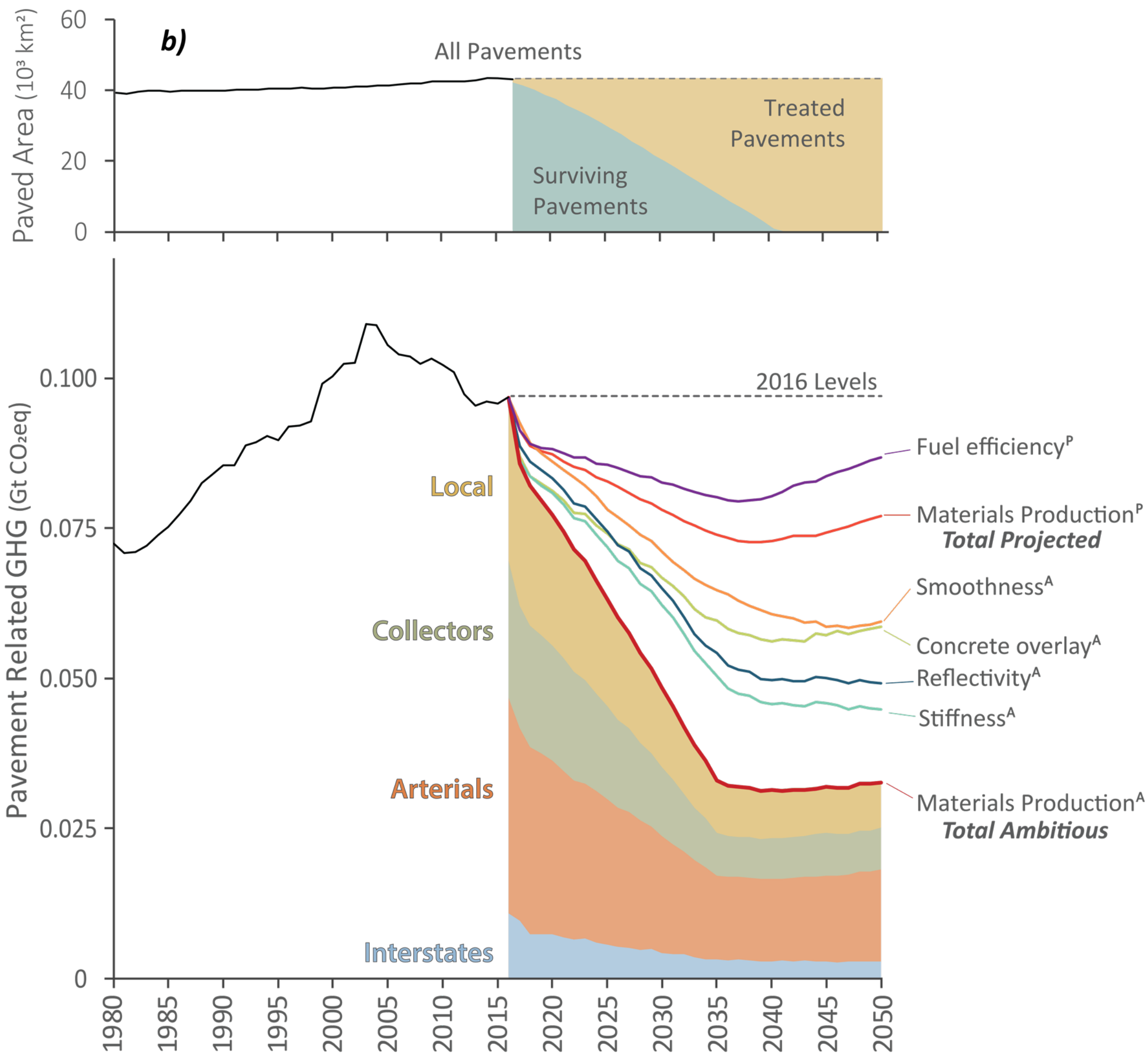
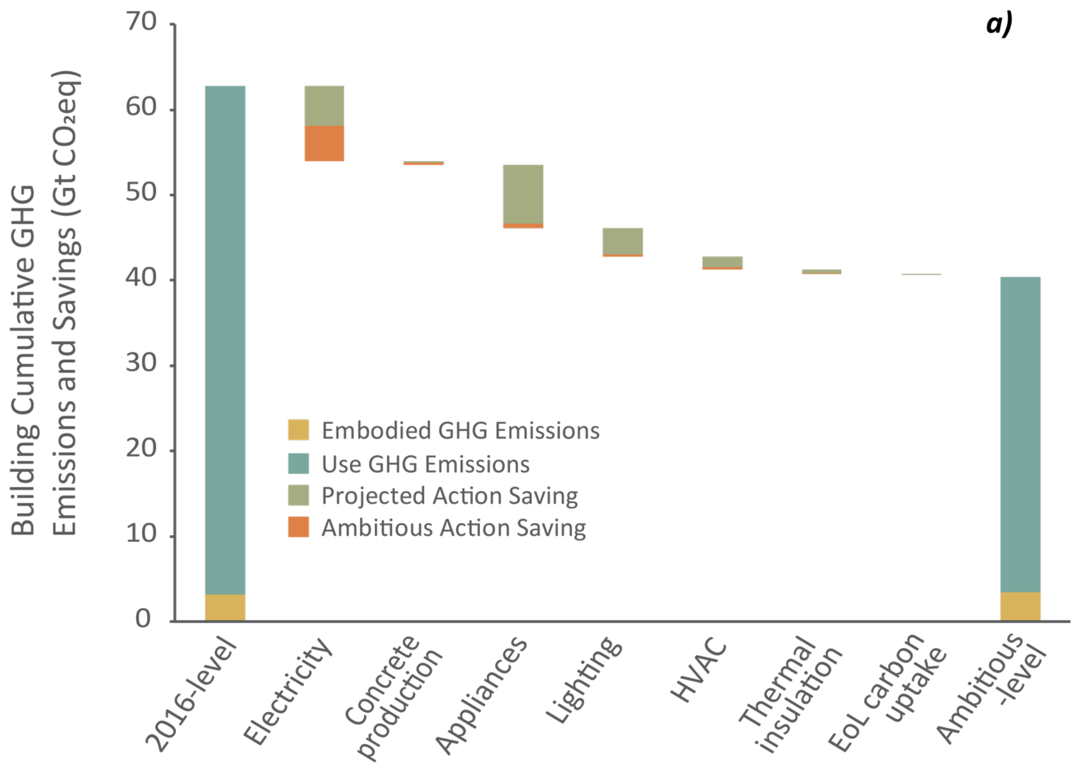


Figure 2. Built area and historical and future estimated GHG emissions in the (a) buildings and (b) pavements sectors. Historical emissions are before 2016. 2016 levels are used as a reference for the reduction of future emissions. Projected and ambitious emissions reductions for the individual attributes 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.



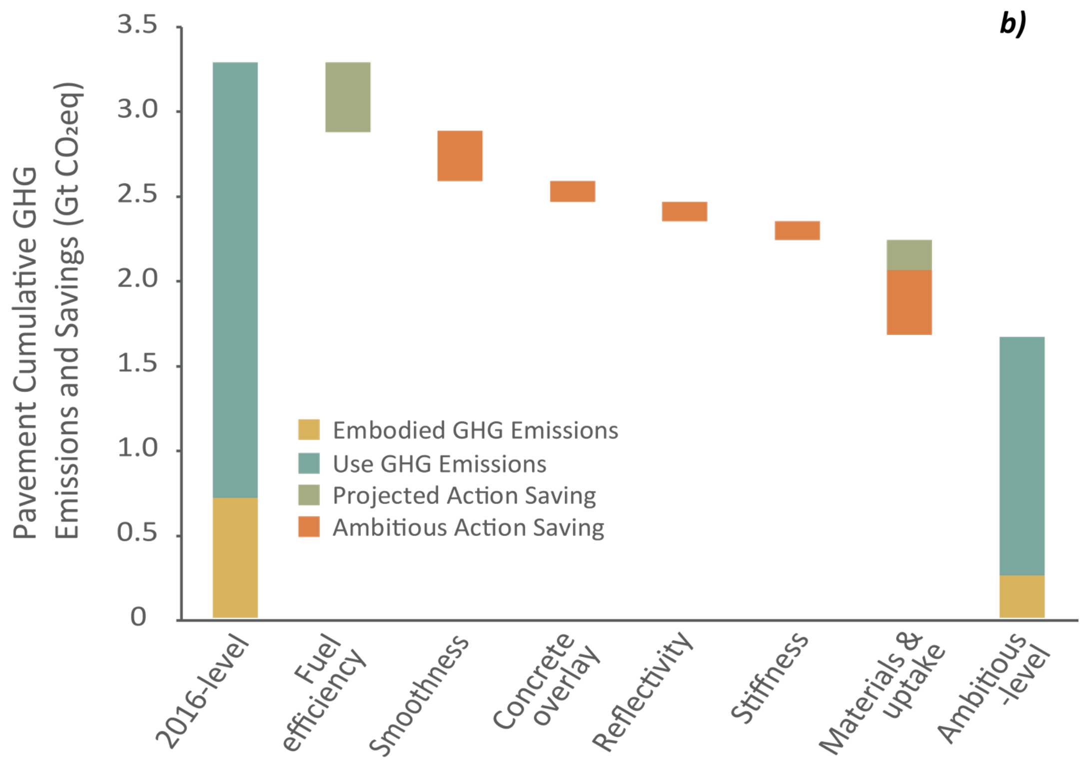


Figure 3. Cumulative 2016-2050 GHG emission reductions under the ambitious scenario for (a) buildings and (b) pavements. Reductions for each category are broken down into projected and ambitious scenario contributions (ambitious builds off of projected). The 2016 level assumes that emissions do not change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

3.2 GHG Abatement Costs

The costs of implementing GHG mitigation strategies under the ambitious scenario are shown in the abatement curves in Figure 4. Both sectors have negative abatement costs for the use of by-products and recycling 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 shown in Figure 4b because its estimated cost is over \$1000/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 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.

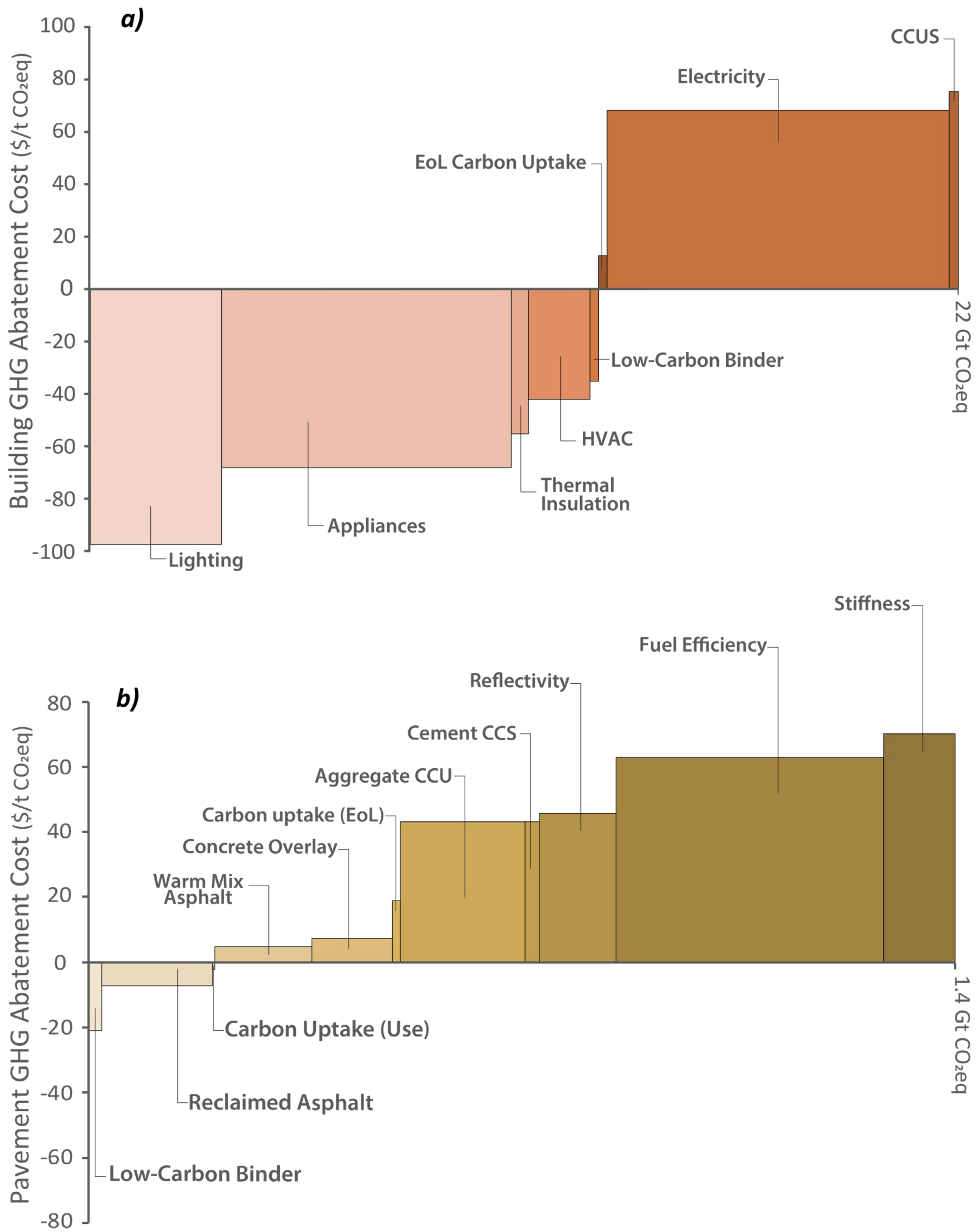


Figure 4. GHG abatement cost for ambitious strategy over 34 years for (a) buildings and (b) pavements. CCUS = carbon capture, utilization, and sequestration. The pavement strategy smoothness is not shown because of the difficulty of estimating an abatement cost that is separate from the budget increase for pavement maintenance and repair. The x-axis quantifies GHG abatement potential for the strategy in CO_2-eq. The cumulative GHG abatement across all strategies is shown at the end of the x-axis.

3.3 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 shown in the inset figures in Figures 5a and 5b, 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 the energy consumption of buildings and pavements constructed after 2017). In the building sector it is noteworthy that embodied emissions are relatively flat and are nearly identical for both projected and ambitious cases. This is the result of competing mechanisms of increasing building construction, increasing materials use to improve energy efficiency, and decreasing impact of concrete from use of low-carbon strategies. Use phase strategies will lower overall energy consumption and GHG emissions in the sector, but from a life cycle perspective operational energy consumption 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, Figure 5b 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. As shown in the upper chart of Figure 2b, it is predicted that the whole pavement network will have been treated at least once by 2040. Therefore, there is a moderate increase in the use phase part of the life cycle GHG emissions around this time period because there is an increase in traffic demand while the fuel efficiency and other solutions reach their saturation point. The solutions for achieving net-zero asphalt and concrete mixtures result in zero emissions in 2035 in the ambitious scenario and the share of embodied impact in the ambitious scenario drops the cumulative embodied emissions to 25% from 30% in the projected scenario.

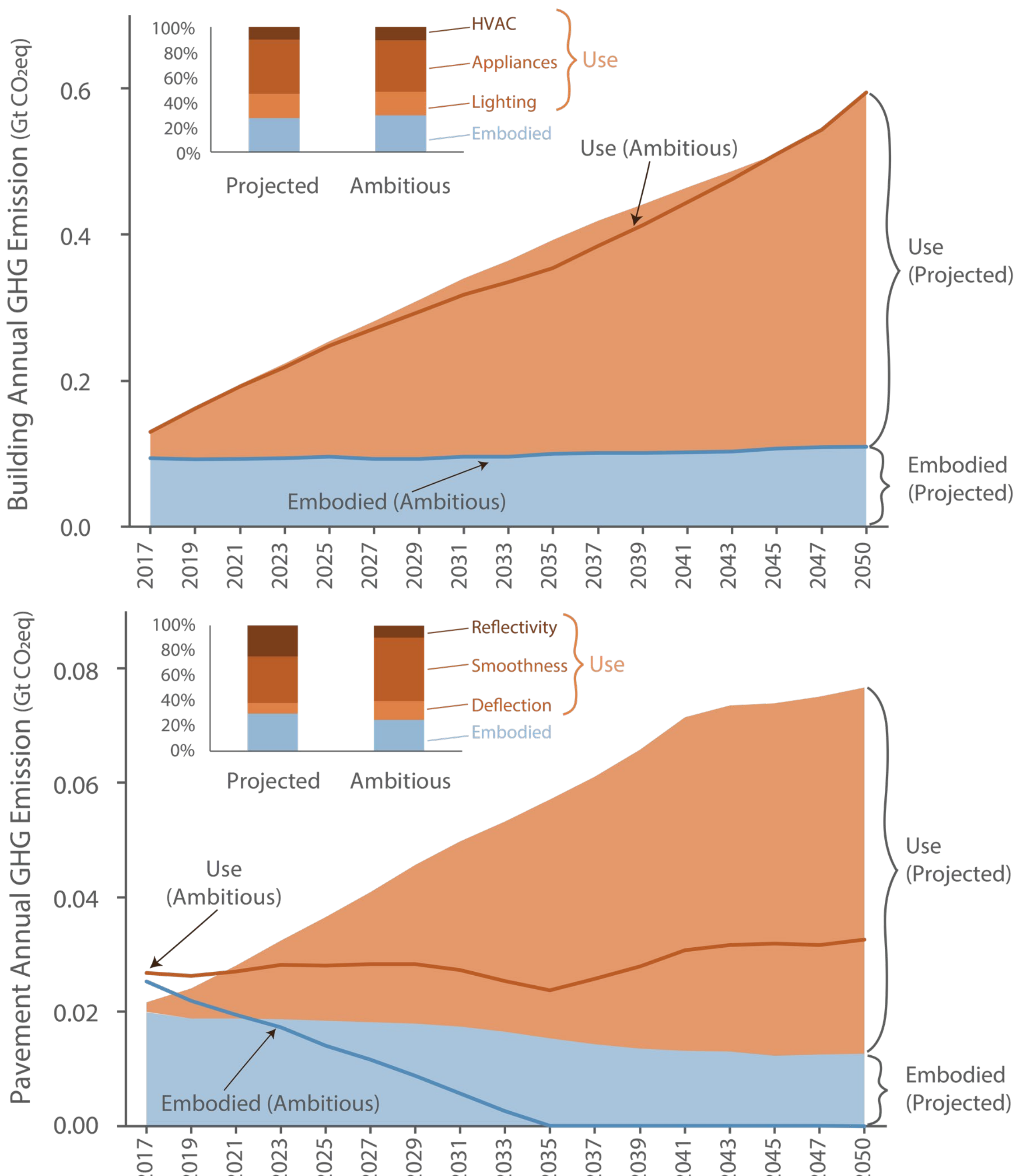


Figure 5. Cumulative embodied and use phase GHG emissions for a) new buildings and b) treated pavement area. Insets show the breakdown of cumulative emissions over the entire time period.

4 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 56%, 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 90,000 t of concrete, would lead to only modest reductions (20%) 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 68%, reaching the 65 – 75% target) even while making use of 260,000 t of concrete (nearly three times the level in the projected improvement scenario).

This analysis also makes plain that use phase emissions will continue to dominate the life cycle GHG emissions of buildings and pavements. 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[27] and the production of synthetic aggregates requires a significant scale-up effort[28]. 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.

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Author contributions

J.G., F.U., and R.K. conceived the study. J.G., H.A., E.V., F.G, and R.K. designed the approach. E.V. developed the building system model and conducted the building sector analyses. H.A. and F.G. developed the pavement system model and conducted the pavement sector analyses. All authors contributed to interpreting the results and writing the paper.

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