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Massachusetts Institute of Technology

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Solutions to achieve carbon–neutral mixtures for the US pavement network

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Solutions to achieve carbon-neutral mixtures for the US pavement network

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Abstract

Purpose

:-Several studies have evaluated GHG mitigation solutions for asphalt and concrete mixtures at the network level. However, proposed solutions usually focus on partial decarbonization; the simultaneous interactions and effects of these solutions have not been fully studied. In this study, the state-level embodied carbon attributed to the US pavement network was calculated using a dynamic material flow analysis and life cycle assessment model.

Methods

:-A pavement management system model was developed to forecast the performance and characteristics of the national pavement network using data science approaches. The annual quantity of materials required for the pavement treatment actions in each state was estimated based on budget allocation and regional decision trees. Then, multiple solutions for achieving carbon-neutral mixtures by 2050 were introduced to the state-level material flows to assess the GHG savings and abatement cost associated with the solutions.

Results and discussion

:-The annual GHG emissions of the US pavement network will increase by 19% if no change in decarbonization occurs (from 11.9 to 13.3 Mt CO_2eq). Under a projected improvement scenario, concrete and asphalt pavements are anticipated to have an average 38% and 14% embodied impact reduction by 2050, respectively. Nevertheless, carbon-neutral mixtures can only be achieved if multiple solutions for reducing, avoiding, and neutralizing the embodied impact are applied simultaneously. The effectiveness of many of these solutions depends on a 100% renewable electricity supply. From a cost perspective, 41% of the GHG savings towards carbon neutrality can be achieved at a negative or almost net-zero cost.

Conclusions

:—Carbon-neutral asphalt and concrete mixtures can be achieved if multiple solutions for reducing, avoiding, and neutralizing the embodied impact are applied simultaneously and the electricity grid is decarbonized rapidly. For future research, the scope of analysis for pavements should reach beyond embodied impacts and incorporate use phase emissions and service life alterations as part of an analysis to holistically assess carbon neutrality from a life cycle perspective.

Keywords: Net-zero;, Abatement cost;, Pavement network;, Optimization.

Introduction

Construction materials are associated with a growing share of global greenhouse gas (GHG) emissions. Between 1995 and 2015, the GHG emissions associated with construction materials production more than doubled, while global GHG emissions have increased by 1.4 times (Hertwich et al. 2020). This growth in GHG emissions requires more intensive and extensive efforts for decarbonizing construction materials.

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Horizontal infrastructure systems, including pavement networks, represent the second-largest consumer of construction materials after buildings (Hashimoto et al. 2007, Miatto et al. 2017, Huang et al. 2018). Every year, millions of tons of materials are added to the pavement stock to extend, maintain, or reconstruct the network. This significant materials consumption necessitates a precise modeling effort to quantify their environmental impacts promptly.

Decarbonization strategies for reducing the embodied impact of pavements have been studied previously (FHWA 2016a, FHWA 2016b). Prevalent solutions in the literature include increasing recycled content, decarbonizing transportation within the supply chain, reducing the heat required for asphalt installation, and reducing the mixing energy in ready-mix concrete plants. In the cement and concrete industries, at the global and national scales, efforts have been made to upgrade cement plants with carbon capture and utilization or storage technologies (here referred to as CCU or CCS) (IEA 2018, Miller et al. 2021). In ~~Additionally~~addition, some studies propose the use of novel, alternative material feedstocks such as using by-products (e.g., post-consumer plastics) or bio-based products (e.g., waste cooking oil). The long-term performance of such solutions will need to be established before they can be broadly deployed in critical infrastructure systems.

To assess the effectiveness of these mitigation solutions, previous studies have employed life cycle assessment (LCA) tools to quantify GHG reduction through individual (or small sets of similar) technical interventions. These studies examine a single mixture design from the time of extraction of raw materials to when the mixture is ready to be transported to the site. A range of 10–36% GHG reduction was reported when warm mix asphalt (WMA) and reclaimed asphalt pavement (RAP) were incorporated into asphalt mixtures (Aurangzeb et al. 2014, Celauro et al. 2015, Thives et al. 2017, Chen et al. 2018). Implementing various CCS technologies in cement plants reduces 32–99% of GHG emissions associated with clinker production (Neuhoff et al. 2014, IEA 2018, Rolfe et al. 2018). Among these technologies, oxy-fuel (80–99% sequester), calcium carbonate looping (89% sequester), chemical absorption (95%), and CO_2 separation using membranes (60–70%) are the most notable ones. According to an IEA projection, 32% of global portland cement emissions can be offset by 2050 with the aggressive implementation of these technologies. Other solutions, such as replacing portland cement with alternative binders or using biofuel or electric aggregate production for asphalt, resulted in 30—67% (Limbachiya et al. 2014, AzariJafari et al. 2019) and 2—7% GHG reduction (Peng et al. 2017) compared to mixtures without any alternative materials. With the current ambition of the construction industry to achieve a carbon-neutral state, the implications and simultaneous effects of these solutions on reducing, avoiding, and neutralizing total anthropogenic GHG emissions have remained poorly understood (Finkbeiner et al. 2021).

Several research studies have examined the embodied emissions and savings associated with asphalt and concrete pavement construction, maintenance, and repair. We found three main research gaps in this literature. First, the geographical scope of these studies was limited to a specific state or city. Second, the decarbonization solutions did not incorporate anticipated improvements in their assessments. For the whole analysis period, foreground and background processes were assumed to remain static. Given the push toward~~s~~ carbon reduction under national and international pledges (and considering the monetary savings from specific mitigation solutions), there is a decreasing trend in the GHG emissions of energy and materials (IEA 2018, U.S. EIA 2019). Given these trends, assuming static performance likely overestimates future GHG emissions. Third, the effectiveness of specific mitigation solutions is highly interdependent; the effectiveness of a solution can depend on the implementation of other solutions. For example, in a scenario where both pavement design optimization and implementation of alternative binders are evaluated, the former reduces the demand for construction materials, including the volume of the binder. As such, it is essential to consider the effect of these solutions in an integrated framework to avoid overestimating the potential saving from their simultaneous implementation.

To address these research gaps and opportunities, we developed a model to predict and quantify the potential embodied impact of future pavement materials demand using coupled material flow analysis (MFA) and LCA. This model considers geographic heterogeneity (at a state level) in the characteristics of

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the current materials stock, the local climate, norms for system maintenance, and available public budgets for infrastructure. Using this information, we identify a range of approaches that can be applied to bring embodied emissions from the US pavement network to a carbon-neutral level. This information was used to develop three scenarios that were then evaluated using these coupled tools: (1) a business-as-usual (BAU) scenario where technology remains static at 2017 levels, (2) a projected scenario intended to represent the implementation of commitments by relevant industry groups and stated national goals, and (3) an ambitious scenario that either intensifies or accelerates the projected scenario strategies to achieve carbon~~-~~ neutrality.

Methodology

In this study, the US road network, which comprises ~~three~~ 3 million miles of pavements, was divided into 10-mile segments; the condition and performance of pavements were forecast using data science approaches (Section 2 of the Supplementary information (SI) document). An overview of the approaches is presented in the "Material flow analysis framework" section below. The following sections present the embodied impact calculation of construction materials and abatement costs associated with the GHG reduction and neutralization solutions.

Material flow analysis framework

To estimate material flows in the US pavement network, we must establish appropriate benchmarks based on forecasts of future materials stocks. The benchmark values provide an understanding of what would happen to pavement materials demand and their associated GHG emissions if no changes occur. Moreover, this benchmarking step clarifies the extent to which various decarbonization strategies are needed to achieve a certain amount of GHG savings. Pavement management system (PMS) modeling is an efficient way of establishing the benchmark and creating performance-based planning. A PMS model incorporates a set of pre-defined steps for collecting, analyzing, maintaining, and reporting pavement performance and required maintenance, repair, and reconstruction (i.e., treatment actions) in the future (see ~~Figure 1~~Figure Fig. 1). In this study, a PMS model was developed and applied to estimate the annual performance and treatment actions applied to the segments during the period of 2017—2050.

~~Figure~~ Fig. 1~~.~~ Illustration of pavement management system (PMS) components and their interaction with materials flow analysis

The PMS model developed for assessing the materials flows incorporates four components:

1. Network assessment

In order to identify and prioritize treatment actions in different road segments in a given year, it is essential to have a clear understanding of the network condition (i.e., annual traffic volume, surface condition, and layers thicknesses). However, data is typically difficult to obtain or is scattered among various databases belonging to producers, federal governments, and local authorities. To analyze the network condition with a reasonable resolution in all the states, two data sources were considered: road statistics reported by the Federal Highway Administration (FHWA), and the Long-term Pavement Performance (LTPP) database. From the FHWA road statistics (see SI document, Section 2.1.1), the distributions of several input parameters were extracted. These parameters include the international roughness index (IRI), annual average daily traffic (AADT), annual average daily truck traffic (AADTT), pavement types, pavement length, lane number, and lane width in terms of miles for each system and route type. The estimation of cost associated with the current and future pavement treatment actions at the state level is described in Sections 2.2–2.3 of the SI document.

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2. Budget allocation model

The budget allocation model is used to make pavement treatment plans for the whole pavement network. The allocation model is based on a bottom-up framework that considers segment heterogeneity in the pavement network (Guo et al. 2020). It first focuses on the segment level to determine the relevant treatment for each segment based on decision trees whose decision criteria are pavement condition (IRI) and pavement age (see ~~Figure~~ Fig. S10 in the SI document). FHWA suggests that when IRI is larger than 2.68 m/km, then the road condition is evaluated as poor. Hence, this value is used for the criterion for reconstruction if the segment age passes 50 years. After determining the relevant treatment based on the age and IRI for each segment, the allocation model moves to the network level to select which segments should receive treatments under the budget constraint. The selection approach is mainly based on the prioritization method. First, the treatment benefit for segment *i* is calculated by Eq. (1):

$$benefit^i = IRI^i_{fixed} - IRI^i_{non-fixed} \quad (1)$$

where IRI^i_{fixed} represents the IRI value if segment *i* receives its relevant treatment, and $IRI^i_{non-fixed}$ is the IRI value if nothing is done to segment *i*. Next, the allocation model ranks all segments based on their benefits as shown in the following equation~~,~~:

$$r_j = rank\left(benefit_j\right) \quad (2)$$

where r_j is the ranked pavement network, and the segment with the largest benefit ranks first. With the consideration of budget constraints, segments that can be maintained are selected by~~:~~

$$S = \arg\min_{r_j} \left(\sum_{s,i \in S, S \in r_j} cost_i - B \right) \quad (3)$$

$$s.t \quad B - \sum_{s,i \in S} cost_i \geq 0$$

where S is the set of selected segments, $cost_i$ represents the treatment cost for segment *i*, and *B* is the budget.

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In the analyses, a critical budget is applied, which represents the minimal budget that could keep the annual pavement network condition stable for the whole analysis period. Historical IRI data from the FHWA database shows that the average condition of the network has stayed in steady condition. Hence, for each system, its *critical* budget implies the network condition almost stays the same and, therefore, the average IRI for the system is almost a flat line for the whole analysis period. The budget allocation process is on a yearly basis. The initial pavement conditions and treatment costs are provided at year = 1.

3. Treatment action selection

According to the local practices of pavement maintenance, repair, and reconstruction, and based on the technical requirements in each climate condition, the thickness and type of treatment actions should vary from one region to another. The actions may induce a materials removal (e.g., diamond grinding), addition (overlay), or simultaneous removal and addition (e.g., mill and fill) in the pavement system. Section 2.5 of the SI document details the type and thickness of treatment action in each region and road type.

4. Pavement deterioration forecast

Pavement deterioration forecast is usually based on age, thickness, and traffic levels. However, age and thickness data are not provided by the FHWA road statistics. To obtain these two values, several linear relationships were developed based on the LTPP database and a regression model was developed for

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forecasting the pavement thickness, traffic, and age of pavements. A pavement deterioration model was developed based on a difference-stationary process and using data from LTPP. It is assumed that pavement deterioration follows a random walk with drift and uncertainties that have a permanent influence on future deterioration levels, so the variance of future pavement performance increases over time. Age, AADTT, and total thickness (TOTTHK) of pavement were incorporated in the deterioration model, which are suggested to be influential factors by previous studies (Swei et al. 2018). The expected deterioration process is shown in Eq. (4).

$$\Delta IRI_{t,i} = \alpha \cdot AGE_{t-1,i}^{\beta_1} \cdot AADTT_{t-1,i}^{\beta_2} \cdot TOTTHK_{t-1,i}^{\beta_3}$$

$$\Delta IRI_{t,i} = a \times AGE_{t-1,i}^{b_1} \times AADTT_{t-1,i}^{b_2} \times TOTTHK_{t-1,i}^{b_3} \quad (1)$$

WHere, coefficients $a, b_i (i = 1,2,3)$ can be obtained through ordinary least squares (OLS). The full equations of deterioration models for each pavement type and region are provided in Section 2.6 of the SI document.

Based on the MFA results obtained from the developed PMS model, the annual asphalt mixtures required for the US pavement network (only traffic lanes) is 208 Mt and will be increased by 24% by 2050. Considering 350 Mt per year of asphalt production in the USA (NAPA 2021), our analysis covers around 60% of the total US asphalt market. Moreover, the estimated amount of cement used for concrete pavements for traffic lanes in 2017 is 1.6 Mt, which is around 6% of the total cement consumption for highways and street infrastructure systems (PCA 2018). The detail of the PMS part of this study, including road statistics, model training database, types of treatment actions in addition to modeling of treatment cost prediction, pavement deterioration, surface condition after the maintenance and repair actions, and budget allocation, are provided in the SI document.

Embodied impact modeling framework

In the second stage of the framework, a dynamic LCA model was applied to calculate annual state-level emissions associated with construction materials procurement. These model components were applied to two scenarios: projected improvement and ambitious improvement. The impact of each scenario on GHG emissions and the GHG abatement costs were calculated. Details on the embodied impact assessment models and data are provided in the SI document (Sections 1.1—1.2) and the SI spreadsheet, respectively. Construction materials for pavement projects are either provided by local governments or private sectors. Depending on the availability and cost of the materials, the decision-maker may prefer a specific type of material or supplier. Since low-carbon construction materials are maintaining their momentum in the market, various suppliers are striving to lower the GHG footprint of their supply chain while keeping their costs in a reasonable range so as not to lose their market share. Hence, several technologies have been adopted in different regions. In the 2017-level scenario, background data was adopted from the ecoinvent database, and a regional bill of materials was collected from the NAPA and NRMCA reports (see the SI spreadsheet). For the projected-level solutions, background electricity data was derived from the US EIA Energy Outlook and its projection until 2050. The embodied impact solutions for concrete come mainly from the IEA technology roadmap. For asphalt, we assumed the maximum level of solution implementation for all US states. The rate of implementation is linearly adjusted to achieve the values specified in Table 1. Detailed assumptions for these scenarios are provided in Section 1.1 of the SI document ~~Section 1.1~~.

To achieve carbon neutrality, two general strategies were considered: (1) aggressive implementation of solutions and (2) innovative solutions under adoption in North America. For concrete procurement, the incorporation of alternative binders, such as slag, fly ash, and limestone, up to 50% have been applied on a large scale at different locations. However, this 50% has been implemented only in a few concrete pavement construction projects in the USA (Rangelov et al. 2022). Currently, the average consumption of alternative

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binders for concrete stayed at 13–23% according to the NRMCA industry-wide program (NRMCA 2019). The reason behind the 50% selection in the alternative binder incorporation is that a greater replacement rate would generally compromise the constructability, mechanical, or durability properties of concrete pavements. Another solution for reducing the GHG emissions of mixtures is to reduce the quantity of binder in the mixtures by means of reducing the space among the coarse and fine aggregates. In fact, improving the aggregate interlocking can lower the binder intensity in concrete mixtures. As reported by Damineli et al. (Damineli et al. 2010), the binder intensity of conventional mix designs (compressive strength of 20-40 MPa) can be as low as 7 kg/m^3/MPa.

Decarbonization of cement and concrete value chains, like any other products and services, requires compensation measures such as carbon capture and utilization or sequestration (CCUS) as there is no alternative way to approach net-zero mixtures (GCCA 2021, PCA 2021). For the cement value chain, carbon capture technologies, such as chemical absorption (Walters 2016, Kearns et al. 2021), have been realized and are under construction by a few cement plants in North America. We assumed the target value of 25% CCS until 2050 for the portland cement consumed in pavements as projected by the cement technology roadmap report (IEA 2018) (assumption for the projected scenario). Nevertheless, according to the EIA roadmap (IEA 2018), up to 65% of the cement CO_2 is feasible to be captured by 2050 using a more expensive but more effective technology of oxy-fuel carbon capture in cement plants (compared to chemical absorption methods). This aggressive scenario was applied to the portland cement production and linearly adjusted until 2050. It should be noted that net-zero pledges implemented so far had no authority or power to make industries or countries obey them and there were no consistent ways of measuring and reporting GHG emissions and reductions. Therefore, measuring the implementation levels has been considered a challenge by different researchers.

Previous studies have shown the feasibility and significant benefits of CCU technology which can be jointly used with the sequestered CO_2 in cement. CO_2 utilization through the production of carbonate-based construction materials is the closest to application at a commercial scale compared to other technologies (NAS 2019a, NAS 2019b). Some of the CCU aggregates approaches are already employed commercially, suggesting the near-term potential for increased adoption of mineral carbonation in the large and growing construction materials market. We considered leveraging CCU technology developed for aggregate manufacturing in concrete and asphalt as one of the viable emerging technologies proposed in the USA as part of an overarching goal to neutralize the accumulation of GHG emissions in the atmosphere. More than 70% of concrete and asphalt mass consists of coarse and fine aggregates. This significant mass of materials allows authorities and suppliers to benefit from the mixture aggregates as a significant, permanent carbon sink. It should be noted that the utilized CO_2 may be permanently stored in the aggregates after the chemical reaction and formation of the carbonate products. Hence, possible end-of-life scenarios for pavement materials (landfilling or recycling) would not cause any issues for the CO_2 permanent storage in the product. The modeling detail, raw material requirements, and assumptions for the CCU implementation are provided in Section 1.1. of the SI document.

For asphalt pavements, lowering heating demand while satisfying the minimum workability requirement and replacing the virgin binders and aggregates with recycled materials are considered the main strategies in different states according to the FHWA report (FHWA 2016). Although several hurdles (mostly specification limits as opposed to the performance limits) exist for maximizing the implementation of these two strategies, in our ambitious scenario, we assumed that all the states can attain the maximum reported virgin materials reduction (50%) and the incorporation of warm-mixed asphalt (100%) until 2050. Also, using recycled binders, such as ground tire rubbers and waste oils (Vahidi et al. 2014, Rahman et al. 2017), in conjunction with the application of RAP has been proven as a viable solution to increase the recycled content in the asphalt mixture. Based on the pilot studies of asphalt mixture incorporating recycled binders

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and RAP, we assumed the maximum incorporation of 50% (currently achieved incorporation percentage that does not adversely affect the mechanical performance of the mixture (Rahman et al. 2017)) by 2050. Also, the adjustment of structural numbers of the surface layer in the flexible pavement design was reported to benefit an 18.5-–25% reduction in the pavement thickness of the state of Alabama and Washington (Timm et al. 2014) without compromising performance. We incorporated this level of reduction as the optimization solution for the asphalt ambitious scenario. The rest of the savings are attributed to the incorporation of synthetic aggregates in the mixtures to reach net-zero mixtures as explained in the previous paragraph. Table 1 summarizes the proposed solutions under the projected and ambitious improvement scenarios. The life cycle inventory and bill of material sources for the foreground unit processes are provided in the SI spreadsheet. In this study, the cut-off approach was considered for the end-of-life of materials. For the background unit system, the "“Allocation, cut-off by classification"” dataset of the ecoinvent database was considered. Therefore, no upstream emissions or credits are assigned to the processes. In addition, in the case of co-production, different materials such as slag, and fly ash were treated based on economic allocation principles. The sources of allocation methods are described in the SI spreadsheet.

The dynamic aspect of this life cycle cycle embodied assessment study incorporates annual changes in materials flows as well as associated emission factors. As discussed in the “Introduction” section, these are typically a steady set of assumptions for the whole analysis period. In this study, we considered the dynamic material flows, and emission factors were calculated using a time-dependent technosphere matrix in the dynamic life cycle inventory stage. In this way, the quantity of intermediate flows contributing to the foreground processes (e.g., cement production) and certain background processes (e.g., electricity and heat generation) were changed according to the solution implementation. In this study, we assumed a linear implementation rate for the solutions discussed in Table 2Table 2. The characterization factors for the life cycle impact assessment method were considered constant throughout the analysis period (static). The results presented in this paper represent the cumulative effect of the solutions in each scenario.

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Table 1. Proposed solutions and level of adoptions under the 2017-level, projected and ambitious scenarios for decarbonizing US asphalt and concrete mixtures (NA = not applicable).

Solution	**2017 level**		**Projected scenario**		**Ambitious scenario (carbon neutral)**	
	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete
Pavement design optimization	Limited implementation	Limited implementation	Limited implementation	Limited implementation	21.7% thickness optimization for construction and repair* (Timm et al. 2014)	18.5% thickness optimization for construction and repair* (Swei et al. 2014, Habert et al. 2020)
Alternative binders	≈0%	13–23% (NRMCA 2019)	≈0%	40% ternary by 2050* (IEA 2018)	50% GTR by 2050* (Vahidi et al. 2014, Rahman et al. 2017)	50% ternary by 2050*
Transportation and electricity grid	0.1–0.72 kg CO_2eq/kWh	0.1–0.72 kg CO_2eq/kWh	EIA Projection (2–38% reduction by 2050) (EIA 2020)	EIA Projection (2–38% reduction by 2050) (EIA 2020)	Renewable electricity and transport (0.02 kg CO_2eq/kWh)*	Renewable electricity and transport (0.02 kg CO_2eq/kWh)*
Carbon capture and utilization (CCU–aggregates)	No implementation	No implementation	No implementation	No implementation	23% of the total aggregates*,†	6% of the total aggregates*,†
Reclaimed asphalt pavement/asphalt shingle	0–28% (NAPA 2018)	NA	Maximum reported value (28%) (NAPA 2018)	NA	Maximum incorporation reported in pilot studies (50%) (FHWA 2020)	NA
Warm mix asphalt	0–100% (NAPA 2018)	NA	100% (NAPA 2018)	NA	100% (NAPA 2018)	NA
Carbon capture and storage (CCS–cement plant)	NA	Limited implementation	NA	Global average by 2050 (25%)* (IEA 2018)	NA	Fully adoption of best performance technology (65%)* (IEA 2018)

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Binder intensity	NA	12.5–17.0 kg/m³/MPa (NRMCA 2019)	NA	Limited implementation	NA	7.0 kg/m³/MPa* (Damineli et al. 2010)

* The strategy was linearly implemented and scaled up on the newly treated roads by the indicated year, and then on all newly treated roads thereafter

† After implementing all the solutions, the quantity of CCU synthetic aggregates was adjusted to achieve carbon-neutral mixtures

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Calculation of marginal abatement cost

The abatement cost calculation comprises two basic elements of the net benefit/burden associated with the implementation of attributes. The following equation was used to estimate the total abatement cost during the analysis period:

$$MAC_n = \sum_{t=1}^{34} \left(F_{t,n} \times \frac{NBC_n}{(1+d)^t} \right) \quad (5)$$

where MAC is the marginal abatement cost of solution n during the analysis period of 2017–2050, F is the materials or energy displaced by the implementation of attribute n, NBC is the net base cost of each attribute, and d is the discount factor (here assumed as 3%). The information and data sources for the abatement cost calculation can be found in the SI spreadsheet.

Results and discussion

The significance of embodied impacts associated with construction materials remains a question among policymakers. Figure. 2 plots the modeled embodied impacts of the pavement network across the 33-year simulation period. These results show that the annual embodied GHG emissions associated with the US pavement network range from 11.9 to 13.3 Mt CO_2eq. This quantity is equivalent to the tailpipe emissions of 9.5—10.6 million passenger vehicles per year (US EPA 2021). As shown in Figure. 2a, if no decarbonizing solutions are implemented, the embodied GHG emissions of the pavement network are expected to increase by 19.5% by 2050 (compared to 2017 levels). This increase occurs because of more frequent future repairs due to climate change and the resulting increase in pavement deterioration (Guest et al. 2020, Qiao et al. 2020). The authors anticipated that the various improvements associated with the projected scenario would lead to a slight reduction in future embodied GHG emissions. Figure. 2b shows that this hypothesis was not correct for the US context. Instead, system emissions increase because the increase in material uses outpaces emissions reductions at the production level for that scenario.

The other important observation from Figure. 2a and b is the share of GHG emissions for different road types. No previous study has characterized the relative contribution of each road type to the total embodied impacts of the nation’s road system. However, from these results, it is evident that all four road types significantly contribute to the system’s total embodied GHG emissions. The minimum contribution belongs to the local roads (17—21%), while the maximum contribution of the GHG emissions comes from the arterial roads (30—33%). In the USA, different road types are managed by different entities ranging from the federal government to local municipalities and private owners. Therefore, all stakeholders must be involved in transitioning to a carbon-neutral road network.

Fig. 2 Annual GHG emissions of the US pavement network for different road types under the **a** 2017-level scenario, **b** the projected scenario

The state-level GHG emissions and the annual GHG emissions of concrete and asphalt mixtures per unit of volume under the projected scenario are shown in Figure Fig. 3. The extensive regional variation for a given compressive strength across different states (350—400 kg CO_2eq/m^3 concrete and 120—160 kg

CO_2eq/m^3 asphalt) necessitates a high-resolution assessment for the estimation of embodied impacts for the US pavement network. This variation mostly derives from regional differences in prevalent mix designs and in the current rate of adoption of mitigation solutions. The representative concrete mixture (~~Figure 3~~Figure Fig. 3~~.~~a) in the Pacific Northwest region (including the states of Oregon, Washington, and Idaho) has the highest GHG emissions due to having the largest binder content among other regions (472 kg/m^3 binders, 22% fly ash and slag). While the data on the concrete mix designs are the industry average values for the same compressive strength level, other performance metrics for road design and construction are not reported. Therefore, assessing the functional equivalency of the mixtures in different regions is not feasible. For asphalt pavements (~~Figure 3~~Figure Fig. 3~~.~~c), the states of Wyoming, North Dakota, and Rhode Island have the largest embodied impacts due to the relatively lower adoption rate of RAP and WMA solutions. Specific state and local authorities have limited recycled content use because no long-term performance evaluation exists (NAPA 2018). Moving toward~~s~~ performance-based specifications in public procurement would allow designers and contractors to use alternative materials to reduce the embodied impact of pavements. It should be noted that asphalt and concrete mixtures are generally not functionally equivalent based on the volume; a comparison between these two mixtures is not recommended without a life cycle perspective. However, as this paper focuses on mixture decarbonization solutions, the unit volume is sufficient to explore the extent to which projected strategies can effectively reduce embodied GHG emissions. For example, as shown in ~~Figure 3~~Figure Fig. 3~~.~~b, implementing alternative binders and adopting CCS to the extent defined in the projected scenario can reduce the average embodied emissions of a concrete mixture by 38% by 2050 (compared to the 2017 emission level). Nevertheless, even with a 38% reduction, more than 230 kg CO_2 per cubic meter of concrete must still be removed or avoided to achieve carbon-neutral concrete. On the other hand, under the projected improvement solutions, it seems more difficult to abate GHG emissions from asphalt mixtures (only 14% emission reduction in 2050 compared to the 2017-level). Under this scenario, the average GHG emissions of asphalt mixtures fall as low as 101 kg CO_2eq/m^3 (~~Figure 3~~Figure Fig. 3~~.~~d). Therefore, achieving a carbon-neutral pavement mixture is contingent upon a more aggressive implementation of the projected solutions and the introduction of new mitigation solutions.

~~Figure~~ Fig. 3~~.~~ GHG emissions per unit volume associated with **a**~~)~~ state-level concrete mixtures in 2017, **b**~~)~~ concrete mixtures under the projected scenario, **c**~~)~~ state-level asphalt mixture in 2017, and **d**~~)~~ asphalt mixtures under the projected scenario. The continuous black lines on (**b**) and (**d**) represent the average embodied impact in the US while the yellow highlighted zones show the maximum and minimum range of the embodied impact for different states until 2050~~.~~

Implication of ambitious actions toward~~s~~ carbon-neutrality of pavement mixtures

As detailed in Table 1, the ambitious scenario includes a range of intensively applied solutions to simultaneously neutralize, reduce, and avoid embodied GHG emissions associated with the pavement network. Figure. 4 plots the modeled results of implementing these solutions for concrete and asphalt pavements under two different scenarios: if the grid intensively decarbonizes and transportation electrifies (right-hand plots (b) and (d)) and if these do not happen (left plots (a) and (c)). These results demonstrate that the effectiveness of these solutions to ultimately achieve carbon neutrality depends strongly on background electricity grid decarbonization as well as electrification of transport systems (in the foreground supply chain, including the transportation of concrete and asphalt ingredients and mixtures to the site). In fact, under the projected grid improvement (~~Figure 4~~Figure. 4~~.~~a, ~~and~~ c), the ambitious solutions appear unlikely to achieve carbon neutrality. If the grid does not decarbonize more rapidly than projected, then the

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environmental burdens associated with the energy used to produce CCU aggregates are larger than that for the CCS technology (7.75 GJ/t CO_2 saving for CCU aggregates (Scott et al. 2021) as opposed to 1.63 GJ/t CO_2 saving for cement plant CCS using oxy-fuel technologies (Voldsund et al. 2019)). For such a case, this results in CCU burdens exceeding the captured CO_2 and ultimately presents a net environmental burden. As a relatively larger portion of synthetic aggregates is required for carbon-neutral asphalt and alternative binder production such as GTR is an electricity-intensive process (353 kWh/t) (Feraldi et al. 2013), grid decarbonization becomes even more important for asphalt materials. For the scenario plotted in Figure. 4.b (ambitious scenario and without ambitious gird decarbonization), asphalt materials achieve an embodied GHG reduction of only 49% percent in 2050. Under these same conditions, (Figure 4Figure. 4.a), the average embodied emission for concrete falls by 84% by 2050. However, both asphalt and concrete mixtures can become carbon neutral by 2050 through the implementation of the ambitious scenario including aggressive grid and transportation decarbonization (Figure 4Figure. 4.b, and d). Mix designs across states achieve carbon neutrality under these same ambitious conditions.

Figure. 4. Sensitivity of ambitious (i.e., achieving carbon-neutral mixtures by 2050) scenario (see Table 1) for concrete and asphalt pavements to the transport electrification and electricity decarbonization, Figures **a**, and **c**, under the projected transport electrification and electricity improvements, and **Figures b**, **and d**, under full renewable electricity sources and transport electrification by 2050. The continuous black curves represent the average embodied impact in the USA while the green highlighted zones show the embodied impact range.

Contribution of ambitious solutions to the GHG mitigation of the US pavement network

As was shown in Figure 4Figure. 4.b and d, the ambitious solutions proposed in this study can effectively result in carbon-neutral asphalt and concrete mixtures by 2050. The expected cumulative embodied GHG emissions of asphalt and concrete in the US pavement network, and, the contribution of each solution to the cumulative total saving are presented in Figure. 5. As shown in Figure 5Figure. 5.a, the ambitious solutions can eliminate 202 Mt CO_2eq from the business-as-usual asphalt emissions during the 2017––2050 period (48% reduction of cumulative GHG emissions). The implementation of ambitious solutions can result in a 26 Mt CO_2eq reduction in the cumulative GHG emissions of the concrete pavement network (58% reduction compared to the 2017-level emissions during the same analysis period——the purple bar chart). While the use of alternative binders is the major contributor to GHG reduction, the importance of cement plant CCS technology in decarbonizing concrete pavements is significant here (22% of total savings). However, carbon capture technologies are still in the process of technology development, and they are relatively costly compared to other more mature technologies. In addition, the effectiveness of carbon capture technologies greatly relies on energy carriers' carriers' environmental impacts. Therefore, it is important to choose the pathways with a specific implementation order that imposes a minimum cost to stakeholders.

Figure. 5. Cumulative GHG emissions of the US asphalt (**a**) and concrete (**b**) pavement network during the 2017—2050 period under the 2017-level and ambitious scenarios. The order of implementation is specified from the bottom attribute to the top in the stacked bar in the middle. CCU = carbon capture and utilization for aggregates production, CCS = carbon capture and storage for portland cement production, RAP = reclaimed asphalt pavement, WMA = warm mix asphalt, Trans & Elect = transport electrification and renewable electricity.

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Abatement cost of decarbonization solutions

With regards to the calculated abatement costs, ~~Figure 6~~Figure. 6 shows the cost of abatement for achieving a carbon-neutral US pavement network during the 2017—2050 analysis period. Generally, replacing virgin materials with locally available recycled contents (e.g., alternative binders and RAP) not only reduces the climate change impact of the pavement materials but also directly reduces the mixture cost. Alternative binder (concrete), RAP, binder intensity, and pavement design optimization savings comprise around 42% of total expected savings, which comes at a negative or negligible cost. Therefore, these solutions should be pursued aggressively in the short term. The adoption and promotion of performance-based specifications and the harmonization of materials standards used for pavement construction can accelerate the adoption of these solutions.

Fig~~ure~~. 6~~.~~ GHG abatement cost for the ambitious strategy over 34 years for the US pavement network. The *x*-axis quantifies GHG abatement potential for the strategy in CO_2eq. The cumulative GHG abatement across all strategies is shown at the end of the *x*-axis. CCU = carbon capture and utilization for aggregates production, CCS = carbon capture and storage for portland cement production, RAP = reclaimed asphalt pavement, WMA = warm mix asphalt, Trans & Elect = transport electrification and renewable electricity~~)~~

Discussion

Ultimately, achieving our GHG goals for the pavement network will require regionally specific policies which remove barriers and incentivize solutions to reducing GHG emissions. Moreover, to fulfill the carbon-neutral scenario, a comprehensive program of investments will be required. One challenge is the cost uncertainty associated with carbon capture pathways and the necessity of supplying the operational energy of these technologies with renewable electricity sources. This is particularly challenging because the cement plant CCS cost is among the highest of all industries (Naims 2016). In addition, the implication of CCU for synthetic aggregates necessitates a significant scale-up effort and the testing of the long-term performance of concrete pavements built with these aggregates. Hence, these embodied impact reduction strategies must receive support in the short term in much the same way that renewable energy technologies have been supported. Also, achieving carbon neutrality for pavement materials depends on the regional energy sources for electricity. While a key component of this will be policy support for large-scale grid decarbonization, another important strategy to explore would be incentivizing low-carbon microgrids for energy-intensive processes such as CCUS technologies. This would require subsidies and incentives to help alleviate the elevated upfront, short-term cost of energy technology installation.

The importance of changing traditional mixture components and intensifying the application of currently available solutions (e.g., alternative binders, RAP, and optimization) is strongly supported by this analysis. Expanded implementation of these solutions, however, requires policymakers at state DOTs and local authorities to revise the limitations in pavement mix design guidelines (NAPA 2018, Hand et al. 2021). While in this analysis the implementation of ambitious solutions increased linearly over time, swift code adoption and government incentives could accelerate the rate of implementation. This would lead to even more significant cumulative GHG savings will occur. The code revision and the implementation of cost-saving solutions can provide an opportunity to reduce emissions as quickly as possible. This strategy

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is vital as a small change in the final cost of products in the construction industry (owing to their low-profit margin) can cause a market shift that will eventually eliminate the expected environmental savings.

Conclusions

This study developed and applied a dynamic material flow analysis combined with a life cycle assessment to investigate the effectiveness of possible solutions to achieve carbon-neutral pavement mixtures by 2050 on a national scale. First, by applying a detailed pavement management system model, we estimated the timing and type of pavement treatment actions that would be expected to occur in the future. From this, the quantity of concrete and asphalt paving materials was estimated. Then, a regionalized LCA was applied using national databases. Three scenarios were evaluated using these coupled tools: (1) a business-as-usual (BAU) scenario where technology remains static at 2017 levels, (2) a projected scenario intended to represent the implementation of commitments by relevant industry groups and stated national goals, and (3) an ambitious scenario that either intensifies or accelerates the projected scenario strategies to achieve carbon- neutrality.

The results show that asphalt and concrete embodied impacts vary significantly from state to state, primarily attributed to variations in typical binder content and in the adoption of RAP and WMA solutions. Under the projected improvement scenario, a 38% and 14% embodied impact reduction is expected for concrete and asphalt pavement systems by 2050 (compared to BAU), respectively. The carbon-neutral goal can only be achieved if multiple solutions are applied simultaneously for reducing, avoiding, and neutralizing the embodied impact.

Under the ambitious improvement scenario (i.e., achieving carbon-neutral mixtures by 2050), carbon neutrality can highly depend on more aggressive electricity grid decarbonization and other energy forms for mixture manufacturing. An analysis of abatement cost shows that alternative binder materials and reduced binder intensity save both cost and embodied emissions and, therefore, should be prioritized in the short term. In fact, 42% of the GHG savings under the ambitious improvement scenario can come at a negative or almost no cost. Carbon capture solutions are essential to reaching carbon neutrality, but these technologies still need to be available at a lower cost. Short-term technology advancement through governmental investment or subsidies can help make carbon capture technologies more attractive for pavement materials stakeholders.

The scope of this analysis includes the carbon neutrality assessment from an embodied perspective. However, given the long service life of pavements, it is important to include and investigate appropriate solutions for reducing the total life cycle GHG emissions of pavement networks and achieving carbon neutrality comprehensively. A key consideration is how new technology solutions will impact pavement durability and performance. Further research should study these impacts and consider the life cycle carbon neutrality of infrastructure systems. Moreover, current innovative technologies used for mixture decarbonization have not been fully implemented in different locations. This study does not consider the efficiency associated with various renewable technologies to generate electricity and these may have adverse effects that are currently not considered within the system boundary. The uncertainty around the scaled industry and productivity of the system can provide more robust insight into the carbon neutrality of the ~~infrastructure's~~ infrastructure’s embodied impact.

Supplementary information

~~Data availability~~

~~Life cycle inventory data and details of pavement management system models in addition to the sources of the bill of materials are provided in the SI document and spreadsheet.~~

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Declarations

Conflict of interest
The authors have declare no competing interests to declare that are relevant to the content of this article..

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Table 2. Proposed solutions and level of adoptions under the 2017-level, projected and ambitious scenarios for decarbonizing US asphalt and concrete mixtures (NA = not applicable).

Solution	**2017 level**		**Projected scenario**		**Ambitious scenario (carbon neutral)**	
	Asphalt	Concrete	Asphalt	Concrete	Asphalt	Concrete
Pavement design optimization	Limited implementation	Limited implementation	Limited implementation	Limited implementation	21.7% geometry reduction* (Timm et al. 2014)	18.5% materials reduction* (Swei et al. 2014, Habert et al. 2020)
Alternative Binders	≈ 0%	13 – 23% (NRMCA 2019)	≈ 0%	40% ternary by 2050* (IEA 2018)	50% GTR by 2050* (Vahidi et al. 2014, Rahman et al. 2017)	50% ternary by 2050*
Transportation and Electricity grid	0.1 – 0.72 kg CO_2eq / kWh	0.1 – 0.72 kg CO_2eq / kWh	EIA Projection (2-38% reduction by 2050) (EIA 2020)	EIA Projection (2-38% reduction by 2050) (EIA 2020)	Renewable electricity and transport (0.02 kg CO_2eq / kWh) *	Renewable electricity and transport (0.02 kg CO_2eq / kWh) *
Carbon Capture and Utilization (CCU – Aggregates)	No implementation	No implementation	No implementation	No implementation	23% of the total aggregates*, ‡	6% of the total aggregates*, ‡
Reclaimed Asphalt Pavement/Asphalt Shingle	0 – 28% (NAPA 2018)	NA.	Maximum reported value (28%) (NAPA 2018)	NA.	Maximum incorporation reported in pilot studies (50%) (FHWA 2020)	NA.
Warm Mix Asphalt	0 – 100% (NAPA 2018)	NA	100% (NAPA 2018)	NA	100% (NAPA 2018)	NA.
Carbon Capture and Storage (CCS – Cement Plant)	NA.	Limited implementation	NA.	Global average by 2050 (25%)* (IEA 2018)	NA.	Fully adoption of best performance technology (65%)* (IEA 2018)
Binder Intensity	NA	12.5-17.0 kg/m³/MPa (NRMCA 2019)	NA.	Limited implementation	NA.	7.0 kg/m³/MPa* (Damineli et al. 2010)

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* The strategy was linearly implemented and scaled up on the newly treated roads by the indicated year, and then on all newly treated roads thereafter.

† After implementing all the solutions, the quantity of CCU synthetic aggregates was adjusted to achieve carbon-neutral mixtures.

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