Title

A Comprehensive Approach to Industrial Decarbonization Efforts within the Building Materials Sector

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A Comprehensive Approach to Industrial Decarbonization Efforts within the Building Materials Sector

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Abstract

The continued increase in global demand for construction materials is driving notable environmental burdens from their production, particularly greenhouse gas (GHG) emissions. In turn, there is growing interest from policy makers, industry sectors, and academics to derive emissions mitigation strategies that can support achieving the global goal of net-zero CO_2 emissions by mid-century. To meet these aims, collective and swift action is required to evaluate the efficacy, feasibility, and equity of GHG mitigation strategies. Yet, current methods do not consistently support systematic assessments leveraging open data sharing platforms, integration of potential co-benefits or unintended consequences of decarbonization efforts on other environmental impacts, the implications for neighboring communities near industrial facilities, or routes to train the next generation of engineers to adequately deal with these complexities.

This research aims to address these research gaps through the formulation of open-datasets and tools, a net-zero emissions roadmap that integrates technology readiness, cost, and strategy efficacy, a geographic-driven investigation of disproportionate impacts, and engineering curricula advancements. In the first stage and second of this research, the cement and concrete industries are examined. Namely, systematic, quantitative methods for addressing the role of varying parameters to alter cement and concrete GHG emissions are derived using openly accessible data. Building from these methods, routes to reaching net-zero GHG emissions are examined for the cement industry in California, where there is a mandate to mitigate these emissions by 2045. In the analysis of routes to net-zero emissions, the effects of decarbonization strategies on the creation of air pollutants, which are a local impact that burden neighboring communities (unlike climate change, which is a global impact), are also considered. Noting the imperative that decarbonization efforts do not impose disproportionate impacts on historically marginalized communities, this research expands to address the geographic distribution of construction building material production relative to various population groups in the United States and methods to integrate community needs are highlighted. Finally, a crucial long-term measure to advancing industrial decarbonization efforts is transforming engineering education to develop future engineers who have a deep understanding of environmental sustainability with an equally strong emphasis on social justice and community engagement. And as such, this work establishes a pilot study course and conducts research on the influence of pedagogical approaches to better preparing engineering students to tackle such complex challenges. Together, these findings will help practitioners derive new methods that can be leveraged to support efforts towards a rapid and equitable industrial decarbonization, driven by new generations of technically competent and socially conscious engineers.

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Table of Contents

1. Introduction

1.1 Motivation

The growing demands for construction and building materials has driven notable environmental impacts from these materials production industries, which in turn have placed them under scrutiny. A key example of this pattern applies to cement and concrete. As the most consumed material on Earth after water, concrete plays a significance role in supporting buildings and infrastructure across different regions.[1] Concrete is composed of Portland cement (referred to herein interchangeably with "cement" unless otherwise noted), water, and aggregates, as well as additives as needed. Yet, due to factors such as the risk averse nature of the construction industry, capital investments needed to change production technologies, and the need to establish long-term performance and viability for alternative resources, society has remained tethered to traditional and emissions-intensive cement production methods[2]. It is the substantial demand for these materials along with cement production process emissions that drive its environmental footprint, contributing especially to global greenhouse gas (GHG) emissions, water demand, and particulate matter emissions, among other impacts.[3] While not the primary focus of this work, an initial exploration will be shown addressing the production of other building materials such as steel, which is responsible for 7% of global anthropogenic CO_2 emissions,[4] and more than half of it is used in construction and buildings.[5]

The Intergovernmental Panel on Climate Change's (IPCC) ambitious target to achieve net-zero CO_2 emissions by mid-century[6] underscores the need for rigorous, systematic methods to assess and mitigate the GHG emissions cement and concrete. In the United States (US), federal initiatives, such as executive order 14057, have prioritized low-carbon construction materials.[7] In California, recent legislative advancements, including the forward-thinking Senate Bill (SB) 596,[8] aim to propel decarbonization efforts in the cement industry by setting ambitious climate goals. While numerous reports from academic,[9–11] non-governmental,[12–14] and industry groups[15–17] have analyzed the substantial

GHG emissions associated building materials decarbonization, none of these analyses present the influences to other environmental impact categories and few use open data modeling methods. As a result, the ability to prioritize strategies that lead to co-benefits in other impacts (as opposed to unintended consequences) and the ability to adapt strategies to meet localized resource availability and community needs are limited.

Although building materials production has prompted environmental policy actions and industrial technology adoption, it is imperative to also consider their broader implications. Unlike the recent growth in academic research and industry investment in cement decarbonization efforts, which as a result have been examined well from a technical perspective[18], the social implications of these efforts have been understudied. Although this exclusion is often to avoid a layer of complexity, it is critical to acknowledge and unveil impacts beyond global climate change. Integration of fields such as Environmental Justice (EJ) remains a crucial concern, as historically marginalized communities often bear a disproportionate burden of industrial activity.[19–21] Thus, research in advancement towards sustainability must be assessed not only for its environmental benefits but also for its social equity impacts.

These topics align with broader educational and professional imperatives, such as those by the Accreditation Board for Engineering and Technology's (ABET)[22] and the National Science Foundation (NSF),[23] where civil and environmental engineers are increasingly expected to embed sustainability and service into their core values. Service-learning as a pedagogy can provide future engineers an opportunity to deepen disciplinary learning (e.g., sustainability topics) while also developing community engagement principles (through service). Such integration not only addresses environmental imperatives but also responds to the critical need for diversity, equity, inclusion, and retention within the engineering discipline.[24,25]

In this research, innovative strategies to propel decarbonization in the production of building materials are explored, particularly with an eye on reducing overall environmental impacts while simultaneously enhancing societal equity. Initial work is focused on investigation of the cement and concrete sector, applying a rigorous quantitative approach to model the environmental impacts of cradle-to-gate production of a wide range of concrete mixture proportions, energy resources used, and processing methods. This research creates a foundation for examining routes to net-zero GHG emissions for cement and concrete production, which is applied to the cement industry in California. Insights are gleaned into potential co-benefits and unintended consequences to other environmental impacts. The scope of work is then broadened to begin examining potential disparities linked to geographic location that influence the manufacture of building materials. Considering the complexity of these multi-faceted topics, a pilot engineering course is then designed to weave environmental justice and community engagement into the fabric of the curriculum, thus preparing future engineers to think and act with an inclusive and sustainable ethos. Overall, this scholarly endeavor is a comprehensive, interdisciplinary effort to provide both the current industry and the next generation of engineers with an extensive perspective and the requisite tools to drive sustainable materials production and use.

1.2 Research Objectives

In this work, methods are developed to quantify the environmental impacts and explore social considerations associated with cement and other construction and building materials sectors. These concepts are then applied to develop a new civil and environmental engineering Service-Learning course, designed to equip engineering students with the knowledge and skills necessary to innovate sustainably and uphold social justice principles. The chapters are structured to provide a multifaceted analysis that goes beyond technical assessment to investigate broader societal implications (**Figure 1.1**).

Chapter 2 introduces OpenConcrete, an open data environmental impact assessment tool for concrete production. This chapter details the development of the tool, from its conceptual framework to its practical applications, while reflecting data collection methods and modeling limitations, as well as emphasizing its adaptability across various regions, scenarios, and materials. A case study spanning all 50 U.S. states demonstrates OpenConcrete's utility in discerning primary environmental impact drivers.

Chapter 3 expands from this systematic, quantitative approach to addressing the environmental impacts from cement and concrete to examine of GHG mitigation strategies within the cement industry. A technology roadmap to meet decarbonization goals is developed based on California's groundbreaking legislation (SB 596[8]) as a case study (namely, reaching net zero GHG emissions for cement used in California by 2045). As multiple low-carbon technology measures are anticipated to be adopted concurrently, this work analyzes both the individual and collective efficacy of these strategies. This work also considers concomitant environmental impacts, the potential effects of costs, and the role of technology readiness level on implementation pathways. Findings reveal interlinked challenges and opportunities.

Chapter 4 integrates the complexities tied to geographic placement of industrial materials production facilities and their impacts on neighboring communities. The disproportionate environmental impacts on historically marginalized communities from the industrial production has been examined by others, but in this work, research extracts the effects of producing construction and building materials. Further, methods for integrating various impacts (beyond individual environmental emissions) are presented. By applying a novel methodological approach at various spatial scales, the chapter offers a critical analysis with an environmental justice perspective. This work provides a nuanced understanding of how certain demographic groups are disproportionately impacted by the physical locations of building materials production facilities.

Chapter 5 presents an assessment of the integration of sustainability principles into engineering education through a new Service-Learning course taught at the University of California, Davis.[26] It reflects an analysis of the impact of this pedagogical shift on student perceptions, capturing both quantitative and qualitative changes that highlight the transformative potential of embedding sustainability and community engagement within engineering curricula.

Collectively, these chapters advance a holistic understanding of the intricate relationships between industrial practices, social equity, and educational strategies. The dissertation weaves together quantitative data and qualitative insights, drawing a comprehensive picture that not only informs but also challenges current paradigms, advocating for an inclusive and sustainable future.

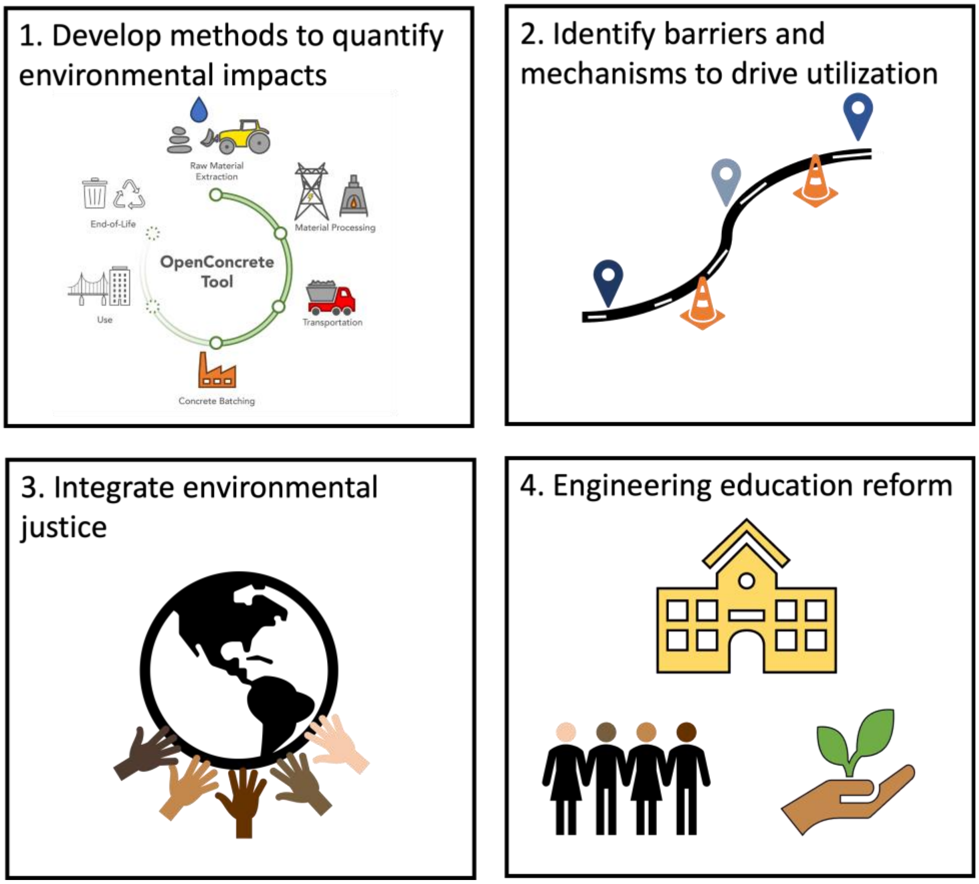

Figure 1.1 Diagram of research objectives for dissertation.

2 OpenConcrete: a tool for estimating the environmental impacts from concrete production

Publication

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Abstract

As the increasing global consumption of concrete drives notable environmental burdens from its production, particularly greenhouse gas (GHG) emissions, interest in mitigation efforts is increasing. Yet current environmental impact quantification tools rely on user decision-making to select data for each concrete constituent, have inconsistent scopes and system boundaries, and often utilize third-party life cycle inventories. These factors limit customization or tracking of data and hinder the ability to draw robust comparisons among concrete mixtures to mitigate its environmental burdens. To address these issues, we introduce a cohesive, unified dataset of material, energy, and emission inventories to quantify the environmental impacts of concrete. In this work, we detail the synthesis of this open dataset and create an environmental impact assessment tool using this data. Models can be customized to be region specific, expanded to varying concrete mixtures, and support data visualization throughout each production stage. We perform a scenario analysis of impacts to produce a representative concrete mixture across the United States, with results ranging from 189 kg CO2-eq/m3 of concrete (California) to 266 kg CO2-eq/m3 of concrete (West Virginia). The largest driver of GHG, nitrogen oxide, sulfur oxide, and volatile organic compound emissions as well as energy demand is cement production, but aggregate production is the largest driver of water consumption and particulate matter smaller than 2.5 microns (PM2.5) emissions.

2.1 Introduction

After water, concrete is the most consumed material worldwide[1], and demand for concrete is continuing to grow globally in both developed and less-developed regions[27]. Concrete is conventionally composed of Portland cement (a hydraulic binder), water, and aggregates. Other common cement-based materials include mortar and grout. The high level of cement-based material consumption drives environmental impacts from this class of materials, with their production leading to an estimated 8%–9% of global anthropogenic CO_2 emissions[1,28,29], 1%–2% of total global water withdrawals[30], and over 6% of emissions of particulate matter smaller than 2.5 microns ($PM_{2.5}$)[31]. The greenhouse gas (GHG) emissions, in particular, pose a significant challenge to the Intergovernmental Panel on Climate Change (IPCC) goal of reaching net zero CO_2 emissions by 2050 to control climate change[6].

Further, these notable GHG emissions from the cement and concrete industries have spurred a large amount of research (e.g., work summarized by Gursel *et al* 2014[32], Miller *et al* 2021[33], and Habert *et al* 2020[34]), industry roadmaps (e.g., the Global Cement and Concrete Association[17], the Portland Cement Association (PCA)[15], and the California Nevada Cement Association[16]), and now regulatory efforts (such as a recent policy passed in California[8]) to curb emissions. To mitigate these emissions, it is imperative to have systematic, quantitative accounting methods that can capture the environmental impacts, are available for public review, and can be easily audited. Yet, inconsistencies in the literature hinder robust comparisons. A brief survey of the literature assessing environmental impacts of concrete is summarized in the Appendix A. When looking at the top 25 most cited papers published from 2015 to 2019: all report GHG emissions; 32% report acidification and eutrophication; 24% report particulate matter (PM) emissions (e.g., $PM_{2.5}$, particulate matter smaller than 10 microns (PM_{10}), and/or other particulate matter); 16% report nitrogen oxides (NO_X) or nitrogen dioxide (NO_2); and 16% report a measure of sulfur oxides (SO_X) or sulfur dioxide (SO_2)[35–58]. Beyond differences in environmental impact categories considered, varying methods and scopes of assessment are applied. In industry, Environmental Product Declarations (EPDs) are becoming prevalent sources for examining environmental impacts (e.g., the repository managed by the National Ready Mixed Concrete Association (NRMCA)[59]). Yet, similar to the academic literature, comparisons across EPDs with the goal of mitigating environmental burdens can be difficult as they were not originally developed for this purpose and have known weaknesses in this regard. These challenges include data quality issues, inconsistencies in information supplied, and varied application of cut-off rules[60].

While GHG emissions have been a focus within the literature, criteria air pollutants (e.g., NO_X, SO_X, $PM_{2.5}$, PM_{10}, volatile organic compounds (VOC), and carbon monoxide (CO)), heavy metals, and water consumption are of critical importance when addressing environmental and health concerns. This is particularly true if GHG mitigation methods could increase these other burdens. Reductions in air pollutant emissions from fuel resources are often seen in tandem with mitigation of GHG emissions[61]. However, in concrete production, environmental impacts can come from varied sources. For example, PM emissions occur throughout the production and supply chains, including from: transportation, raw material preparation (e.g., quarrying, crushing, grinding), clinker production, and concrete batching[62]. Likewise, heavy metal emissions (e.g., lead (Pb)) in concrete production come from both raw materials and the fuels used[33]. Water demands occur throughout the supply chain, including water as a constituent in concrete and water use during mineral extraction, material manufacturing, and construction[30,63,64].

Life cycle assessment (LCA) methods allow for quantification of environmental impacts from products, such as concrete. Multiple tools capable of performing LCAs of concrete mixtures currently exist, 15 of which we reviewed in a prior study[65]. The Appendix A (table S2.2) provides a synopsis and further details of each tool. Among these tools, seven focus on construction projects and buildings with limited customization for different concrete permutations, seven require purchasing of a license (thus limiting public review and auditing), and three are dedicated pavement tools. Only two tools (GreenConcrete[66] and Global Cement and Concrete Association (GCCA) EPD tool[67]) are dedicated concrete tools.

Here, we introduce a unified, environmental impact assessment tool for concrete and other cement-based materials (herein referred to jointly as concrete) production called OpenConcrete. For this tool we have developed calculations in Excel, and we synthesize herein, for the first time, structured open data for determining the environmental impacts of concrete. This paper presents the OpenConcrete tool's scope of analysis, data sources, input assumptions, and modeling methods used to estimate environmental impacts of concrete. To demonstrate how OpenConcrete is adaptable to different regions, scenarios, and material mixtures, a case study examining the production of a representative concrete mixture in each of the 50 states within the United States (US) is shown. The case study results are also used to examine primary drivers of different environmental impact categories. A sensitivity analysis investigating OpenConcrete's input parameter's influence on the 11 environmental impact categories modeled is provided.

2.2 Methods – development of OpenConcrete

OpenConcrete quantifies flows that contribute to emissions of GHGs, NO_X , SO_X , VOCs, CO, PM_{10}, PM less than 2.5 microns ($PM_{2.5}$), and Pb, as well as direct energy demand, water consumption, and water withdrawals. (Note: herein, when both water consumption and withdrawals are discussed concurrently, they are referred to as water demand). The scope includes impacts associated with raw material acquisition through concrete production (i.e., a cradle-to-gate assessment), see Figure 2.1 OpenConcrete addresses both process-derived (i.e., PM emissions from raw material resources as they are ground or limestone decarbonation emissions) and energy-derived (i.e., emissions from the production and/or use of energy resources, including transportation-related emissions) flows. For this analysis, emissions of three key GHGs are quantified: CO_2, CH_4, and N_2O. These emissions are examined concurrently using 100a global warming potentials from the IPCC[68]. Modeling assumptions and data sources for each constituent and production process considered are discussed below.

Cement production. Energy-derived emissions for cement production are predominantly from kiln thermal energy fuel requirements and electricity demands. Due to high variability in material resource acquisition and the propensity for cement plants to be placed at quarries that produce the majority of the natural resources required[63], transportation of raw materials to the kiln is considered negligible.

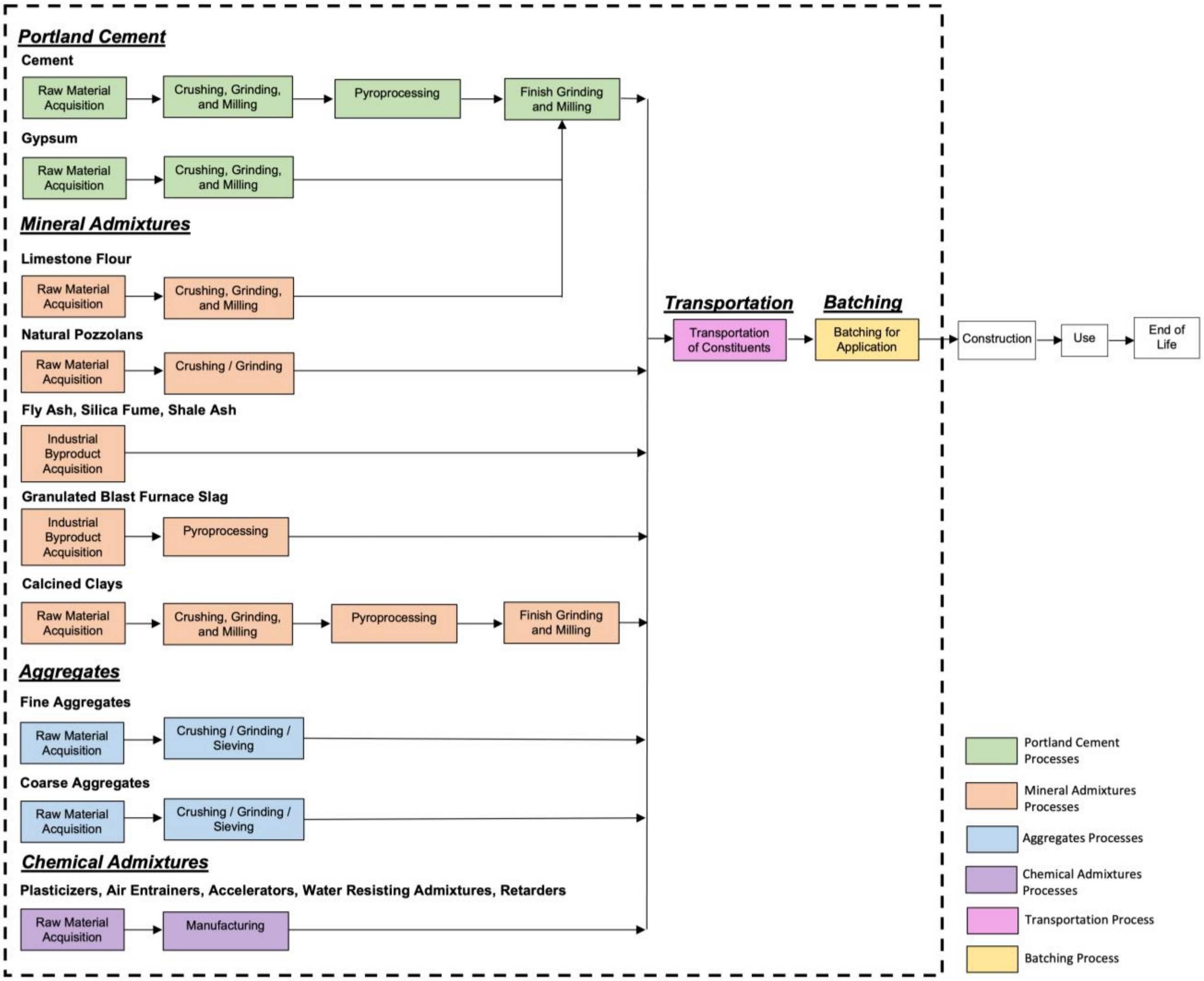

Figure 2.1. A simplified process flow diagram to show the scope of the assessment.

In this tool, kiln efficiency by type is based on data from the Getting the Numbers Right (GNR)[69] as part of the Cement Sustainability Initiative (CSI), using values reported for the world average in the year 2016 (note: data used are from the GNR when it was under management by the World Business Council for Sustainable Development; this project is now managed by the GCCA). The kiln efficiency for each cement producing state is from the PCA[63]. For states that do not produce cement (based on United States Environmental Protection Agency (USEPA) data)[70], but use cement, the US average value for kiln efficiency and electricity mix is used. The electricity requirements, by kiln type, are based on data from the PCA[63].

Process-derived emissions for cement production include both calcination emissions and emissions of air pollutants from the processing of raw material and limestone decarbonation. The calcination emissions included are based on stoichiometry, assuming 65% lime content in clinker and 95% clinker in cement, with the remaining 5% of cement modeled as gypsum. The tool's default setting is type 1 Portland cement; however, users can select different types of cements from a drop-down menu (e.g., LC3, Portland limestone cements) in the tool or manually specify proportions of clinker and gypsum (see Appendix A). The process-derived air emissions are calculated as cement manufacturing total emissions minus energy-derived emissions using data from the USEPA[62], the United States Geological Survey (USGS)[71], and GNR[69]. Water demands are based on median data from distributions by process reported in Miller *et al* 2018[30].

Mineral admixtures. This tool incorporates several mineral additives, namely: limestone filler, gypsum, natural pozzolans, interground limestone, fly ash, blast furnace slag, calcined clay, silica fume, and shale ash. The energy demand for limestone filler, a constituent added during concrete batching, is based on data from the National Renewable Energy Laboratory (NREL)[72]. The energy demand is adapted to reflect electricity use at each processing stage. This adaptation is made using lower heating value (LHV) factors from the greenhouse gases, Regulated Emissions and Energy use in Technologies (GREET) model[73]. Process-based air emissions for the limestone filler are based on data from the USEPA[74] and, as with cement, the water demand is from Miller *et al* 2018[30]. For this work, the energy-derived and process-based emissions for gypsum and natural pozzolans are modeled as the same as those for limestone filler. The water demands are based on median values for the production of each of these materials as reported by Miller *et al* 2018[30].

Interground limestone, which is limestone ground in during cement manufacturing, is extended from the limestone filler model by using the same energy required for limestone filler with an additional electricity demand for grinding. The additional grinding electricity is approximated at the lower end of clinker electricity demand (30% of the 110 kwh/t reported by Jankovic *et al* 2004[75], which is on the lower end of energy reported by Ghiasvand *et al* 2015[76]). The lower end is selected because limestone is softer than clinker; but it must be noted that studies have shown that intergrinding, especially in a laboratory setting, could lead to higher processing times to achieve the desired gradation. The model for interground limestone reflects the same process-based PM emissions and water demands as is modeled for limestone filler.

Two primary industrial byproduct mineral admixtures are modeled: fly ash and blast furnace slag. The fly ash is modeled as not requiring energy inputs, following an assumption published by the USEPA[77]. While the degree to which it is done varies, the transport of fly ash sometimes includes the use of water and is incorporated based on data from Miller *et al* 2018[30]. For granulated blast furnace slag, the energy demand for the production of reactive slag is based on an industry EPD[78]. The water demand for this admixture is based on the same report[78]. For the purposes of this work, shale ash and silica fume are incorporated as additional mineral admixtures; they are modeled as having the same impacts as fly ash based on a modeling suggestion for silica fume from the PCA[63].

Finally, the thermal energy and electricity demands to produce calcined clay as a mineral admixture are considered, based on Miller *et al* 2018[33]. The air pollutant emissions for calcined clay production are based on those reported for cement (accounting for differences in quantity of raw material needed and excluding calcination emissions). Water demand is based on modeling inputs from Miller *et al* 2018[30].

Aggregates. For fine and coarse aggregates, energy demand is based on a report from the PCA[63], with slightly lower energy demands being reported for fine aggregates. The process-based air emissions are from the USEPA[74] and water demand is from Miller *et al* 2018[30]. Process-based air emissions capture factors such as PM from practices including crushing, grinding, and sieving. Water demand incorporates process-related water consumption, such as that for dust suppression.

Chemical admixtures. The energy demand and water demand for six classes of chemical admixture are modeled in this work based on EPDs from the European Federation of Concrete Admixtures Associations Ltd: (a) plasticizers and superplasticizers[79]; (b) air entrainers[80]; (c) hardening accelerators[81]; (d) set accelerators[82]; (e) water resisting admixtures[83]; and (f) retarders[84]. Process-based emissions are not modeled for these admixtures.

Batching. Additional energy-derived and process-derived impacts are considered for the batching of concrete constituents listed above. The energy demand is based on the approximate electricity consumption reported by the Lawrence Berkeley National Lab[85]. Regardless of other inputs selected by the user, this electricity demand remains a constant per unit volume of concrete. Process-based emissions for batching, as well as aggregate transfer, cement unloading, SCM unloading, hopper loading, and mixture loading are based on data from the USEPA[86]. Based on available data, uncontrolled air emissions are modeled for batching, aggregate transfer, and hopper loading; controlled emissions are modeled for SCM unloading. Controlled emissions for cement unloading and mixture loading are modeled based on estimates using a fraction of total emissions reported by the USEPA to reflect emissions controls for similar processes[86]. Water demands are from Miller *et al* 2018[30]; including the energy-derived emissions and the water as a constituent (modeled as the quantity of water required for the batch itself). The water used as a concrete constituent is modeled as not requiring any energy to get to the batching location. While this is an underestimate of energy demand in most cases, the variability in energy demand and associated emissions with getting the water to the concrete manufacturing site is considered too great to include.

Transportation. OpenConcrete contains models for three modes of transportation: truck, rail, and ship. For transportation by truck, energy demand is based on the average value reported by Michaelis *et al* 1995[87]. These data sets can be updated by the user to model region specific fuel efficiency, different transportation modes, and potential future changes in transportation modes; the user can directly change the data within the OpenConcrete excel tool (see Appendix A). The energy demand for the remaining transportation modes and the air emissions for all three modes are based on median values from distributions fit to data from NREL and the European Commission[88,89]. For these distributions, a single point is used if there is only one datum, a uniform distribution is used if there are two data, a triangular distribution is used if there are three data, and a lognormal distribution is used for four or more data. Water demands are based on medians of the distributions reported in Miller *et al* 2018[30] for each of these transportation modes. It should be noted, no process-based emissions are considered in the transportation models; all energy demand, air emissions, and water demands are a function of energy production and use in transport.

Thermal energy. The use of thermal energy, predominantly in the cement kilns, is a large contributor to total energy demand, air pollutant emissions, and energy-related water demand. The GHG and air pollutant emissions associated with this energy use, by resource type, are quantified using the median values of distributions for GHG emissions and air pollutant emissions from Miller *et al* 2020[31]. Water demand, by thermal energy resource, are median values from estimates and modeling assumptions by Miller *et al* 2018[30]. The default thermal energy mix modeled in the tool is based on national statistics reported by the USGS[71]; however, this can be updated as desired by the end-user.

Electricity. As with thermal energy, the resources used in the production of electricity contribute to GHG emissions, air pollutant emissions, and water demands. The GHG emissions, by energy resources, are taken as the median values from distributions presented by Miller *et al* 2020[31]. Air pollutant emissions, by energy resource, are based on the same estimates and modeling assumptions discussed in Miller *et al* 2020[31], again reflecting median values from distributions. Water demands are based on the median values of distributions presented in Miller *et al* 2018[30]. The tool allows manual user-input for electricity mix or selection from a drop-down menu of US state electricity grids, which are based on 2018 USEPA data[90], such that a different electricity mix can be selected for every constituent.

Impacts by constituent and process. OpenConcrete allows users to manually enter concrete mixtures, based on concrete constituent amounts (in kg) per volume of concrete (in m^3). To perform an assessment for concrete mixtures with varying constituents, an intermediary step in which all flows for any given constituent or process that could be used in the mixtures (e.g., aggregates, batching) is tabulated on a separate sheet within the tool. These constituents and processes can then be used to determine GHG emissions, air pollutant emissions, energy demand, and water demand from production of concrete. It should be noted that energy demand is modeled based on assuming the amount of MJ required for cradle-to-gate production. It does not reflect differences in energy resources, or differences between electricity and thermal energy, nor does it capture differences between high temperature processes and low temperature processes (beyond differences in their required MJ).

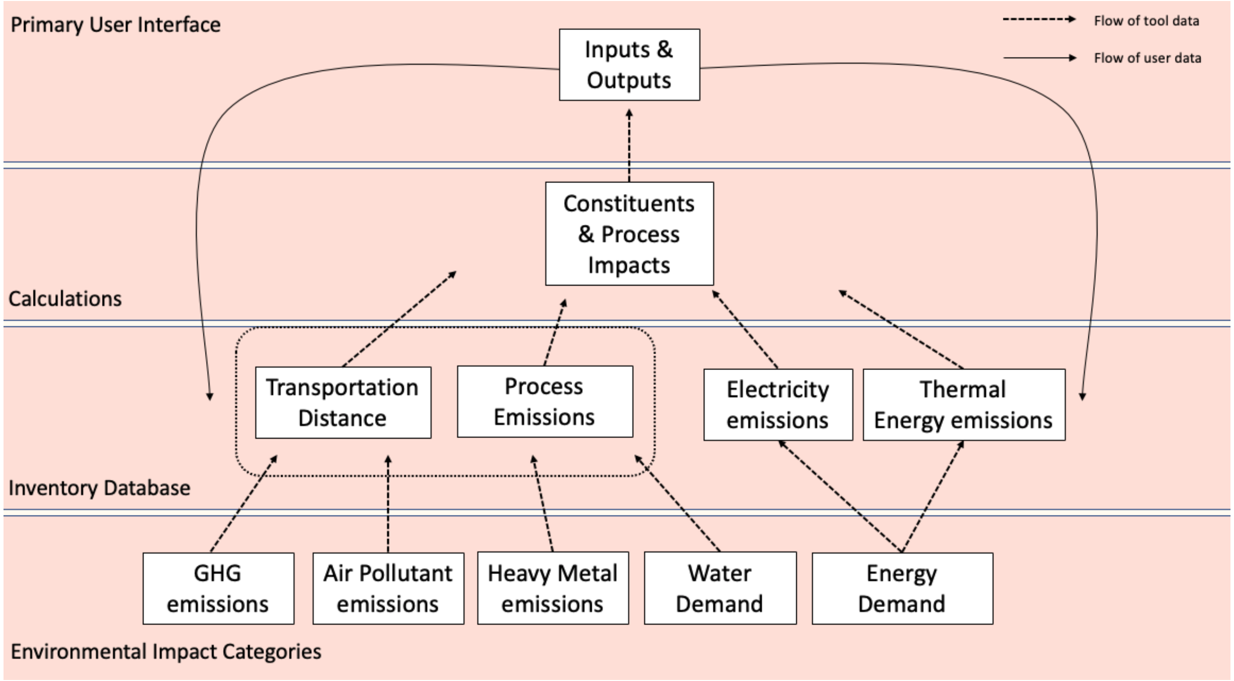

Figure 2.2. Flow diagram of tool and user data through the OpenConcrete tool.

Functional units. The functional unit of the outputs from this tool is per 1 m^3 of concrete. Impacts for each constituent (e.g., cement, fly ash, aggregates) are calculated per 1 kg of that material. Batching has a functional unit of 1 m^3 of concrete. Transportation impacts are measured per 1 metric ton-km traveled. For mixtures of cement-based materials, the functional unit is 1 m^3 of cement-based material.

Data flow. OpenConcrete accepts user-input data to output environmental impact results (see tool data flow diagram in Figure 2.2). The user inputs data in the 'inputs and outputs' sheet, which is then coupled with data in the inventory database to perform calculations in the 'constituent and process impacts' sheet, with final outputs reported in the 'inputs and outputs' sheet. All sheets within the tool are detailed in apendix A. The 'process emissions' box in Figure 2.2 includes the environmental impacts from the previously discussed sections: cement production, mineral admixtures, aggregate, chemical admixtures, batching, and transportation.

2.3 Demonstration Results

2.3.1 U.S. National Comparison of GHG Emissions

To demonstrate the capabilities of OpenConcrete, an analysis to determine the environmental impacts of concrete production in each state within the US is presented here. To do this, the electricity grids (from[90]) and cement kiln efficiencies (from[91]) of each state are input into the tool. As mentioned in Section 2, the US averages for electricity grid and cement kiln efficiencies are used for states that do not produce cement. Although this tool can output multiple environmental impacts, this analysis focuses on GHG emissions (kg CO_2-eq/m^3 of concrete). The results for the other environmental impacts can be found in appendix A (Figure S2.1). A US national benchmark concrete mixture from the NRMCA (Table 2.1), is used to compare the environmental impacts of concrete production across the US.

Table 2.1. National benchmark concrete mixture from NRMCA[92] used to perform analyses.

Constituent Materials, kg/m^3 concrete								
Portland Cement	Fly Ash	Slag	Mixing Water	Coarse Aggregate	Fine Aggregate	Air Entraining Admixture	Plasticizer & Superplasticizer	Set Accelerator
210	37	10	181	996	861	0.028	0.085	0.709

The CO_2-eq intensity to produce concrete in each state ranges from 189 to 266 kg CO_2-eq/m^3 concrete, with California as the lowest and West Virginia as the highest (Figure 2.3). The variation in each state's electricity mix and kiln efficiency drives the range of CO_2-eq intensity of concrete production shown in Figure 2.3. This variability highlights the influence of regionally specific inputs when performing environmental accounting. This analysis is incorporated in OpenConcrete by allowing the user to select a state where concrete is produced.

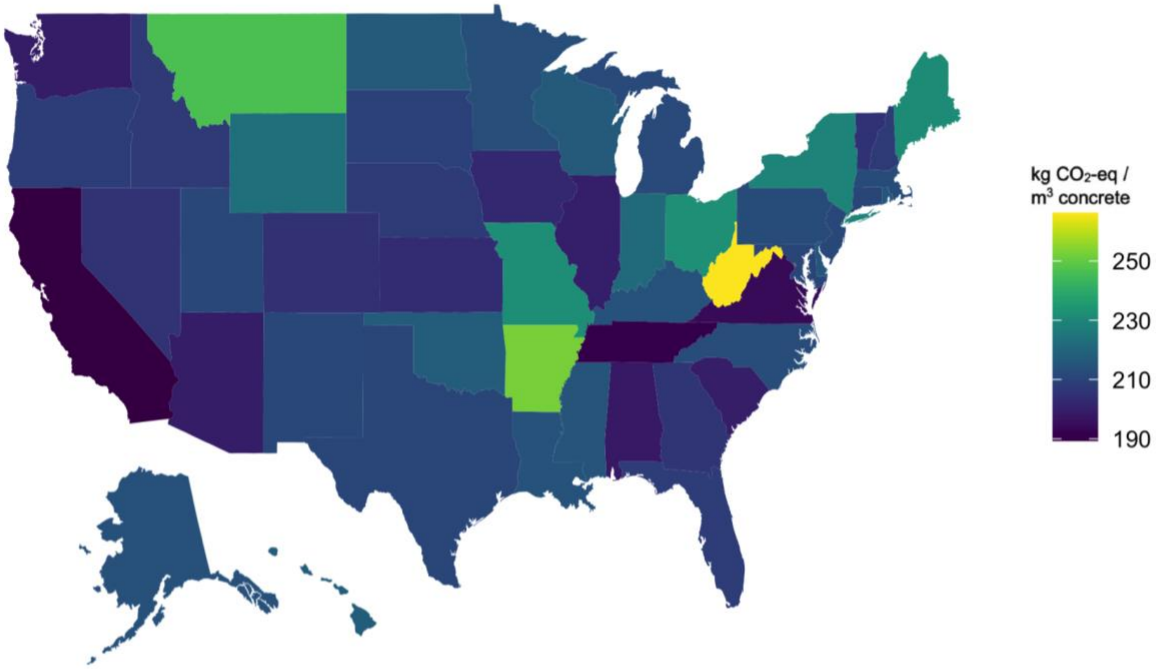

Figure 2.3. Map with the environmental impact (kg CO_2-eq/m^3 concrete) per state.

2.3.2 Environmental Emissions per Constituent

Using the mixture from Table 2.1 in OpenConcrete, we are able investigate the contributions of various concrete constituents to the different environmental impact categories (Figure 2.4). For this chart, the US average electricity mix, and kiln efficiencies are applied. For simplicity and to highlight key impact categories, Figure 2.4 shows a subset of 7 of the 11 impact categories (all categories shown in Appendix A Figure S2.2). For this concrete mixture, the GHG, VOC, NO_X, and SO_X emissions, and energy demand are largely driven by the cement content. However, $PM_{2.5}$ emissions are driven by aggregate content. Aggregate production results in high amounts of $PM_{2.5}$ emissions largely due to the dust released during quarrying and preparation operations. Water consumption is also driven by aggregate content rather than cement content; significantly, while batching water is discussed as a key area to mitigate resource consumption in concrete, it contributes only about 10% of water consumption. For a cradle-to-gate analysis of aggregates, water is used during quarrying (as dust suppression) and for the energy used during the extraction and refinement of raw materials.

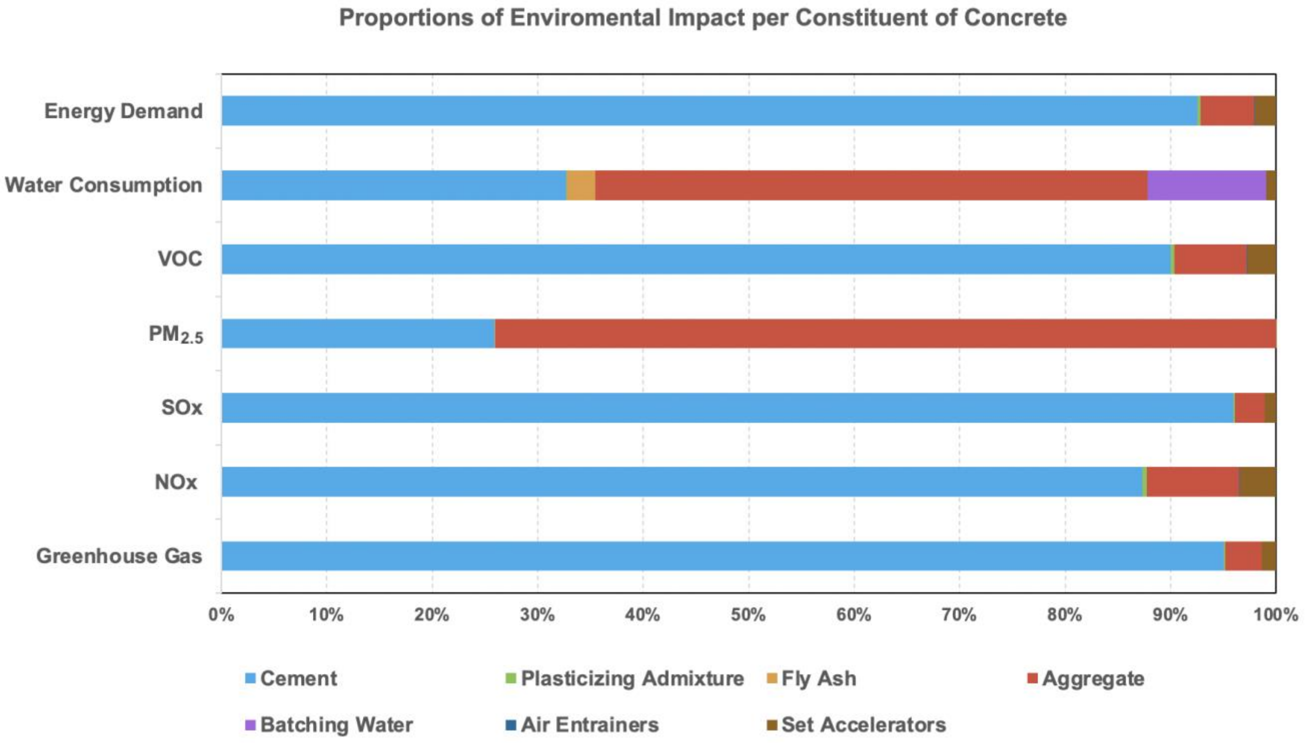

Figure 2.4. Proportions of cradle-to-gate environmental impacts based on contributions from different concrete constituents. Note: some constituents within an impact category (e.g., impacts from batching water in total NO_X emissions) are not visible in the figure due to their low proportional contribution.

2.3.3. Sensitivity Analysis

A sensitivity analysis was performed with OpenConcrete to exemplify the effect of input parameters on the 11 environmental impacts modeled. The sensitivity analysis was conducted by independently varying three inputs (a) electricity grid (b) kiln thermal energy (i.e., the fuel mix in cement kilns) and (c) cement kiln efficiency. Scenarios were selected to result in either the greatest reductions or increases in GHG emissions based on resources already used and potentially scalable using current technologies (e.g., coal has the highest GHG intensity for electricity production, wind gas the lowest GHG intensity for electricity, solid waste has the highest GHG intensity for thermal energy production, natural gas has the lowest GHG intensity for thermal energy, etc.), provided in Table 2.2. The baseline to which these scenarios are compared is the NRMCA concrete mixture (from Table 2.1) produced in California. The results in Figure 2.5 show the sensitivity of each environmental impact category to the inputs from Table 2.2 to create 1 m^3 of concrete, presented here as a percent (%) increase or decrease in impact relative to the baseline.

Table 2.2. High and low scenarios for each parameter analyzed in sensitivity analysis.

	Electricity Mix	**Thermal Energy**	**Kiln Efficiency**
Higher GHG emissions scenario (High)	100% Coal	100% Solid Waste	100% Wet
Lower GHG emissions scenario (Low)	100% Wind	100% Natural Gas	100% Preheater/Precalciner

While the scenarios selected had notable, and anticipated shifts in GHG emissions, complementary reductions or increases were not consistently noted in the other environmental impact categories. The VOC emissions were the most sensitive to change, particularly for shifts in thermal energy mix, which resulted -64% to 369% difference from the baseline. Pb emissions were among the least sensitive to the scenarios examined, with negligible variation based on a change in electricity mix and -0.012% to 0.44% change with altered kiln efficiency. In most cases, the environmental impacts increase in the high GHG emissions scenarios and decrease in the low GHG emissions scenarios. However, in the following cases the high scenario GHG emissions results in a decrease in impact: the change in thermal energy mix for NO_X and SO_X emissions, and the electricity mix for CO emissions and water consumption. The thermal energy for CO is the only case that results in an increase in impact for the low scenario. Notably, because the energy demand impact does not change with adjustments to electricity mix or thermal energy mix, there is no sensitivity to their alteration (Figure 2.5k). It should also be noted that the minimal shifts in the low kiln efficiency scenarios are due to the baseline scenario taking place in California, where 85% of the cement plants have already utilize preheater/precalciners systems (note: this is based on data from the PCA[91]). Greater reductions for the low kiln efficiency scenario would be seen if the baseline scenario was in a region with lower cement kiln efficiency (e.g., West Virginia, where 0% of cement plants use preheater/precalciners [91]).

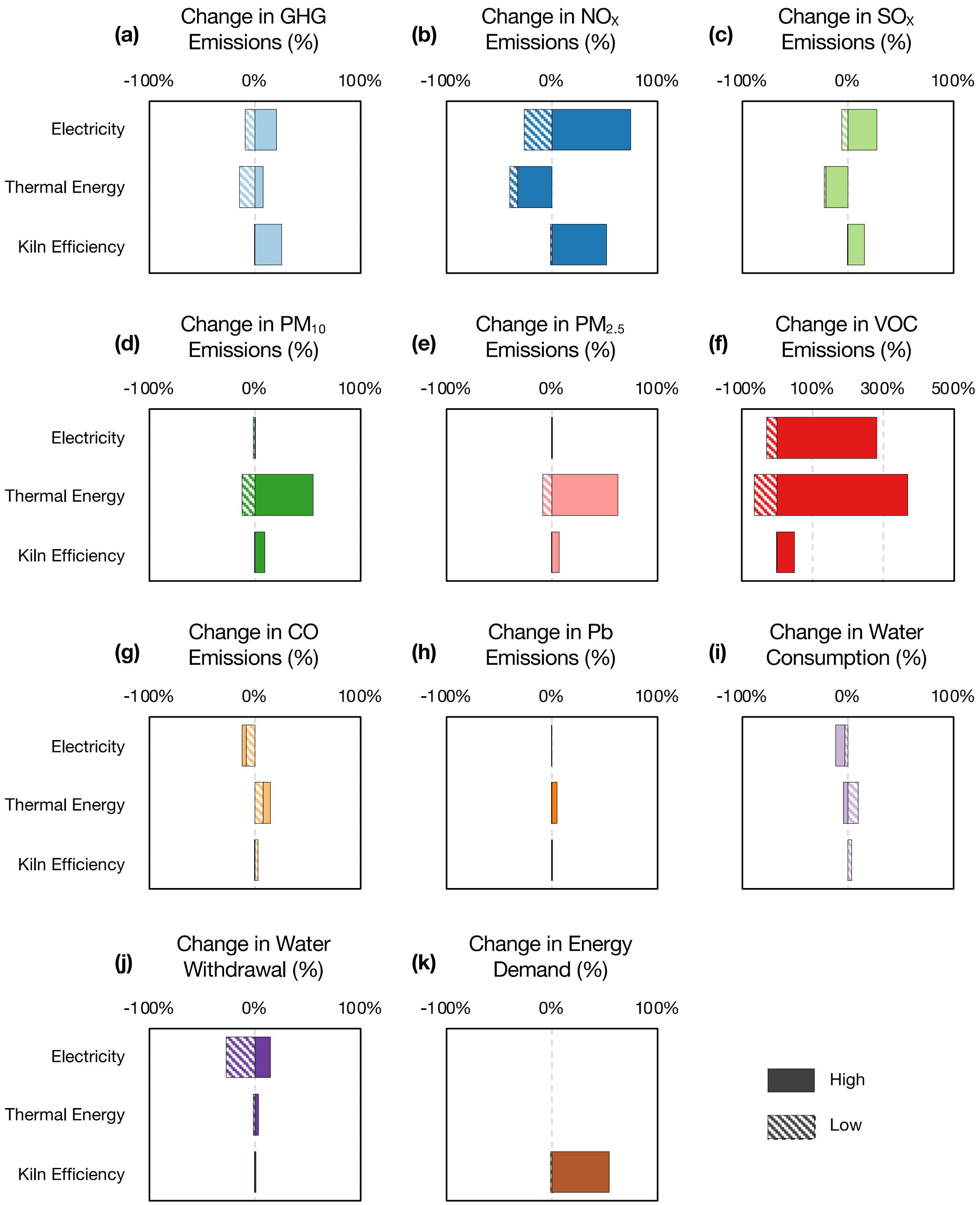

Figure 2.5. Results of a sensitivity analysis considering scenarios with a change in each of three parameters: (i) electricity; (ii) thermal energy; or (iii) kiln efficiency, selected based on anticipated increases in GHG emissions (high) or decreases in GHG emissions (low). Percent change in impacts from the production of the NRMCA concrete mixture in California are shown for (a) GHG emissions, (b) NO_X emissions; (c) SO_X emissions; (d) PM_{10} emissions; (e) $PM_{2.5}$ emissions; (f) VOC emissions; (g) CO emissions; (h) Pb emissions; (i) water consumption; (i) water withdrawal; and (k) energy demand. Note: All figures are to the same scale except for Figure 2.5f.

2.4 Limitations

OpenConcrete has several limitations that should be considered in its implementation. It does not include regional thermal energy fuel mixtures for different states in the US within the data set, as these data were not readily available.; however, users can update the thermal energy mix with their own inputs. The only environmental impacts considered for chemical admixtures (e.g., plasticizers, air entrainers) are from their energy demands, so additional burdens associated with chemical- or other process-derived impacts are not captured in this tool. Models for CO and Pb emissions are limited to cement kilning and transportation, based on available models.[62,93] NO_X emissions are only considered from energy demand, including transportation. This tool focuses on cradle-to-gate impacts, and as a result, construction, use, and end-of-life are not within the scope. However, studies have suggested these life cycle phases can lead to notable effects on environmental impacts; for example, carbonation during use and end-of-life stages has been reported to uptake as great as 43% of CO_2 production emissions (note: uptake from carbonation is influenced by various factors such as clinker-to-cement ratio, compressive strength and surface area).[94] The model for fly ash is based on assumptions from the USEPA, which treats the material as a waste product and does not allocate emissions from its production. However, allocation of impacts from the industrial processes (e.g., coal power plants) could be included by users, as the inventories are readily editable, or in future work expanding the tool. The kiln efficiency per state is based on data from 2002 due to data availability; however, cement plants in some states have improved significantly in recent years and should be updated in future versions. This kiln efficiency per state data is also from the PCA, whose membership does not encompass all cement plants in the U.S. Inclusion of cement plants beyond those who are member of the PCA should be considered in future work. While OpenConcrete can be used to evaluate the environmental burdens associated with different concrete mixtures, it does not consider performance metrics (e.g., compressive strength, durability, etc.) and, by itself, should not be used to determine the eco-efficiency of concrete mixtures. Recent studies that have addressed the issue of eco-efficiency should be reviewed for incorporation into future work.[95–98]

2.5 Conclusion

With the need to mitigate GHG emissions, there have been recent policy and industry efforts to lower CO_2-eq emissions from cement and concrete production. However, there remain limitations in availability of transparent, customizable models to draw robust comparisons among concrete mixtures to mitigate environmental burdens. OpenConcrete is a freely available tool and presents a new synthesis of open data that allows user-control when performing environmental impact assessments of cement-based materials. The scope of this tool focuses on cradle-to-gate impacts from concrete production (i.e., the scope does not include construction, use phase, or end of life). OpenConcrete includes environmental impacts beyond CO_2-eq, which can inform efforts to advance climate change mitigation while providing a broader perspective of environmental burdens. This can support selection of mixtures or GHG emissions mitigation strategies that lead to co-benefits in other impact categories and help avoid unintended consequences. The inclusion of multiple chemical and mineral admixtures allows for robust evaluation of many variations of concrete mixture designs.

Cement and concrete production are continuing to increase, which poses a barrier to achieving most climate goals. As such, a robust and methodological means of calculating the environmental impacts of concrete production which provides for specific conditions (e.g., kiln efficiencies, electricity mixes) will assist in understanding and monitoring the burdens of concrete production, allowing for region-specific decision making towards concrete with improved environmental impacts.

3 Meeting industrial decarbonization goals: a case study of and roadmap to a net-zero emissions cement industry in California

Publication

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Abstract

Recent decarbonization policies are expected to significantly impact high greenhouse gas (GHG) emitting industries, as they will be forced to find ways to operate with a lower environmental footprint. Due to the energy required for the kilns and the unavoidable chemical-derived emissions during manufacturing, in addition to its high global consumption levels, the cement industry is anticipated to be among the early industries affected. California State Bill (SB 596) is one of the first rigorous legislative measures that sets GHG emissions from cement production to net-zero by 2045. As such, a case study on California cement production is evaluated here. While several groups have developed cement technology roadmaps with GHG mitigation strategies, these roadmaps do not consider concomitant environmental impacts, such as those that can influence local populations, thus limiting potential implementation from a policy perspective. Here, we examine several GHG emissions mitigation strategies for cement production and show the greatest reduction from an individual measure is from implementing carbon capture storage for cement kiln flue gas (87%), use of alternative clinkers (78%), or use of alkali-activated materials (88%). Yet even if GHG emissions are reduced, use of high-polluting energy sources could increase risks to human health impacts. Further, the efficacy of these decarbonization measures is lowered if multiple measures are implemented simultaneously. Finally, we examine the potential to meet net-zero emissions, focusing on California production due to recent legislation, and find a pathway to 96% GHG emissions reduction. Notably, these reductions do not reach goals to hit zero emissions, suggesting direct air capture mechanisms will need to be implemented.

3.1 Introduction

The notable environmental impacts from concrete and cement production pose a challenge to meeting the goal posed by the Intergovernmental Panel on Climate Change (IPCC) to reach net-zero carbon dioxide (CO_2) emissions by mid-century.[6] Concrete is a critical component of infrastructure and has supported development as early as the Egyptian and Roman empires.[2] Although technology has improved to expand the performance and applications of concrete, the main materials required to create concrete have remained consistent for decades: Portland cement (a hydraulic powder, referred to herein as cement), water, and aggregates. As global development increases, so do the projections for future concrete demands.[27] Emerging economies in regions like South Asia and West Africa are projected to rely heavily on cement demand as a means for growth.[99] Today, concrete production is responsible for about 9% of annual global CO_2 emissions.[11] Cement production alone accounts for ~7% of these global CO_2 emissions,[13] making it the largest component of greenhouse gas (GHG) mitigation strategies for concrete and other cement-based materials (herein referred to jointly as concrete). These considerable emissions from cement production are driven by three factors:

(1) the substantial amount of cement produced annually (~ 4 billion metric tons per year globally[100]).

(2) the chemical decarbonation of cement's primary raw material, limestone ($CaCO_3$ to CaO); this reaction inherently releases CO_2 and accounts for approximately 60% of total CO_2 emissions from cement production.

(3) the thermal energy demand for kilning, which facilitates limestone decarbonization and accounts for about 35% of total CO_2 emissions (the remaining ~5% of emissions are attributed to the electricity demand).

To drive down GHG emissions from cement and concrete, these industries have drawn much attention. Most impressively California recently passed senate bill SB 596, that set the goal of net-zero GHG emissions from cement production by 2045, a first in United States (US) state legislation.[8]

California is not only the second largest producer of cement in the US (with more than 10 million metric tons produced each year[93]), but also it releases the lowest GHG emissions per kg of cement produced compared to other US states. Thus, it is uniquely poised to be a leading case study for meeting industrial decarbonization goals. However, for this goal to be achieved, it will require swift and aggressive actions by policy makers, government regulators, and industry. Without collective and immediate action from states and regions beyond California, unprecedented natural disasters resulting from climate change, such as the 2022 extreme flooding in Pakistan[101] and the prolonged fire seasons in the West Coast of the US,[102] will continue at an accelerating rate. To support these efforts, several academic,[10,11] non-governmental,[12,13] and industry groups[15–17] have developed technology roadmaps to meet both global and regional climate goals. These reports highlight key technologies for GHG emissions mitigation within cement production currently under consideration by different regions, that are intended to be rapidly deployed to meet these climate targets.

While there are several GHG emissions roadmaps to net-zero for cement, they estimate GHG emissions quantifications without presenting the influence to other environmental impact categories and only one (Cao et al. 2021[103]) uses open data modeling methods. In doing so, such work limits the ability of future customizable analyses to be specific to region or cement plant and prevents monitoring of consequences to other environmental impacts beyond GHG emissions (e.g., particulate matter with diameter less than 2.5 μm ($PM_{2.5}$) and volatile organic compounds (VOCs)). The latter issue is particularly pertinent to limiting unintended local consequences of implementing measures to curb global GHG emissions, which while benefiting climate goals, could cause disproportionate burdens to local populations.[104] Under a business-as-usual scenario, GHG emissions from cement production will only continue to increase in response to the rising global cement demand.[103,105] To ensure this increase in demand does not compromise the mid-century climate goals set forth by California and other regions, a clear pathway with incremental goals and timesteps is necessary.

In this work, we provide a summary of key, frequently discussed GHG mitigation technology strategies and consider their efficacy at contributing to net-zero GHG emissions goals. We base our analysis on the production of cement in California, as this is the first region to have passed legislation requiring this shift for the industry. Noting that measures are frequently considered in isolation, we then examine how the efficacy of measures changes as a function of using multiple mitigation strategies in sequence. Further, we use these measures to quantify the ability to meet net-zero emissions and the effects of these measures on other environmental impacts that could influence local populations (and as a result, policies). Finally, we discuss potential qualitative cost impacts associated with each strategy.

3.2 Methods

To quantify the reduction of GHG emissions from mitigation strategies and to initiate exploration of co-benefits or unintended consequences of net-zero pathways to other environmental impacts, we conduct a series of environmental impact assessments based on life cycle assessment methodologies. Noting pressing legislation in California, we conduct measurements using current cement production in California as our baseline. We use environmental inventories and impact assessment models from OpenConcrete (see Appendix A for model details), an open data environmental quantification tool,[106] which reports GHG emissions (modeled using 100a global warming potentials for CO_2-eq from the IPCC[107]) as well as 10 other environmental impacts. Here we examine emissions of nitrogen oxide (NO_X), sulfur oxide (SO_X), particulate matter (PM) with diameter less than 10 µm (PM_{10}), $PM_{2.5}$, VOC, carbon monoxide (CO), and lead (Pb), as well as water consumption and energy demand. This assessment focuses on cradle-to-gate, just before cement is sent for concrete production (see Figure S3.1).

Here, noting that the majority of GHG emissions from concrete are associated with cement production and California's legislation targets the cement industry, we focus on the efficacy of technologies within the cement sector. The type of cement plant (e.g., new build or retrofit) is not considered in this study. The basis of comparison is 1 kg of cement or 1 kg of a cement alternative. The baseline to which these strategies are compared to uses the US Environmental Protection Agency's (USEPA's) Power Profiler for California in 2020 to determine electricity grid[90] and the California Air Resources Board Greenhouse Gas Mandatory Reporting Program for 2017 to determine cement kiln fuel mixture.[108] We examine 6 mitigation methods that are highlighted by the International Energy Agency (IEA),[105] the Global Cement and Concrete Association (GCCA),[17] and the Portland Cement Association (PCA)[15] as key methods to reduce GHG emissions from cement production in California. Namely, we consider:

1. ***Energy efficiency and "clean" electricity grid use.*** Increased energy efficiency provides emissions reductions by lowering the energy demand, and thus emissions from energy resources. For the purposes of this work, we consider this strategy to also include switching the electricity mix used during cement production towards less carbon intensive energy solutions (e.g., renewable energy such as wind power). In California, all plants have already adopted the use of dry kilns with preheaters and precalciners.[10,12] In this work, this mitigation strategy switches the electricity mix used in California (from the USEPA[90]) to one with 100% wind power (modeled as zero GHG-emitting electricity sources, based on emissions factors in OpenConcrete[106]).
2. ***Fuel switching in kilns***. The GHG emissions associated with the fuel required to heat cement kilns in California represents about 35% of total GHG emissions from cement production.[12] Fuel switching happens at the clinker production level by replacing the fuel used in cement kilns from high emitting resources (e.g., coal) to less carbon intensive fuels (e.g., natural gas, biomass). Natural gas as a kiln fuel generates less GHG emissions to produce 1 kg of cement than coal (environmental impacts of fuel types are based on values in OpenConcrete[106]), while biomass and certain waste fuels are frequently considered to have neutral (net-zero) GHG emissions.[105] However, it must be noted that the carbon accounting of such energy resources as net-zero is not consistently accurate. In some cases, biomass and certain waste

fuels cannot entirely replace conventional fuels if they cannot provide a high enough temperature in the kiln[109] or if local policies preclude use of particular energy resources. A switch to natural gas is already happening in the US, while the switch to biomass for kiln fuel is currently happening in Europe.[10,12] On the global stage, cement companies in Europe and China are currently exploring electrification of cement kiln,[110,111] presenting an opportunity for California to adopt. It should be noted that novel fuel alternative technologies such as concentrated solar[112] and hydrogen fuels[113] have also been discussed to reduce thermal demand in cement kilns; however, due to a lack of technical maturity these strategies are not included in this study.

3. ***Clinker reduction through use of mineral additives.*** High amounts of CO_2 emissions occur during clinker production due to chemical-derived emissions from the decarbonation of limestone in kilns in addition to emissions from the fuel combustion required to heat the kilns. Consequently, decreasing the clinker demand of cement can reduce its associated GHG emissions. Supplementary cementitious materials (SCMs) as partial substitutes to cement are a common method to lower the amount of clinker in cement or high-clinker content cement in concrete; it must be noted, it is most common in the US (and in California) to include SCMs at the concrete batching stage. Here, we consider common SCMs such as fly ash, ground granulated blast furnace slag (GBFS), natural pozzolans (including calcined clays), and limestone among these mineral additives (environmental impact data for all SCMs are from OpenConcrete[106]). Depending on the mineral additive used, the levels of clinker replacement can range from 15-90% while still meeting performance requirements[114–119] (Table S3.1 shows clinker replacement levels considered here). While currently less common in California, clinker reduction can also occur at the cement production stage (see Figure S3.1) as is commonly the case of binary blended cements, such as with Portland-Limestone cements (PLC) and ternary blended cements, such as Calcined clay limestone cements (LC^3).

These blended cements can have clinkers replacement levels from 15-45% while still meeting performance requirements.[120,121]

4. ***Clinkered alternative cements.*** Clinkers other than the conventional Portland clinker can require lower energy inputs and/or solidify through carbonation instead of hydration, resulting in lower CO_2 emissions from cement production. The level of market replacement via these alternative clinkers is dependent on resource availability and their ability to meet required performance characteristics. These cements can be a less emissions intensive option due to the lower temperatures required for production (e.g., belitic clinkers), a change in chemical composition allowing for less process emissions (e.g., calcium sulfoaluminate clinkers) or replacing limestone with an alternate raw material with lower process emissions (e.g., magnesium-based cements). In this work we consider four types of alternative clinkers (Belite Ye'elimite Ferrite (BYF), Calcium Sulfoaluminate–belite Cement (C$AB), Carbonatable Calcium Silicate Cement (CCSC), Magnesium oxide cement from forsterite (MOMS)) whose changes to thermal demand and raw material compared to conventional Portland cement are summarized in earlier work (see Appendix B for detailed descriptions).[122]
5. ***Alkali-activated materials.*** Alkali-activated materials (AAMs), sometimes referred to as geopolymers when the solid precursors have low calcium content, are a potential replacement for conventional Portland cement. In lieu of conventional cements, a combination of alkali-activators (e.g., sodium hydroxide (NaOH)) and solid precursors (e.g., GBFS, fly ash) are used to act as a binder for concrete mixtures. This strategy eliminates the thermal demand and calcination emissions resulting from clinker production. Further, a large range of combinations are possible to create AAMs, which allows this solution to be versatile and adjusted based on local resource availability.[123] Table S3.2 summarizes the AAMs considered from our earlier work[33,124] and from the literature[125]. Environmental impact data

for solid precursors are modeled from OpenConcrete, while ecoinvent v2.2 is utilized for alkaline activators.

6. ***Carbon Capture, Utilization, and Storage (CCUS).*** Carbon capture, utilization, and storage (CCUS) can be incorporated at the cement and/or concrete production stages. Within this supply chain, post-combustion carbon capture and storage (CCS) of cement (which captures the flue gas generated from fuel combustion and limestone decarbonization) is the most widely researched technology, but it can also be used in carbon capture and utilization (CCU) at the concrete level batching.[126] Some studies have reported that the injection of CO_2 at concrete batching can reduce the quantity of cement needed in concrete, thus reducing the GHG emissions associated with cement production,[127,128] while others have reported an increase in GHG emissions in some cases.[129] We note that in California, some cement plants are attempting to collaborate with emerging companies to incorporate CCU systems at the cement plant level.[130] Current barriers to CCS implementation in California, and in the whole US, include the lack of pathways for pipeline installation and the time-consuming permitting required for permanent CO_2 storage (e.g., injection into geological reserves). In this work, post-combustion CCS is modeled with MonoEthanolAmine (MEA) scrubbing to chemically separate CO_2 from the flue gasses collected, based on models from The International Energy Agency (IEA).[131] Environmental impact inventory data for MEA production is leveraged from ecoinvent 2.2.[132] A combined heat and power (CHP) plant powered by natural gas is modeled to provide steam for MEA regeneration, as well as meet the remaining electricity requirements of the cement plant. The energy demands for the CHP are modeled based on Ravikumar et al 2021.[129] The amount of CO_2 captured (~90% of total post-combustion cement production CO_2 emissions) is modeled based on reports from the IEA.[131]

Lastly, the calculated GHG emission reductions are used to generate a technology roadmap for years 2025, 2035 and 2045.The timeline of deployment for each mitigation technology is based on their technology readiness levels (TRLs) pulled from reports for each of the considered technologies.[133–135] The TRL scale follows the National Aeronautics and Space Administration (NASA)[136] classifications, commonly used in the US. The solutions range from ready for immediate deployment (e.g., increased use of SCMs) to requiring further technology validation (e.g., alternative-clinker cements).

3.3 Results

3.3.1 Efficacy of emissions-reducing strategies

A summary of the effects of the GHG emissions mitigation strategies considered in this work are presented in Table 3.1. Here, the efficacy of each strategy is considered relative to the baseline of current California Portland cement production (0.846 kg GHG per kg cement). We note that cement kiln efficiency improvements could not be considered as the technologies in our baseline scenario of cement production because California already uses energy-efficient kilns. However, switching the electricity mix used throughout the production of cement and concrete was examined and only provides a 4% GHG emissions reduction. In California, about 74% of a cement kiln's fuel mixture is from coal and petroleum coke, and 9% is from natural gas.[108] By using a fuel source with lower GHG emissions per MJ fuel and with appropriate properties to satisfy required processing conditions (e.g., natural gas),[137] fuel switching leads to a 15% decrease in GHG emissions to produce 1 kg of cement. If this were entirely natural landfill gas, a greater reduction in GHG emissions is possible due to its even lower carbon intensity.[138] Due to the lower calorific value of most organic materials, the biomass fuel switching scenario modeled here utilizes 80% biomass and 20% natural gas, and results in 8% reduction in GHG emissions. Electrifying the cement kiln with renewable energy provides the greatest reduction at 38%.

At the concrete batching stage, a 50% reduction in clinker with GBFS replacement leads to a 33% reduction in GHG emissions per kg of cement produced. Whereas at the cement production stage, a lower level of reduction in clinker with interground limestone (here modeled as 15% weight of cement to reflect blended PLC) leads to a 15% reduction in GHG emissions per kg of cement produced. LC^3 is a ternary blended cement (e.g., a mixture with Portland cement and two other mineral binders) which reduces the clinker content by 45% (here modeled as 15% from interground limestone and 30% from calcined clay) and leads to a 40% reduction in GHG emissions.

The C$AB cement modeled here reduces the thermal energy demand required in the kiln by 36%, which leads to a 42% reduction in GHG emissions. In the case of the magnesium oxide cement (MOMS), the thermal energy demand reduces by 56%, which alone yields a 78% reduction in GHG emissions. The periclase magnesium oxide (MgO) in this cement also uptakes 0.524 kg CO_2 per kg of cement product, which brings the total reduction in GHG emissions for MOMS to 140%. The elimination of thermal demand and calcination emissions established by AAMs, allows for over 80% reductions in GHG emissions for mixtures with only one alkaline solution and the same solid precursors (GBFS and natural pozzolans). However, when the mixture utilizes different solid precursors (calcined clay and limestone filler), the efficacy of this strategy reduces to 63%. A 18% increase in GHG emissions compared to conventional cement is seen when an AAM uses the same solid precursors (GBFS and natural pozzolans) but with higher proportions of two alkaline solutions (sodium hydroxide and sodium silicate). Due to the high versatility in AAM mixture combinations, a large range of environmental impacts are possible as seen here.

Post-combustion CCS at the cement plant results in an 87% reduction in GHG emissions based on our model. This strategy produces conventional cement while capturing the flue gas from fuel combustion and limestone decarbonization. It is important to note, the energy required to capture the CO_2 emissions increases energy demand by 98% compared to conventional cement production. The rationale for differences between percent reduction in GHG emissions and percent efficiency of the CCS system is detailed in the Appendix B.

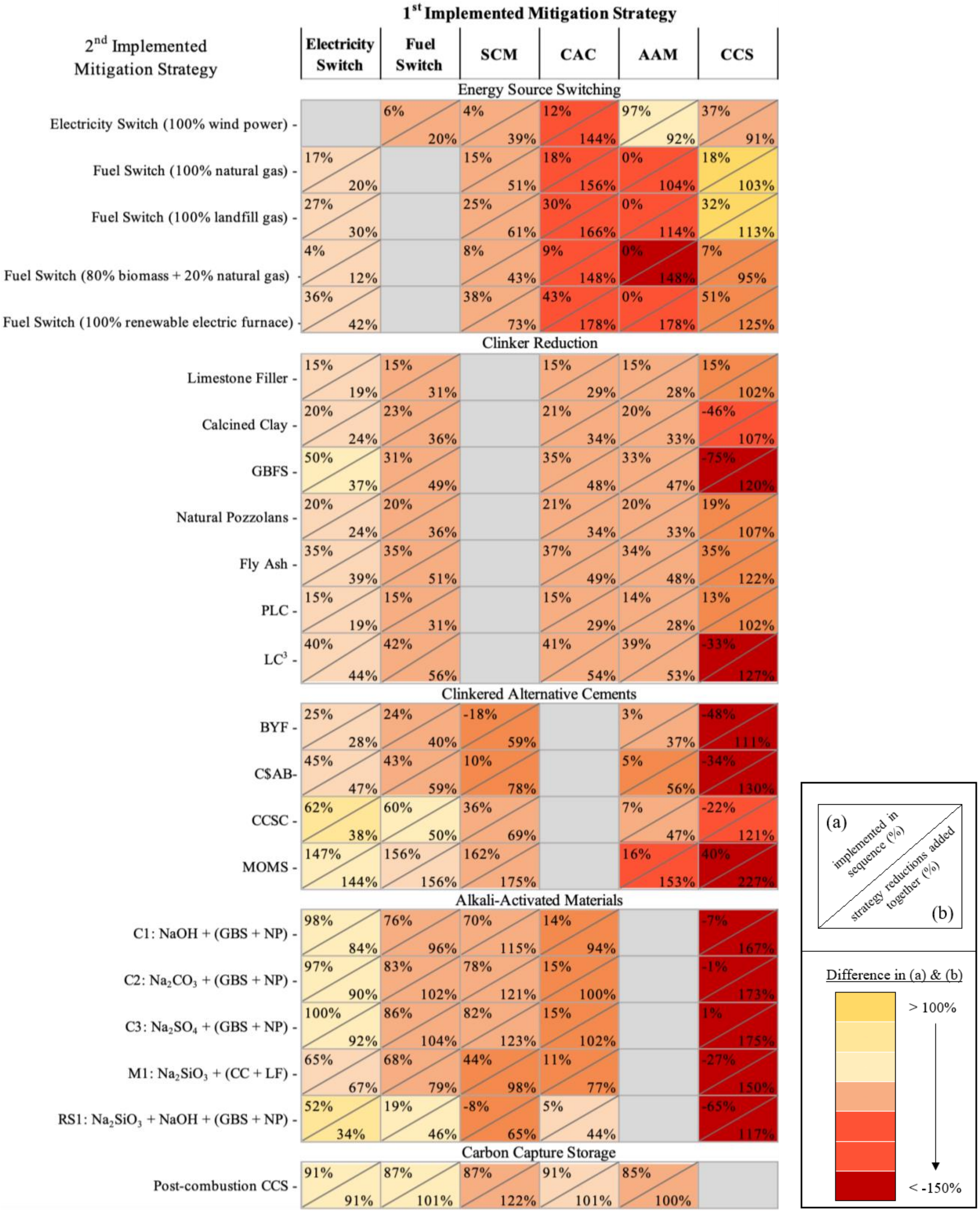
Table 3.1. Strategies with percent reductions in greenhouse gas emissions (GHG) for each strategy if implemented alone.

Mitigation Strategy	**GHG Intensity**	**% Reduction in GHG emissions**
Baseline (California)	0.846	N/A
Electricity Switch	**(kg GHG / kg cement)**	
100% Wind Power	0.814	4%
Fuel Switch	**(kg GHG / kg cement)**	
100% Natural Gas	0.719	15%
100% Landfill Gas	0.636	25%
80% Biomass + 20% Natural Gas	0.779	8%
100% Renewable Electric Furnace	0.524	38%
Clinker Reduction at concrete plants X% SCM + (100-X)% cement	**(kg GHG / kg cement)**	
Limestone Filler	0.723	15%
Calcined Clay	0.680	20%
GBFS	0.565	33%
Natural Pozzolans	0.680	20%
Fly Ash	0.552	35%
Clinker Reduction at cement plants X% SCM + (100-X)% cement	**(kg GHG / kg cement)**	
Portland limestone cement (PLC)	0.724	14%
Calcined clay limestone cements (LC^3)	0.512	40%
Clinkered Alternative Cements	**(kg GHG / kg cement)**	
Belite Ye'elimite Ferrite (BYF)	0.650	23%
Calcium Sulfoaluminate–Belite (C$AB) Cement	0.493	42%
Carbonatable Calcium Silicate Cement (CCSC)	0.570 (0.353*)	33% (58%*)
Magnesium Oxide Cement (MOMS)	0.185 (-0.339*)	78% (140%*)
Alkali-Activated Materials (AAMs) Mixture Number: Alkali Activator + (Solid Precursors)	**(kg GHG / kg AAM)**	
C1: NaOH + (GBFS + natural pozzolans)	0.166	80%
C2: Na_2CO_3 + (GBFS + natural pozzolans)	0.121	86%
C3: Na_2SO_4 + (GBFS + natural pozzolans)	0.101	88%
M1: Na_2SiO_3 + (calcined clay + limestone filler)	0.310	63%
RS1: NaOH + Na_2SiO_3 + (GBFS + natural pozzolans)	0.997	+18%**
Carbon Capture Storage (CCS)	**(kg GHG / kg cement)**	
Post-combustion CCS	0.112	87%

* reduction when cements solidify via carbonation, ** + indicates increase in GHG emissions

3.3.2 Influence on combined mitigation efficacies

When examining each mitigation strategy in isolation, the reduction in GHG intensity for some technologies appear significant (e.g., 88% reduction for AAMs). If two strategies are implemented together (e.g., 88% reduction for AAMs and 87% reduction for CCS), it may initially appear that the total reduction of these two strategies can achieve over a 100% reduction in GHG emissions or net-negative (in the case of AAMs and CCS, 175%). However, once a mitigation strategy is implemented, the magnitude reduction from the following implemented strategies decreases. So, if all cement plants have already implemented CCS technologies, the new GHG-intensity becomes 0.112 kg GHG emissions per kg of cement (see Table 3.1) and then implementing the most effective AAM mixture will only actualize a 1% reduction in emissions (see Figure 3.1). Similarly, if the electricity grid used for all cement plants is already fully renewable, adding fuel-switching to natural gas will only yield a 17% decrease in GHG emissions per kg of cement instead of what might be an anticipated 20% reduction by adding both individual efficacies from Table 3.1. Figure 3.1 shows the changes in efficacy of combined strategies. The change in emissions reduction of each mitigation strategy is based on the time in which other strategies are deployed. To keep it simple, we assume only one technology type is first implemented. However, all technology types are considered as secondly implemented. For the first implemented technologies, the electricity switch is modeled as 100% wind power; the fuel switch is 100% natural gas; the SCM is modeled as fly ash; the clinkered alternative cement is modeled as magnesium oxide cement; the AAM mixtures includes Na_2SO_4, GBFS and natural pozzolans; the CCS is post-combustion at cement plants. The color shading represents the difference in efficacy between the two methodologies. Because their effectiveness changes as mitigation strategies are implemented, it is critical to look at these strategies in combination with each other when addressing climate goals. Savings gained from technologies we implement later down the line (after some mitigation measures have been put in use) will not be as effective as they are modeled today.



2nd Implemented Mitigation Strategy	1st Implemented Mitigation Strategy: Electricity Switch	Fuel Switch	SCM	CAC	AAM	CCS
Energy Source Switching						
Electricity Switch (100% wind power)		6% / 20%	4% / 39%	12% / 144%	97% / 92%	37% / 91%
Fuel Switch (100% natural gas)	17% / 20%		15% / 51%	18% / 156%	0% / 104%	18% / 103%
Fuel Switch (100% landfill gas)	27% / 30%		25% / 61%	30% / 166%	0% / 114%	32% / 113%
Fuel Switch (80% biomass + 20% natural gas)	4% / 12%		8% / 43%	9% / 148%	0% / 148%	7% / 95%
Fuel Switch (100% renewable electric furnace)	36% / 42%		38% / 73%	43% / 178%	0% / 178%	51% / 125%
Clinker Reduction						
Limestone Filler	15% / 19%	15% / 31%		15% / 29%	15% / 28%	15% / 102%
Calcined Clay	20% / 24%	23% / 36%		21% / 34%	20% / 33%	-46% / 107%
GBFS	50% / 37%	31% / 49%		35% / 48%	33% / 47%	-75% / 120%
Natural Pozzolans	20% / 24%	20% / 36%		21% / 34%	20% / 33%	19% / 107%
Fly Ash	35% / 39%	35% / 51%		37% / 49%	34% / 48%	35% / 122%
PLC	15% / 19%	15% / 31%		15% / 29%	14% / 28%	13% / 102%
LC^3	40% / 44%	42% / 56%		41% / 54%	39% / 53%	-33% / 127%
Clinkered Alternative Cements						
BYF	25% / 28%	24% / 40%	-18% / 59%		3% / 37%	-48% / 111%
C$AB	45% / 47%	43% / 59%	10% / 78%		5% / 56%	-34% / 130%
CCSC	62% / 38%	60% / 50%	36% / 69%		7% / 47%	-22% / 121%
MOMS	147% / 144%	156% / 156%	162% / 175%		16% / 153%	40% / 227%
Alkali-Activated Materials						
C1: NaOH + (GBS + NP)	98% / 84%	76% / 96%	70% / 115%	14% / 94%		-7% / 167%
C2: Na_2CO_3 + (GBS + NP)	97% / 90%	83% / 102%	78% / 121%	15% / 100%		-1% / 173%
C3: Na_2SO_4 + (GBS + NP)	100% / 92%	86% / 104%	82% / 123%	15% / 102%		1% / 175%
M1: Na_2SiO_3 + (CC + LF)	65% / 67%	68% / 79%	44% / 98%	11% / 77%		-27% / 150%
RS1: Na_2SiO_3 + NaOH + (GBS + NP)	52% / 34%	19% / 46%	-8% / 65%	5% / 44%		-65% / 117%
Carbon Capture Storage						
Post-combustion CCS	91% / 91%	87% / 101%	87% / 122%	91% / 101%	85% / 100%	

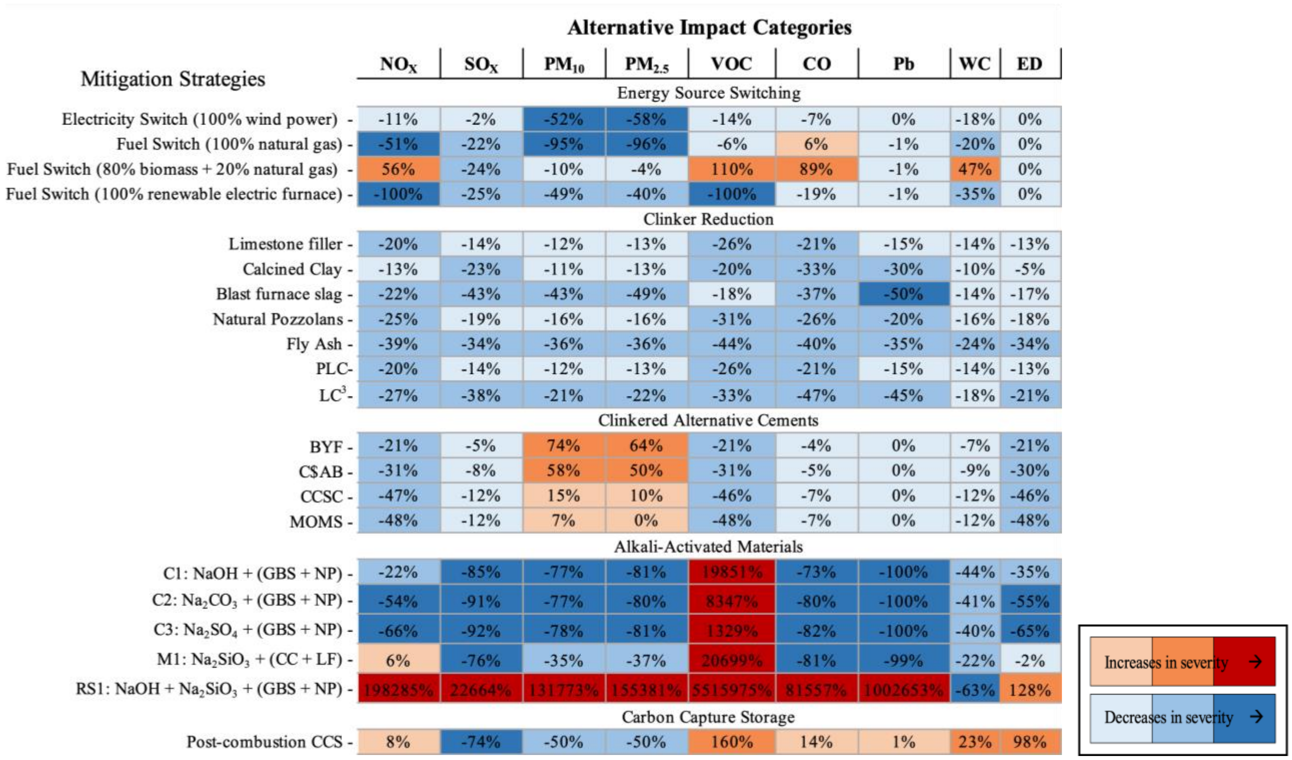
Figure 3.1. Changes in efficacy if technologies are (a) implemented in sequence and (b) as strategy reductions added together. The color shading represents the difference in (a) and (b), or the difference in methodology used to calculate the combined strategy efficacy. (CAC – clinkered alternative cements; CCS – carbon capture storage; NP – natural pozzolans; GBS and GBFS – both refer to Granulated Blast Furnace Slag)

3.3.3 Co-benefits and unintended consequences of GHG emission mitigation strategies

In addition to GHG emissions, cement production also drives environmental burdens in NO_X, SO_X, PM, VOC, Pb and CO emissions as well as water consumption and energy demand. Air pollutants are linked to human health impacts, quality of life and mortality rates.[139] Particularly, NO_X, SO_X and VOC emissions are precursors to PM emissions, which are linked to a wide range of diseases. These local burdens will affect populations neighboring cement plants, but they will not have the same global burdens as climate change. It is critical to explore the effects of mitigation mechanisms on varying environmental impacts concurrently to ensure technologies mitigate human health impacts in addition to GHG emissions. As such, Figure 3.2 displays the influence of the GHG emissions mitigation strategies to nine additional environmental impact categories.

For most GHG emissions mitigation methods considered in this work, other environmental impacts follow similar reduction trends (i.e., there are co-benefits). However, there are a few key outliers. AAM mixture RS1 shows increases to all additional impact categories considered (i.e., there are unintended consequences) , except for water consumption. For the CCS modeled in this work all impact categories, except for $PM_{2.5}$, PM_{10} and SO_X emissions, are increased due to the production and regeneration of the chemical (MEA) used to separate CO_2. The instances with increases to environmental impacts for RS1 are attributed to its high proportion of alkali solutions, and we note AAMs can be engineered with desirable performance and lower quantities of activator. In Figure 3.2, water consumption is reduced for all strategies considered (with the exception of CCS). SO_X emissions are reduced for all strategies, except for AAM mixture RS1. Pb emissions and energy demand are reduced for all categories except for AAM mixture RS1 and for CCS. NO_X emissions are reduced in all strategies except for CCS, due to the increase in thermal demand modeled, and for two cases of AAMs, due to the high proportion of alkali solutions. In the cases of alternative cements and AAM mixture RS1, both PM_{10} and $PM_{2.5}$ emissions (herein referred to jointly as PM) are increased. The alternative cements modeled all have a higher amount of raw material than our baseline cement, and thus a higher amount of

PM emissions associated with raw material extraction. For all remaining cases, the PM emissions are also reduced. VOC emissions are reduced in all strategies except for AAMs and CCS, both due to the increases in chemical solutions. Particularly high increases to VOC emissions for all AAM cases result from the addition of alkali-activator solutions (e.g., NaOH), which have high VOC emissions during production. Based on emissions factors used in this work, natural gas has a higher CO emissions-intensity compared to coal or petroleum coke fuel (the majority of fuel used in California cement kilns), and therefore switching to fully natural gas emits slightly higher CO. Although increasing biomass fuels in cement plants can promote a circular economy by incorporating natural resources, emissions factors used herein indicate potential for higher NO_X, VOC, CO emissions as well as water consumption. This is due to the increased emissions from upstream agricultural impacts from farming the primary plant. Addressing these trade-offs when selecting climate-beneficial solutions provides a more comprehensive understanding of potential unintended consequences as well as co-benefits, allowing local governing agencies to provide targeted regulatory protections (for strategies with unintended consequences) and incentives (to accelerate use of strategies with co-benefits).



Mitigation Strategies	NO_X	SO_X	PM_{10}	$PM_{2.5}$	VOC	CO	Pb	WC	ED
	Alternative Impact Categories								
	Energy Source Switching								
Electricity Switch (100% wind power)	-11%	-2%	-52%	-58%	-14%	-7%	0%	-18%	0%
Fuel Switch (100% natural gas)	-51%	-22%	-95%	-96%	-6%	6%	-1%	-20%	0%
Fuel Switch (80% biomass + 20% natural gas)	56%	-24%	-10%	-4%	110%	89%	-1%	47%	0%
Fuel Switch (100% renewable electric furnace)	-100%	-25%	-49%	-40%	-100%	-19%	-1%	-35%	0%
	Clinker Reduction								
Limestone filler	-20%	-14%	-12%	-13%	-26%	-21%	-15%	-14%	-13%
Calcined Clay	-13%	-23%	-11%	-13%	-20%	-33%	-30%	-10%	-5%
Blast furnace slag	-22%	-43%	-43%	-49%	-18%	-37%	-50%	-14%	-17%
Natural Pozzolans	-25%	-19%	-16%	-16%	-31%	-26%	-20%	-16%	-18%
Fly Ash	-39%	-34%	-36%	-36%	-44%	-40%	-35%	-24%	-34%
PLC	-20%	-14%	-12%	-13%	-26%	-21%	-15%	-14%	-13%
LC^3	-27%	-38%	-21%	-22%	-33%	-47%	-45%	-18%	-21%
	Clinkered Alternative Cements								
BYF	-21%	-5%	74%	64%	-21%	-4%	0%	-7%	-21%
C$AB	-31%	-8%	58%	50%	-31%	-5%	0%	-9%	-30%
CCSC	-47%	-12%	15%	10%	-46%	-7%	0%	-12%	-46%
MOMS	-48%	-12%	7%	0%	-48%	-7%	0%	-12%	-48%
	Alkali-Activated Materials								
C1: NaOH + (GBS + NP)	-22%	-85%	-77%	-81%	19851%	-73%	-100%	-44%	-35%
C2: Na_2CO_3 + (GBS + NP)	-54%	-91%	-77%	-80%	8347%	-80%	-100%	-41%	-55%
C3: Na_2SO_4 + (GBS + NP)	-66%	-92%	-78%	-81%	1329%	-82%	-100%	-40%	-65%
M1: Na_2SiO_3 + (CC + LF)	6%	-76%	-35%	-37%	20699%	-81%	-99%	-22%	-2%
RS1: NaOH + Na_2SiO_3 + (GBS + NP)	198285%	22664%	131773%	155381%	5515975%	81557%	1002653%	-63%	128%
	Carbon Capture Storage								
Post-combustion CCS	8%	-74%	-50%	-50%	160%	14%	1%	23%	98%

Figure 3.2. Increases and decreases to nine alternative impact categories for decarbonization strategies considered. Shades of blue indicate a co-benefit in alternate impact category (i.e., reductions in environmental impact), while shades of red indicate a consequence to an alternate impact category (i.e., increases in environmental impact). (WC – water consumptions; ED – energy demand)

3.3.4 Decarbonization Roadmap

The roadmap in Figure 3.3 introduces mitigation strategies based on the expected technical maturity at each stage,[133–135] and with the California State Bill (SB 596) goal of net-zero GHG emissions from cement production by 2045 in mind. The TRLs associated with each technology and estimated years for implementation is provided in Table 3.2. It is important to note that the versatility of AAM mixtures result in significant ranges in TRLs in Table 3.2 (i.e., many AAM mixtures are still being tested in the lab, while others have been utilized in completed construction projects[140,141]). Taking an aggressive combination of mitigation strategies, we find a 96% reduction potential in GHG emissions is possible by 2045. The combination to reach 96% reduction requires California's electricity switch to 100% wind power, a kiln fuel switch to 100% renewable electric furnace, 100% of Portland cement to be made with CCS technologies (representing 80% of the cement market), of which all cement is substituted by 35% replacement with fly ash, 10% of cement market will be of clinkered alternative cements, and the remaining 10% of the market will be alkali-activated materials. Because clinkered alternative cements and AAMs are versatile with relatively low TRLs, the amount modeled to substitute conventional Portland cement is based on areas where regulatory support is possible, such as in public construction (estimates of public construction in California from the PCA[142]). Two additional plausible roadmap scenarios (a low technology adoption and a high technology adoption) are provided in Appendix B Figure S3.2 and S3.3.

Table 3.2. Technology Readiness Levels (TRLs) for each mitigation strategy and estimated years of implementation.

Mitigation Strategies	**TRL**	**Year**
Energy Source Switching		
100% Wind Power	9	2025
100% Solar Power	9	2025
100% Natural Gas	9	2025
100% Renewable Natural Gas	2	2045
80% Biomass + 20% Natural Gas	8	2035
100% Renewable Electric Furnace	7	2035
Clinker Reduction		
Limestone filler	9	2025
Calcined Clay	7	2035
Blast furnace slag	9	2025
Natural Pozzolans	9	2025
Fly Ash	9	2025
Portland limestone cement (PLC)	9	2025
Calcined clay limestone cements (LC^3)	7-8	2035
Clinkered Alternative Cements		
BYF Cement	2-4	2045
C$AB Cement	2-4	2045
CCSC Cement	2-4	2045
MOMS Cement	2-4	2045
Alkali-Activated Materials		
C1: NaOH + (GBS + NP)	2-4; some cases 7-8	2035
C2: Na_2CO_3 + (GBS + NP)	2-4; some cases 7-8	2035
C3: Na_2SO_4 + (GBS + NP)	2-4; some cases 7-8	2035
M1: Na_2SiO_3 + (CC + LF)	2-4; some cases 7-8	2035
RS1: Na_2SiO_3 + NaOH + (GBS + NP)	2-4; some cases 7-8	2035
Carbon Capture Storage		
Post-combustion CCS	7	2035-2045

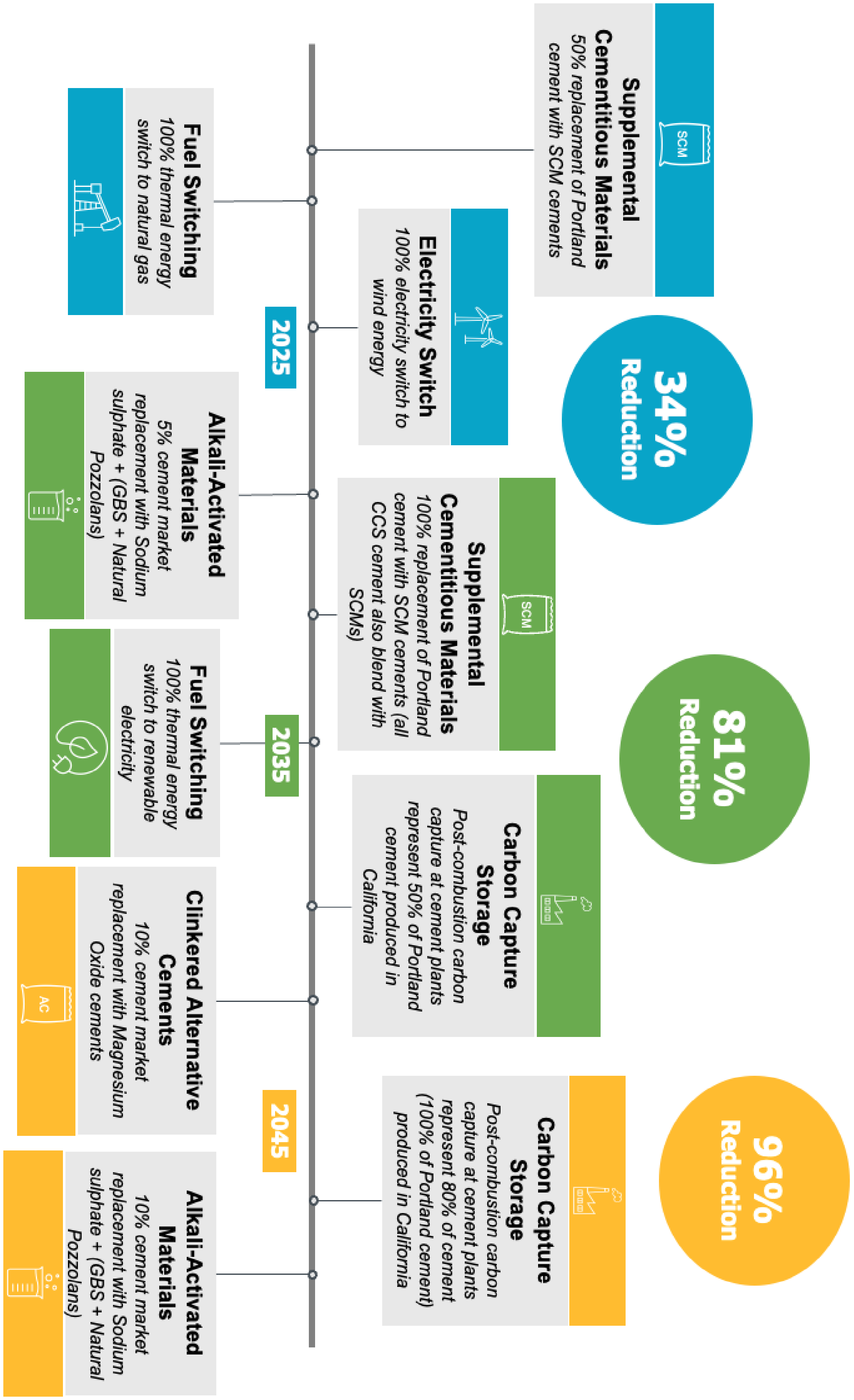


Figure 3.3. Technology roadmap a plausible technology scenario of greenhouse gas (GHG) emissions mitigation strategies for years 2025, 2035, 2045.

Although a 96% reduction is a significant improvement in GHG emissions, this means for California to meet net-zero emissions technologies beyond cement production will need to be utilized. Recent studies have found direct air capture (DAC) to achieve net-negative CO_2 emissions[143,144] (e.g., DAC technologies emits less CO_2 than is captured and stored). Technologies like DAC will play a crucial role in assisting the cement sector in achieving net-zero emissions.

3.3.5 Cost Considerations

While not the focus of this work, cost is an important consideration when evaluating emerging cement technologies as it impacts their feasibility, timeline, accessibility, and potential for widespread

Table 3.3. Influences to cost for cement mitigation strategies compared to conventional cement.

Mitigation Strategy	Influences on Cost
Electricity Switching	Renewable energy prices have seen declines in recent years. It is projected to be a cost competitive option for fossil fuels, as the cost to build new renewable energy plants (e.g., solar farms and onshore wind) is lower than coal plants.[145]
Fuel Switching	The U.S. Department of Energy estimates a $60/tonne CO_2 cost increase for switching from coal to natural gas in 2040.[146] Pilot projects have shown production costs doubling for cement with use of electrification.[147]
Supplementary Cementitious Materials (SCM)	Can provide cost savings on thermal demand/fuel due to the reduced clinker demand. SCMs which are wastes from industrial processes (e.g., fly ash, GBFS) are limited to the production of their primary products. Increase in demand, with limited supply can influence the cost of these mineral additives. Will impact the cement/clinker supply chain; purchase of alternate material may be more expensive but can also be partially offset by reduction in cement clinker costs.
Clinkered Alternative Cements	Some alternative cements (e.g., reactive belite Portland cement) can result in energy cost savings due to lower thermal demands while others (e.g., BYF) can increase costs due to increases to raw material demands.[148]
Alkali-Activated Materials (AAM)	AAMs would disrupt the cement market, as it is an entirely new material to conventional cement. Depending on the type of raw materials selected for these mixtures, some studies found AAMs to be cost competitive to Portland cement,[149] while other studies found increases in cost by 40%.[150]
Carbon Capture Storage (CCS)	Current estimates have shown CCS installations to be two times the cost of installing a new cement plant.[10] Although this can impact the material cost of CCS cement, preliminary studies have shown that end-users may not experience much changes in cost (~1%)[151].

adoption. Table 3.3 qualitatively shows influences on costs for the GHG emissions mitigation strategies assessed in this work. It will be critical for California, and future regions, to provide regulatory protection and financial support (e.g., incentives) when costs may act as a barrier to implementation by the cement industry.

3.4 Conclusion

As mid-century approaches, action towards meeting climate targets needs to happen quickly and collectively. There have been recent policy and industry efforts to lower GHG emissions from cement and concrete production; however, there remain limitations in utility of transparent, customizable models to draw robust comparisons among concrete mixtures to mitigate environmental burdens. Region-specific technology roadmaps developed with open data tools will assist government and industry to work together in achieving these goals. Monitoring of environmental impacts beyond GHG emissions can inform efforts to advance climate change mitigation, while providing a broader perspective of environmental burdens that should be considered based on the needs of the local populations. Particularly, when considering mitigation strategies with high GHG emissions reduction potential, such as CCS, it is critical to quantify potential shifts in other environmental burdens and provide regulatory protections when necessary. Reduction potentials in currently available technologies show high GHG emission reduction potentials in California's cement industry, but they also highlight the need to include technologies outside the industry to reach net-zero emissions by mid-century (i.e., through the advancement of methods such as DAC). It is important to note that technologies along the value-chain and beyond the life-cycle scope of cement production (e.g., improving material efficiency in concrete; recycling concrete to promote a circular economy) must also be utilized concurrently to support swift decarbonization action. Only when all stakeholders work together to consider how mechanisms can be scaffolded will these regional and global climate goals be achieved.

4 Spatial implications of building materials production facilities and potential disproportionate impacts on neighboring communities

Publication

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Abstract

The construction and building materials (CBM) production industries, such as cement, steel, and plastics which are responsible for a substantial share of global CO_2 emissions, face increasing pressure to decarbonize. Recent legislative initiatives like the United States (US) federal Buy Clean Initiative and the World Green Building Council's decarbonization plan for Europe highlights the urgency to reduce emissions during their production stages. However, there remains a gap in addressing the localized environmental and social impacts of these industries as well as necessary understanding of how decarbonization efforts may change local impacts. This study introduces a method for quantifying the geographic disproportionate impact (I_d) of 12 CBM production facility categories on communities of color and low-income demographics across the US at three spatial scales – county, state, and nation. We apply this form of a spatial analysis as it does not exclude any forms of localized impacts (e.g., particulate matter emissions, releasing toxic leachates, emitting noise pollution, driving resource scarcities) nor does it exclude compounding impacts (e.g., individual facilities that meet regulations but are collocated leading to accumulated impacts). This study reveals that CBM facilities are often located in regions that impose disproportionate impacts to groups from historically marginalized, here focusing on communities of color and communities considered low-income, with greater disproportionate burdens in regions with higher concentrations of these groups. Based on this spatial understanding, we provide methods that can be implemented to support community engagement and mitigate damages to populations neighboring industrial materials manufacturing. These findings and methods can be

implemented in future studies of manufacturing and resource use alternative to advance comprehensive investigations into impacts to localized communities.

4.1 Introduction

The buildings and construction sector accounts for an estimated 37% of global energy and process-related CO_2 emissions[152]. A notable amount of these emissions is released during the materials production stage (sometimes referred to as the embodied carbon). As a result, recent decarbonization policies aim to significantly impact the high greenhouse gas (GHG) emitting industries within this sector. For example, in the United States (US), executive order 14057 launched a federal Buy Clean Initiative to prioritize use of lower-carbon construction materials[7], and the World Green Building Council (WorldGBC) launched a plan for the European Union to decarbonize the buildings and construction industries with an emphasis on embodied carbon[153]. Policies for climate change mitigation tied to fuel and energy use (e.g., for fuel standards in California[154]) have been reported to have co-benefits, showing improvements in impacts to air quality that can reduce burdens to local communities near the associated combustion sites.[155] The interlinkages between decarbonization efforts and localized burdens must integrate Environmental Justice (EJ). EJ, according to the US Environmental Protection Agency (USEPA), is the "fair treatment and meaningful involvement of all people regardless of race, color, national origin, or income, with respect to the development, implementation, and enforcement of environmental laws, regulations, and policies." Although environmental injustice and activism have been taking place for many years throughout the world, the formal EJ movement in the US began around the 1980s.[156] As the building material sectors progress in their decarbonization efforts, it is crucial to examine EJ impacts concurrently to avoid unintended consequences or worsen disproportionate impacts on specific, localized communities. Yet while EJ impacts from industries like transportation[157–160] and energy production[154,161–164] are widely reported, the EJ for the building materials sector is not.

Materials-production GHG emissions are driven by a combination of energy-derived sources (e.g., from combustion of fuels) and process-derived sources (e.g., through chemical conversion and material handling). For example, the production of cement, a hydraulic binder used to make construction materials like concrete and mortar, results in an estimated 7% of global anthropogenic CO_2 emissions annually.[115] The emissions from cement production are a result of using fossil fuels in the cement kilns and process-derived CO_2 emissions from calcination (in which limestone is decarbonated to create a reactive calcium compound for the formation of calcium silicates in cement),[3] as well as the enormous amount of consumption of cement, in excess of 4 billion metric tons (Gt) annually.[93] Other popular construction materials also have varied emissions sources. Steel production, of which over 50% goes into the built environment,[5] is responsible for another estimated 7% of anthropogenic CO_2 emissions[4]. It has CO_2 emissions from energy resources, as well as process emissions from the use of coal as a reducing agent and from limestone decarbonation (as lime is used as a flux to remove impurities steel alloys).[14] For plastics production, which contributes over 3% of global GHG emissions[165] and where nearly 20% of production is for construction use[166], there are energy-derived emissions as well as emissions from processes and other factors, such methane leakage.[167] As a result, there is a global burden from materials-derived GHG emissions, and decarbonization efforts for many building materials must tackle both energy-derived and process-derived emissions.

In addition to global GHG emissions, construction and building materials (CBM) production are also responsible for local environmental burdens, such as air pollution related particulate matter (PM) emissions, heavy metals exposure, and localized resource scarcities. Exposure to PM emissions cause a wide range of diseases, which impacts quality of life, and can lead to millions of premature deaths annually.[139,168] Heavy metals exposure can similarly cause human health issues; however, for heavy metal exposures there are commonly concerns associated with a number of neurological, cardiac and other diseases[169]. Unlike CO_2 emissions, PM and metal emissions are more likely to remain near the production facility, and there can be a range of impacts on neighboring communities depending on factors such as degree of exposure and underlying health issues.[170] And just as with CO_2 emissions, these emissions are not only driven by energy resources, there are process-derived impacts as well.

Quarrying activities, which are necessary for most conventional mineral-based materials, can produce PM emissions[171], as well as other impacts, including altering land use and creating overburden waste[172]. Metal mining and smelting activities can lead to gaseous emissions, solid waste, and wastewater containing heavy metals.[173] And the chemicals used in the production of materials like plastic can release processing compounds with significant burden of disease to exposed populations.[174] There are many other forms of ecosystem damages that can accrue from industrial production facilities, but among the more unique issues for materials production are localized resource scarcities, in which expected demand for a resource is greater than its local availability. Such impacts have been noted for common resources like sand and water.[30,175] Further, because quarrying activities are needed for raw material acquisition, there are a series of quarrying impacts that can occur, including altering land use and creating overburden waste.[172]

The impacts from manufacturing on a local level has been shown to systematically cause disproportionate impact on historically marginalized communities.[176] In the US, studies have shown an inequality and disproportionality in exposure to PM emissions for particular racial groups compared to others.[176,177] The effects from historical practices, such as redlining, have resulted in impacts to present-day health risks and outcomes.[178] However, current frameworks to improve environmental sustainability do not always promote EJ.[179] Most EJ research has focused on social implications;[158] the emphasis of such studies when examining materials production and demand have typically tied to planning decisions in specific locations (e.g., Ezeugoh *et al.* 2020[180] and De Sousa Silva *et al.* 2018[181]). Switches in technology to decarbonize CBM can alter such parameters as well as potentially create new emissions to air, water, soil, and waste depending on the resources used. Some innovations in decarbonizing other sectors, such as electricity generation from renewables instead of fossil resources,[182] have contributed to co-benefits in reducing health impacts.[61] Yet initial studies suggest co-benefits may not be as consistent from decarbonization methods for CBM due to the combination of process and energy-derived impacts as well as factors such the need for large quantities of resource consumption, such as the disproportionate burdens from using industrial byproducts in concrete to lower GHG emissions.[104]

In this work, we develop a method to measure the geographic disproportionate impact (I_d) of CBM categories within the US, focusing on two demographic indicators: people of color and people considered low-income. We apply this method at three spatial scales to determine the disproportionate impact relative to demographics within the (a) county (b) state and (c) nation. We investigate 12 CBM categories based on the North American Industry Classification System (NAICS) and map each CBM production facility in the US. Then we analyze the spread of I_d values at each spatial scale across all 12 CBMs and examine changes in I_d as they relate to ranges of demographic indicators. Finally, we synthesize key additional analysis methods that can be paired with this form of Geographic Information System (GIS) and spatiotemporal analysis to understand effects to localized communities.

4.2 Methods

4.2.1 Data sources

For this study, we leverage 2020 National Emissions Inventory (NEI) point data summaries[183] to identify CBM facilities which release emissions monitored by the USEPA, namely criteria air pollutants[184]. The CBM categories are created by organizing 2017 NAICS codes[185] based on construction material type (see Supplemental Methods for detailed explanation of categories), and these 2017 NAICS codes are used to match the NEI datasets. The 12 CBM categories investigated in this study include: (a) wood products, (b) asphalt, (c) plastics and rubber, (d) clay products, (e) glass products, (f) cement, (g) concrete, (h) lime, (i) gypsum products, (j) iron and steel, (k) alumina and aluminum, and (l) non-ferrous metals. Regional demographic information (e.g., people of color and people of low-income) at the census block group level is collected from the US Census Bureau's American Community Survey (ACS) 5-year summary (2017-2021)[186]. The Demographic Index (DI) is defined as the average between the percentage of people of color and percentage of people considered low-income in a region, based on methods from the USEPA's Environmental Justice Screening and

Mapping tool (EJScreen) 2.2[187] (Eq. 4.1). In this work, all mention of demographic groups specifically refers to people of color and people considered low-income, which are jointly categorized as DI.

$$DI = \frac{\%\, people\ of\ low\ income + \%\, people\ of\ color}{2} \qquad \text{(Eq. 4.1)}$$

4.2.2 Disproportionate impact equation

Here, we determine disproportionate impact (I_d) by location using proportionality indices (geographic disproportionality). Namely, geographical $\mathrm{I_d}$ is an indicator of the disproportionate burden associated with CBM facilities being located in areas with people of color and people considered low-income (i.e., agnostic of the quantity of environmental burden). This approach prioritizes analyzing spatial distribution of facilities rather than on their type or quantity of emissions. While not all facilities within the US meet regulatory thresholds, there are mandates in place and repercussions for not meeting these health-related guidelines. However, the concentration of multiple industries in one area can lead to cumulative emissions exceeding desired boundaries for population exposure even when the individual facilities meet required thresholds for quantities of emissions to the environment. This issue is further complicated by the lack of a standardized method to map the dispersion of various pollutants, such as PM emissions, heavy metals, and water pollution, to impacted communities and measure their human health impacts presents a significant challenge. Further, examination of individual types of emissions can inadvertently exclude impacts to neighboring communities, factors such as other emissions, noise pollution, and property value loss. As such, a geographical $\mathrm{I_d}$ is investigated here. In this work, a region of analysis is defined by a Census Block Group (CBG), as it is the smallest geographic area with demographic information from the US Census Bureau's ACS 5-year summary[188]. The I_d (the geographical disproportionate impact) is determined using the following relationship:

$$I_d = \frac{F_i}{F_{total}} \qquad \text{(Eq. 4.2)}$$

where F_i is defined as subgroup i of those in a particular outcome for a specified CBM category and DI range. Namely, this parameter is used herein to represent the percent of CBGs with a selected CBM affecting a particular DI range. Here, we address variation in demographic groups, broken down by 10% increments, where DI is between [0, 0.1], (0.1, 0.2], (0.2, 0.3], (0.3, 0.4], (0.4, 0.5], (0.5, 0.6], (0.6, 0.7], (0.7, 0.8], (0.8, 0.9], (0.9, 1]. Then, we define percent of regions with a selected CBM industry (e.g., of all regions with a given industry, the percent that are located in a region with 60%-70% low-income persons). This ratio can be calculated as:

$$F_i = \frac{F_{Industry,i}}{total\ number\ of\ CBGs\ with\ that\ industry\ within\ the\ region} \qquad \text{(Eq. 4.3)}$$

where $F_{Industry,i}$ = the number of CBGs with a specified CBM industry in a particular DI range in a region (e.g., county, state, nation), F_{total} = total in an outcome group for a DI range, namely, used herein to represent the percent of CBGs in a particular DI range broken down by 10% increments (e.g., of all regions, the percent of regions with 60%-70% low-income persons). This ratio can be calculated as:

$$F_{total} = \frac{F_{DI,i}}{total\ number\ of\ CBGs\ within\ the\ region} \qquad \text{(Eq. 4.4)}$$

where $F_{DI,i}$ = the number of regions in a particular DI range corresponding to the range for $F_{Industry,i}$.

This geographically based proportionality index, I_d , can be interpreted based on the value of the ratio between F_i and F_{total}. If the ratio is equal to 1.0, then the proportions of subgroups are equal, and we would consider there to be no disproportionate impact. A ratio greater than 1.0 indicates that the subgroup is more prevalent in the outcome group (e.g., a sub-population that is more prone to an industry being located nearby than the total population). A ratio less than 1.0 indicates that the subgroup is less prevalent in the outcome group (e.g., a sub-population that is less prone to an industry being located nearby than the total population). We examine this geographical disproportionate impact at 3 spatial scales, namely, the effects on a percent of the population within a given demographic group relative to that demographic group within the country, state, and country.

4.3 Results

4.3.1 Construction building material facility locations and Demographic Index (DI) maps

To visualize the regions of interest, Figure 4.1a shows the number CBM facilities per US county; an individual map of facilities for each of the 12 CBMs is provided in Appendix C (Figure S1). Figure 4.1b presents the average DI among all CBGs (including those which do not have CBM facilities present) for each US county, using demographic data from the ACS 5-year summary for years 2017-2021. Any CBM facility located in a CBG with no residents is not included in this study. Among all CBGs where at least one CBM facility exists, the US average DI value is 33% (slightly lower than the US average for all CBGs, which is 35%). Among all CBGs included in this study, for state averages, Arizona has the highest county DI, with both the mean and median at 54% and 55%, respectively. Conversely, New Hampshire records the lowest average county DI, with both the mean and median at 8%. Nottoway County in Virginia experiences the maximum value for county level DI (i.e., average DI of all CBGs per county) in the US at 100%. This peak is due to the only CBM facility in the entire county being in a CBG where 100% are people of color and people considered low-income. Union County in Ohio experiences the lowest-value county level DI at 2%, where two CBM facilities exist.

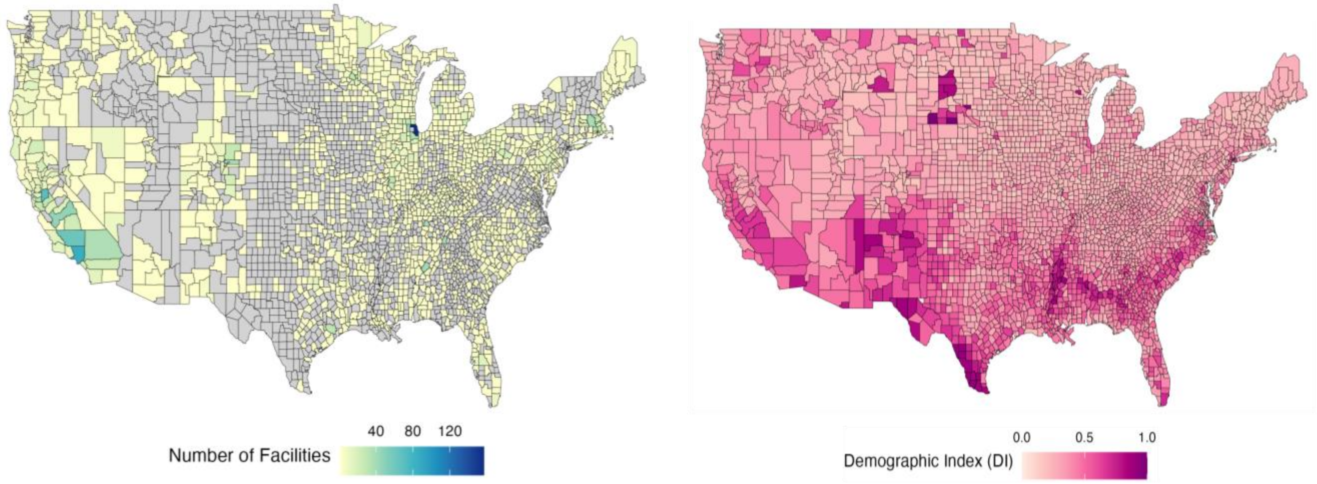

Figure 4.1. (a) Count of Construction Building Materials (CBM) facilities per county in the United States and **(b)** average percentage of people of color and people considered low-income per county (i.e., Demographic Index (DI)) in the United States, including all Census Block Groups (CBGs).

4.3.2 Disproportionate Impact (I_d) for each construction building material category

To compare results across CBM categories, Figure 4.2 displays the range of I_d values for each CBM facility per category relative to those demographic groups within (a) the county (b) the state and (c) the nation. At all three spatial scales, on average CBM facilities are located in regions that drive disproportionate impacts to people of color and/or low-income (i.e., $I_d > 1$); distributions of I_d values for each material type for all three spatial analyses are provided in the Supplemental Materials (Figure S2). In our analysis at the county, state, and national levels, we find 11%, 33%, and none of the facilities, respectively, are located in regions where the demographic groups are less prone to a CBM facility being located nearby than the total population, indicated by an I_d value of less than 1. This result indicates further that most facilities are causing disproportionate impacts on the demographics measure by our DI (i.e., 89% of facilities at the county level, 67% at the state level, and 100% at the national level).

For the county level analysis (Figure 4.2a), the overall (including all CBM categories) mean I_d value is 1.80. In this case, non-ferrous metals facilities exhibit the highest mean I_d value at 3.79, which indicates that non-ferrous metals facilities are currently located in regions with the highest geographic-based disproportionate burdens relative to county demographic groups – a reflection, in part, of highly localized production. Conversely, concrete facilities are frequently distributed in areas with the lowest geographic disproportionate burdens, with a mean I_d of 1.41 at the county level – a reflection of concrete production being widely distributed to support building and infrastructure development. This analysis shows low variability of disproportionate impact values across all CBMs, with an average interquartile range (IQR) of 1.00. Here, cement and clay display the greatest variation in disproportionate impacts, as evidenced by an IQR of 2.00 for both industries. This quantitatively indicates that cement and clay facilities are situated across the widest range of regions studied.

For I_d values relative to demographic groups within the state (Figure 4.2b), the overall mean is 1.52. This value suggests that, on average, CBM facility locations impose disproportionate impacts relative to state demographics. At this spatial scale, gypsum product facilities are located in areas with the highest geographical disproportionate burdens, which is exhibited by a mean I_d value of 5.26. Whereas concrete facilities are placed in regions with the lowest disproportionate burdens relative to the demographic groups investigated in our study, with a mean I_d of 1.19. This analysis exhibits 38% less variability in data across all CBMs compared to the county level, with an interquartile range (IQR) of 0.62. In this case, gypsum facilities are located in a wide range of regions examined, which is exhibited by having the largest IQR of 5.39.

Relative to national demographics, the overall mean I_d value is significantly greater than both the county and state analysis at 48.1 (Figure 4.2c). This over 26-fold increase in mean compared to the county level analysis is primarily due to the cumulative count of CBGs across the nation (denominator in Eq. 4.4) being consistent for all I_d values, unlike at other spatial scales (e.g., county and state), which vary depending on region. (Figure 4.2c). Here, lime facilities are largely located in regions exhibiting the highest disproportionate burdens, with a mean I_d at 58.5. Whereas plastics and rubber facilities are commonly found in areas with the lowest disproportionate impacts, with a mean I_d at 46.6. This analysis exhibits the highest variability in data across all CBMs compared to other spatial scales, with an average interquartile range (IQR) of 9.91. In this case, lime facilities are located in the most varied regions (among all facilities which have I_d values), with an IQR of 23.0. These findings highlight the significance of different spatial scales for comparisons of demographic groups, showing that in general high disproportionality is noted when comparisons are drawn to larger geographic regions.

Finally, on average greater disproportionate burdens are observed in regions with higher concentrations of people of color and people considered low-income (Figure 4.2d). This trend is displayed in Figure 4.2d, which shows the county-level mean I_d values for every CBM category along with the total average among all categories at each DI Range.

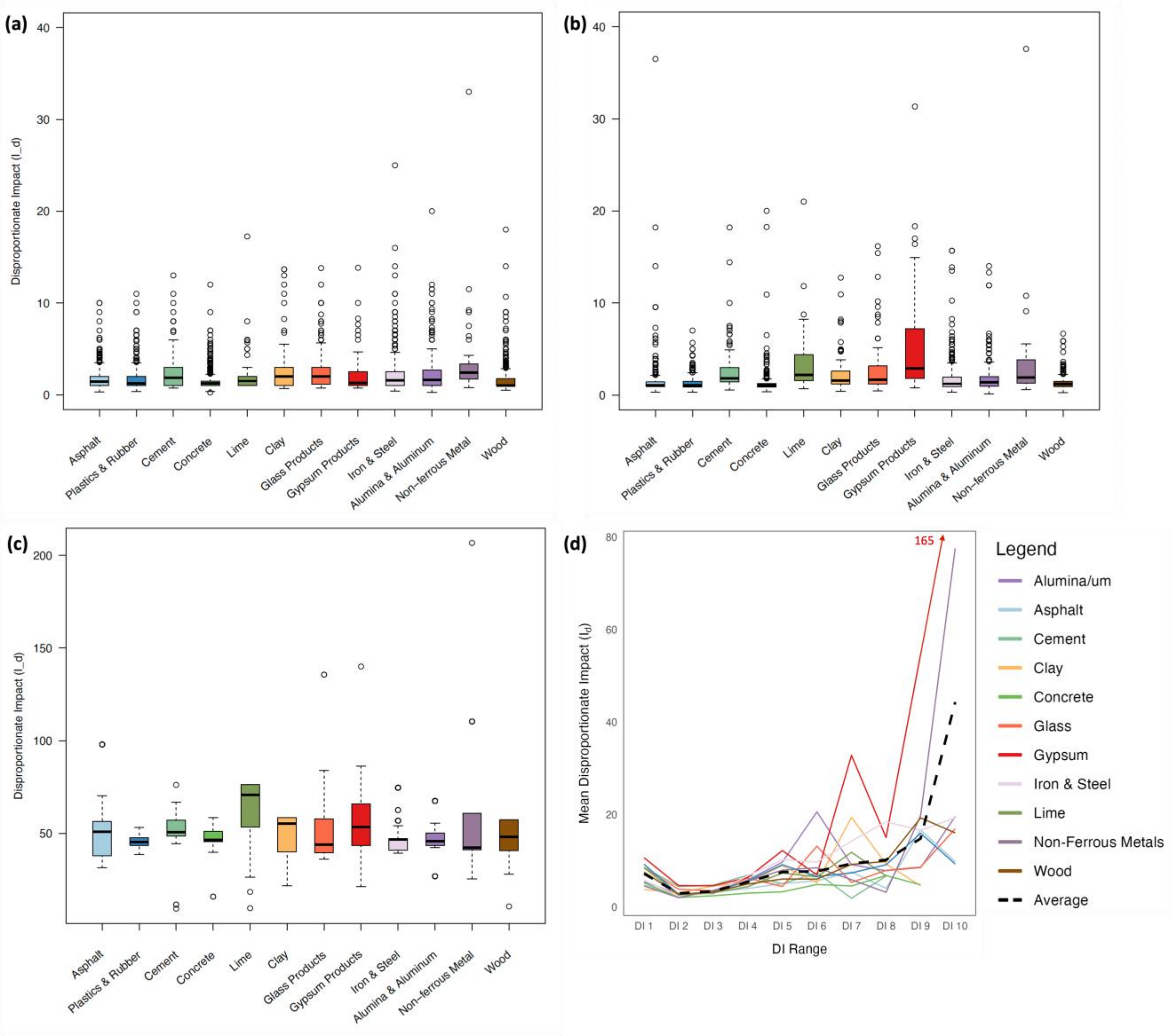

Figure 4.2. Boxplot of geographical disproportionate impacts (I_d) per Construction Building Material (CBM) category for the entire United States relative to those demographic groups within **(a)** the county **(b)** the state and **(c)** the nation. **(d)** Mean county level geographical I_d per CBM category for each Demographic Index (DI) range (note: to enhance data interpretability, the y-axis does not extend to include the maximum mean I_d value for gypsum, which is 165; however, this is displayed directly in the figure).

4.3.3 United States maps of Disproportionate Impact (I_d)

To reflect these disproportionate impacts, Figure 4.3 displays the average I_d values for all CBM facilities in US counties relative to demographics within the (a) county (b) state and (c) nation. For the county level analysis, facilities located in Alabama are situated in regions that exhibit the highest geographic disproportionate burdens to people of color and people considered low-income, with the highest statewide average I_d at 2.19 (Figure 4.3a). However, facilities in Alaska (not shown), New

Hampshire, North Dakota, and South Dakota are distributed such that on average there is no disproportionate impact associated with their physical location relative to these demographic groups. Each of these states have the lowest statewide average I_d at 1.00. It is important to note that this trend is in part because Alaska, New Hampshire, and North Dakota have the smallest amount CBM facilities included in this study, with only one, three, and two facilities in the entire state, respectively, and among the smallest populations in the US. The state-level analysis displays an 89% increase in the highest statewide average I_d at 4.13, in which facilities in New Jersey exhibit the highest geographic-based disproportionate burdens (Figure 4.3b). Similar to the county level, here, facilities in Alaska and New Hampshire are generally located in areas which experience no disproportionate impact, with the lowest statewide averages both at 1.00. Lastly, the national level again shows an over 26-fold increase in the highest state average, with New Hampshire facilities being in regions with the highest disproportionate burdens and the average I_d at 57.9 (Figure 4.3c). This is due to the cumulative count of CBGs across the nation (denominator in Eq. 4.4) being much larger than the number of CBGs within a particular DI range for the three CBM facilities in New Hampshire. In this analysis, facilities in Idaho are located in regions with the lowest geographical disproportionate impacts, having the lowest statewide average I_d at 43.5.

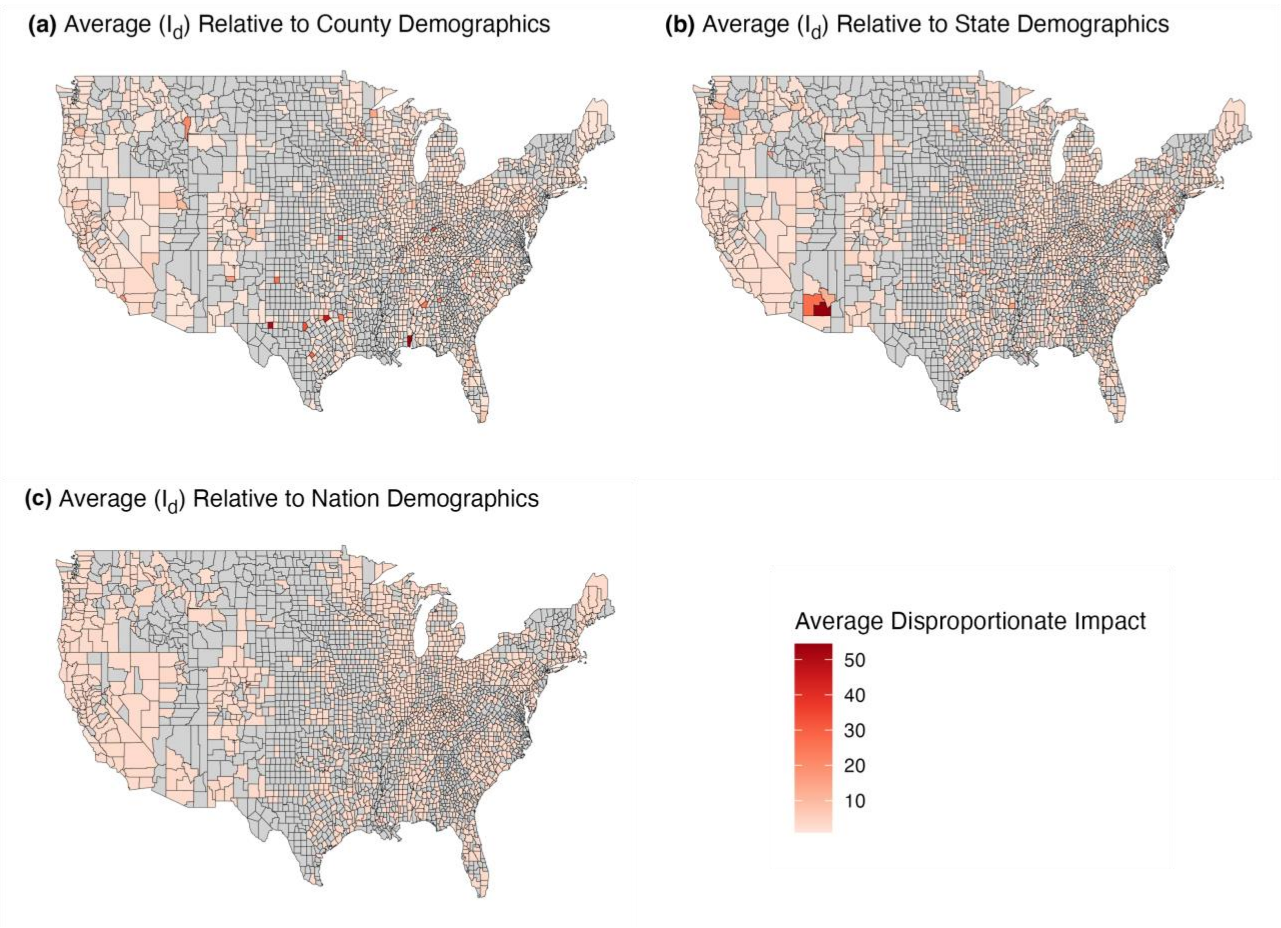

Figure 4.3. Average Disproportionate Impact (I_d) values for all Construction and Building Materials (CBM) facilities in United States counties relative to demographics within the (a) county (b) state and (c) nation.

4.4 Impacts on Neighboring Communities

Although this work provides a starting point in integrating environmental sustainability and social impact through spatial analysis, it is crucial to consider other factors to develop comprehensive and community-centered models. Understanding the impacts of industrial facilities on neighboring communities is a multidisciplinary endeavor that often involves analyzing environmental, health, social, and economic factors. With all these methods, data can be paired with socioeconomic characters of communities from census data and GIS data, as was done in our analysis above, to identify disproportionate equity impacts. Here, we review a collection of methodological approaches that can allow for considerations of these additional factors and expand and refine this work.

4.4.1 Environmental monitoring of pollutants

Environmental monitoring can be used to quantify environmental burdens from facility practices. Localized monitoring methods can be used to identify areas of concern and monitoring over time and location can allow evaluation of probable causes of adverse effects on the environment.[189] For example, analysis of data from before and after a mitigation is instituted can indicate whether the mitigation is reducing the characteristics measured. Analysis of data from multiple monitors at set distances from a cement facility can indicate the extent of impact and suggest whether pollution is coming from the facility or from other sources. These assessments can be of biophysical characteristics (such as changes in air, water, and soil quality) and biophysical impacts (such as waste)[190]. Monitoring efforts to assess potential areas of concern and change, can include[191]:

- Air Quality Monitoring - setting up stations to continuously monitor air quality, which can be focused on pollutants of key concern or pollutants known to be emitted by the facility.
- Water Quality and Quantity Monitoring - sampling and analysis of water bodies near the facility to measure potential contamination (e.g., heavy metals, chemicals) caused by processes on site, as well as measurement of ground water level.
- Soil Analysis - examining soil samples for contaminants to identify any leachate or spillage from the facility that can affect local agriculture and ecosystems.
- Noise Monitoring – using sound level meters to indicate potential damage to, stress on, or interference with sleep or other behaviors of humans and fauna.
- Waste Monitoring - measuring quantities and types of waste (e.g., mine tailings, hazardous waste) generated by the facility, as well as transport and disposal pathways.

Each of these monitoring techniques requires professional/technical support to design a study, calibrate equipment, establish data gathering points, and analyze data.

4.4.2 Assessment of health impacts

Assessing community health impacts has been linked to assessing environmental impacts since the National Environmental Policy (1969) established a focus on the effects of large projects and recently, has expanded to include disproportional impacts based on socio-economic factors to focus on health-equity[192]. A primary means of assessing community health impacts is through analysis of quantitative epidemiological data that indicate incidence and prevalence of disease often across time and across geographic areas. These can be used to compare the health of populations living near the facility with that of populations farther away, looking for correlations between proximity to the facility and health issues (e.g., Wong and Raabe 2000[193]). Qualitative health surveys can be conducted to collect descriptive data from populations of interest, such as local communities. Such surveys can inquire about personal health as well as health concerns,[194] including any potentially linked to a specific industrial facility. Reliance on such surveys must be tempered by consideration of the size and representativeness of the sample, response rates, and accuracy of memory of health history. Even with these caveats, health surveys can offer suggestions of areas to further examine. A substantial amount of structured and unstructured data is collected by hospitals and clinics, though access might be limited if data bases have not been designed to provide anonymity for patients. As with epidemiological data, analysis of hospital medical data by location can identify trends in medical conditions and can be correlated to quantitative measures of pollution from materials production[195].

4.4.3 Economic parameters

There are several economic parameters beyond demographics that could be considered in the examination of an industry, its effects on neighboring communities, and GHG emissions mitigation strategies. Assessments can include consideration of job creation versus job loss, changes in property values, and the facility's overall economic contribution to the local economy. Tracking such parameters can be used to indicate potential economic effects on neighboring communities. Beyond the employment directly in the manufacturing facilities, there are upstream and downstream industries that manufacturing influences, which could also lead to employment (e.g., mining, transportation, product assembly)[196] as well as employee expenditures within the community. Such assessment can also be paired with consideration for the local housing market, including how the presence of or distance from the facility influences property values, rental rates, and housing demand. For example, multiple studies in Europe have shown that residential property values go down with increased proximity to industrial manufacturing sites[197,198].

4.4.4 Community engagement and ethnographic studies

Obtaining input from members of adjacent or nearby communities and understanding their goals and priorities is critical to mitigating negative outcomes from production facilities. Such engagement can foster buy-in for changes that are going to be made and ensures that the community is heard if there are any concerns. This is uniquely different from corporate social responsibility, which has received criticism. Namely, in some cases, employees have had a limited role in corporate social responsibility, which has limited its inclusivity[199]. It has been argued that a corporate code of social responsibility without community engagement can conceal a strategy of simply business as usual[200]. This issue has been emphasized for mining-related industries[200]. It has been highlighted that organizations should move towards recognizing the interconnectedness between local communities, particularly indigenous communities, and future sustainability goals [201]. Community involvement that relies on tours and contributions to local non-profits is not the same as engagement. Methods for community engagement could employ surveys and interviews, which can help gather insights directly from the residents about their perceptions, concerns, and experiences related to the industrial facility. As with health surveys, sample size and representativeness, as well as response rate, can limit usability. Focus groups can also be conducted, bringing together diverse community members to discuss specific aspects of the facility's impact, offering qualitative data and nuanced understandings. Organizations can run listening sessions to collect information about members of the neighboring communities' experiences.

While distinct from community engagement, ethnographic studies can further bolster understanding of neighboring communities, their goals, and their concerns. Namely, through fieldwork, living in a community, a better understanding can be gained about the circumstances of the people being studied[202]. Often called participant observation, researchers immerse themselves in the community, observing daily life and community-facility interactions, gaining a deeper understanding of the lived experiences of residents. However, while participant observation can provide rich, qualitative data on individual and collective experiences, perceptions, and attitudes towards the industrial facility, its time-intensity and lack of reproducibility of results limits it utility.

4.4.5 Secondary data analysis (including legal and policy analysis)

There are several forms of secondary data analysis that can provide perspective on community response to neighboring cement plants. Secondary data are data that were collected for another purpose. A review of the existing academic studies, industry reports, and case studies from similar contexts can be used to predict and understand potential impacts. Ideally, such work would be organized thematically or methodologically, synthesizing findings to illustrate the current state of knowledge and the evolution of the field, as well as highlighting existing limitations. Analysis of secondary data can also play a critical role in determining expected impacts on neighboring communities (as well as burdens external to the community) in the absence of primary data (such as direct emissions monitoring or community health data). Quantitative secondary data such as data gathered by government agencies, NGOs, and other organizations can often provide material for analysis of potential impacts without the cost of original research. For example, an air pollutant emissions calculations based on industry-dependent energy demands[203,204], state reported energy resources used[205], and nationally reported emissions factors by energy resource and combustion type[206] can permit assessments comparable to various forms of monitoring.

Reviews of legal compliance of the facility with environmental, health, and safety regulations, can provide useful insights for the community. Most pointedly, these could include court cases, recorded violations, and grievances against industrial facilities (e.g., William and Onciano 2022[207]) and alternative technology companies offering GHG emissions reduction methods. For violations on environmental aspects, inadequate monitoring, reporting, or action to mitigate impacts to water, air, and soil, there are direct implications of potential effects on the neighboring communities. However, cases involving labor-relations can also be used to understand if there are potential other issues that may affect the community. Further, complaints regarding management methods can be strong indicators of the potential efficacy of regulatory measures. For example, in the past there were many complaints filed by the Federal Trade Commission with regard to vertical integration and mergers with cement companies and ready-mixed concrete producers[208]. And in Europe, it has been argued that there are both legal and illegal cartels that have influenced cement industry monitoring efforts, information exchange, and pricing schedules[209].

Part of such work can also include both assessments of the effectiveness of current policies and assessments of the effectiveness of policies in other areas in protecting the community, as well as guiding responsible industrial practices. Examining policy effectiveness could include checking if it has measurable goals, utilizing before-and-after data to assess performance metrics, soliciting expert and public feedback, examining stakeholder benefits against costs, noting any unintended effects, and ensuring transparency and accountability. In considering other policies, several policies have been implemented in the US to quantify or address the embodied carbon of materials (which would encapsulate emissions such as those from cement production) (e.g., toolkit by the Carbon Leadership Forum[210]). Internationally, policies addressing embodied carbon have also been explored and/or implemented (e.g., Rowland et al 2023[211] and report by the French Ministry of Ecological Transition and Territorial Cohesion[212]).

4.5 Discussion

Recent policies aimed at industrial decarbonization are anticipated to significantly impact construction and building materials industries, as they will be required to adopt practices that reduce their environmental burdens. This new focus provides an opportunity to monitor and address social burdens, such as historical EJ concerns, at the same time. However, there is a current data gap in applying EJ concepts to building materials production. We provide a method which measures the disproportionate impacts of building material production facilities on communities of color and of low-income, at three spatial scales. We find that, across each of these spatial scales, a majority of CBM facilities are causing disproportionate impacts. Further, on average, as regions increase in percentages of people of color and people considered low-income, we also see increases to disproportionate impact. These findings provide insights into the spatial distribution of CBM facilities and their disproportionate impacts on demographic groups in the US. The wide range of I_d values across different spatial scales indicates that the extent of disproportionate impact varies greatly by location, suggesting targeted interventions could alleviate localized burdens. By pairing modeling results for industries with high disproportionate impacts to neighboring community-assessment, analysis of methods that will support decarbonization goals while limiting localized burdens can be better understood. As this is a first step to address this gap, it is important to note that the quantitative method implemented herein is a geographic-based indicator, and it does not reflect the relative environmental emissions per CBM facility analyzed. Additionally, the US Census Bureau used to collect demographic data generally underreports communities that are particularly vulnerable to environmental injustice such those who are unhoused, indigenous/native, and migrant workers. It will be critical to address and mitigate these limitations in future work as research on the social implications of construction building materials grows.

5 Integrating service-learning with sustainability engineering to broaden student learning outcomes

Publication

Currently, under review with Journal of Civil Engineering Education (an ASCE journal).

Abstract

Engineering emphasizes service and public welfare as core to the discipline. New generations of engineering students envision service and social impact work as significant components of their future careers. However, engineering education prioritizes traditional academic learning outcomes, which often do not include community engagement or service. Service-learning is a form of community engagement applied in classrooms that pairs well with traditional engineering academic learning outcomes. By addressing this gap in engineering curricula, it can prepare students for their professional roles in the workplace. Here, we introduce an upper-division undergraduate civil and environmental engineering course that integrates both Service-Learning and the Engineering Design Process while emphasizing environmental sustainability and environmental justice concepts. We analyze pre-course and post-course student survey responses and find increases in student knowledge, confidence (i.e., self-efficacy), and perceived usefulness of course concepts (i.e., academic learning outcomes). We also observe students exhibiting increased awareness and connection to their own social identities and recognized them as strengths in their future careers (i.e., personal outcomes). Further, we confirm social impact, sustainability, and climate change to be persistent motivators for students selecting engineering as their discipline. Although we discover a consensus among young engineers regarding their dissatisfaction with current sustainability efforts and feelings of climate anxiety, we also find increases in students' hope in spite of these barriers after the course (i.e., social outcomes). Cumulatively, these findings indicate that a service-learning course in sustainability engineering can lead to increased learning outcomes which align with the current needs for and desires of early engineers.

5.1 Introduction

The growing urgency of environmental challenges, particularly the climate crisis, demands sustainability to be fundamental to the role of civil and environmental engineers. To ensure these challenges are approached equitably, engineers must view these issues with community engagement principles in mind[213]. Sustainability principles are a required part of the Accreditation Board for Engineering and Technology's (ABET) civil and environmental engineering program criteria[22]. Additionally, the National Science Foundation (NSF) highlights understanding of the environment, links to health outcomes, and community engagement as critical concepts[23] – a priority echoed in the United Nations' Sustainable Development Goals (UNSDGs)[214]. Further, engineering as a profession underscores public welfare and societal needs as core to the field's fundamental principles[215]. However, civil engineering curricula at higher education institutions have not historically prioritized service, community, or public welfare in their courses for students[216].

Service-learning is an educational experience that integrates disciplinary learning and community engagement[217]. When applied, service-learning is a credit-bearing academic course where students (a) participate in a service activity defined by a community goal and (b) reflect on their experience to deepen their course learning and gain a broader appreciation for their major[218]. This type of learning is known to lead to academic, social, personal and civic responsibility outcomes for students[219] and aligns with undergraduate research experiences (e.g., community-based research) presented by the National Academies[220]. Additionally, integrating academic learning with community engagement allows for students to link their personal and professional cognitive development[221]. While the adoption of service-learning as a pedagogy in engineering programs has generally been slow [222], notable exceptions exist, such as Purdue University's Engineering Projects in Community Service (EPICS) program[223] and the Louisiana State University (LSU) Community Playground Project[224]. It is crucial for more engineering institutions to integrate service-learning into their curricula to emphasize the importance of service and environmental sustainability in engineering education. Together, these can play a crucial role in equipping young people with the knowledge and skills to make informed decisions to contribute to societal needs [225].

Furthermore, although there is a growing emphasis on diversity, equity, inclusion, and justice (DEIJ) on college campuses in the United States (U.S.), issues persist in attracting and retaining a diverse student body in engineering [226,227]. Namely, Hispanic/Latinx, African American/Black, Native America populations**,** and White women are underrepresented at each level of engineering in higher education (BS, MS, and PhD), earning approximately one half, one third, one fifth, and one half of all the expected degrees for each population group, respectively [228,229]. Integrating core engineering principles like service into curriculum is particularly well suited to address these challenges, as helping society and social service are known drivers for historically marginalized groups choosing to study engineering [24,25]. It has also been suggested that such courses have benefits of increased student retention and forming pipelines to faculty positions [230]. Further, environmental concepts which highlight human concerns, such as the effects of material sustainability, has also been shown to be a key avenue to engage a new generation in engineering[231]. Altogether, these concepts can support increased diversity and inclusion in engineering to expand the intellectual talent pool, broaden perspectives brought to problem solving, and strengthen the workforce.

In this work, we evaluate an upper-division undergraduate civil and environmental engineering course that utilizes a Service-Learning approach to teach course content that emphasizes environmental sustainability and environmental justice concepts. We examine quantitative responses from pre-course and post-course surveys from students in the course to measure student academic learning outcomes. Further, we analyze long-form qualitative responses to questions related to their motivations for selecting engineering, social and personal identities within engineering, goals for their careers, and their feelings on current environmental sustainability efforts. The initial long-form responses are paired with shifts in responses received at the end of the course to examine personal and social outcomes.

5.2 Methods

5.2.1 Course Overview

We introduced a pilot upper division undergraduate civil and environmental engineering course over a 10-week quarter, which combined Service-Learning with a Project-Based Learning (PBL) approach. PBL is defined as an active student-driven approach to teaching which emphasizes context-specific learning, involving students throughout the learning process (e.g., goal setting, collaboration, and constructive investigations), and reflection on real-world practices [232]. The motivation to use both approaches in this class was (1) to provide a community engagement opportunity for students to attract diverse students and broaden their academic experience and (2) to offer more hands-on educational opportunities in preparation for the workforce in response to earlier anecdotal student feedback. Throughout the course students worked with a local community partner to design an engineered alternative for the community partner's operation. The course was structured to provide students with hands-on experience focusing on how environmentally sustainable solutions can be designed and implemented in the community. Lecture and homework content spanned from learning and practicing the key steps of the engineering design process, reviewing effective community engagement practices, discussion of environmental and social justice cases within engineering, professionalism (through project management principles), and practice using Life Cycle Assessment (LCA) (quantitative methods for assessing environmental sustainability of products made). And the course activities included lectures, homework assignments, lab activities, and assembling of a product for the community partner. The course concluded with the students completing an engineering design alternative and implementing the engineered design alternative on-site with the community partner. In this course design, each of the six stages of Bloom's taxonomy were integrated in the course[233].

For the first offering, our community partner was a local ecological garden. Ten undergraduate students designed, built, and installed a worm composting bin for them. The worm bin is used by the ecological garden to introduce topics like reducing food waste, addressing food justice, and reducing climate impacts to local K-8 students. However, the ecological garden workers faced challenges with the existing worm composting bin such as deterioration, overly heavy lids, and walls too high for smaller children. As such, the course tasked the engineering students with designing and installing a new bin. The students who participated in the course ranged from 2nd year to 5th year undergraduate civil and environmental engineering students. The course provided upper division elective credits, which can be applied to their graduation requirements, demonstrating the department's commitment to the course. Students learned woodworking skills using equipment like the table saw, miter saw, jointers and planers, power tools, and levels to build their final design. To tune the course to this specific partner, discussion of constructability and vermi-composting were added as lecture topics.

The course centered most lessons and assessments on the Engineering Design Process to reinforce core engineering principles (Figure 5.1a). This process served as a guideline for the instructors when designing the course assignments and for the students when designing their final project. As part of the course, students started with the "Ask" phase by interviewing the community partner about their goals and current challenges/limitations for the worm composting bin. Then students were guided to performed "Research" to supplement their interview findings. Using their research, students entered the "Imagine" stage where they developed their own individual preliminary designs, which were shared with the community partner at the ecological garden. The community partner provided feedback to the students, which they incorporated into their group "Plan" for their final design (after the imagine stage students self-selected to be part of a group designing either: (a) base bin or (b) the lids for the composting bin). Once the plans were developed, students presented their final design proposal to the community partner. Finally, students entered the "Create" phase where they utilized woodworking equipment to bring their designs to life. Practitioners of community engagement follow a similar process to engineering design, to ensure community expertise and community objectives are central to the work (Figure 5.1b). By following the Engineering Design Process students were also able to practice the factors that drive community throughout their design process (e.g., community partner's expertise was central to throughout the design process, the design was co-created with the community partner, students and the community partner had time to reflect together). Although timing did not permit full incorporation of the remaining phases, students practiced “Test” and “Improve” phases of the engineering design process through reflections in their final project reports. Further, after the course completed, the instructors maintained contact with the ecological gardens to learn about how the project tested with time. Plans to incorporate improvements are currently underway. These findings will be shared with the previous engineering students to emphasize the importance of these stages and continuous learning.

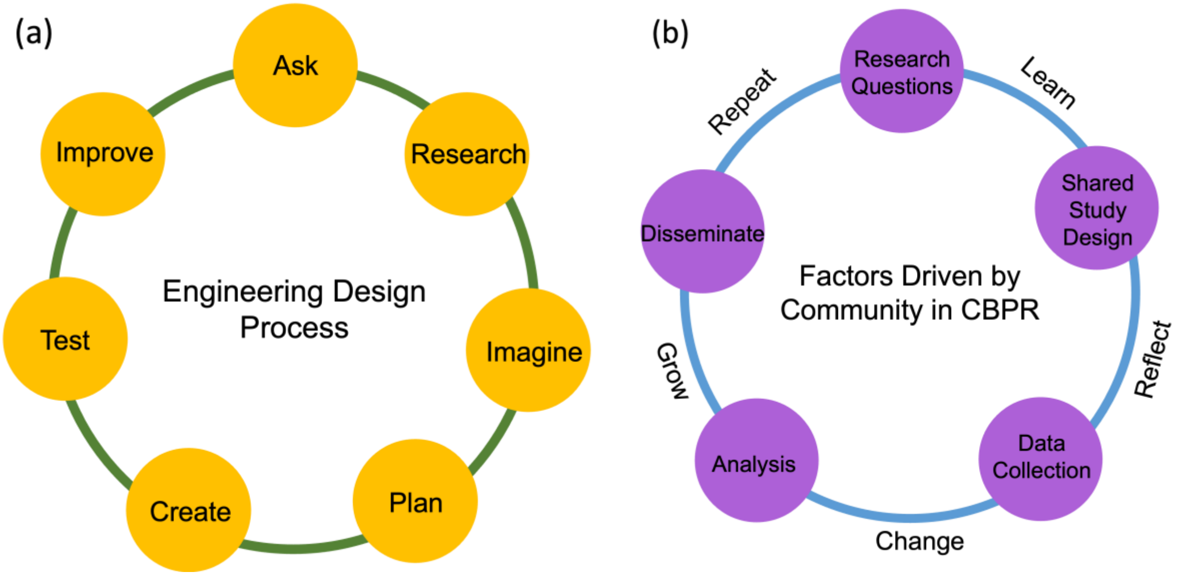

Figure 5.1. (a) The engineering design process, modified from Carberry et al. 2010[234] and (b) factors driven by community in Community-Based Participatory Research (CBPR), modified from Milton et al. 2023[235].

5.2.2 Survey

Quantitative and qualitative assessment of the students’ experiences included pre- and post-course surveys to inform impact on learning outcomes (e.g., ability to apply knowledge), personal outcomes (e.g., sense of personal efficacy and belonging), and social outcomes (e.g., reduced stereotypes), as well as review of student assignments. The survey asked the same quantitative and qualitative questions at the beginning and the end of the academic quarter (10 weeks apart). The instructors reviewed informed consent with the students before administering the survey and obtained it from all participants. Students provided this data anonymously, as the survey first asks students to create a unique reproducible identifier to ensure confidentiality of their responses. The first series of prompts were quantitative, using a 0 to 3 adaptation of the Likert scale to assess students' sense of knowledge about, confidence in applying, and perceived usefulness of 14 topics that are introduced in the course (scales presented in Table 5.1). Following this, students responded to a set of open-ended questions where they are encouraged to write out longer personal responses (Figure 5.3). Finally, students received a reminder of informed consent and are asked to select the level they feel comfortable with sharing and publishing their responses. The official survey along with all questions are provided in Appendix D.

Table 5.1. Likert scales for assessment of knowledge, confidence, and usefulness of course concepts.

Knowledge: to assess the level of knowledge a student feels they have of the concept		
	0	I have no knowledge of the concept
	1	I have some knowledge of this concept
	2	I have more than average knowledge of this concept
	3	I have a substantial amount of knowledge about this concept
Confidence: to assess how confident a student feels they can apply this topic in their lives		
	0	I am not confident in my ability to apply this concept in my personal/academic life
	1	I am somewhat confident in my ability to apply this concept in my personal/academic life
	2	I am more confident than most in my ability to apply this concept in my personal/academic life
	3	I am very confident in my ability to apply this concept in my personal/professional life
Usefulness: to assess how useful a student feels a topic is for their career		
	0	This concept or strategy is neither useful nor relevant for my career aspirations
	1	This concept or strategy is somewhat useful and/or relevant for career aspirations
	2	This concept or strategy is useful and/or relevant for my career aspirations
	3	This concept or strategy is very useful and/or relevant for my career aspirations

5.3 Results

5.3.1 Quantitative Responses

The students' quantitative survey results are displayed in Figure 5.2. Before the course, on average students found all topics useful (i.e., a score of 1 or greater). The results showed on average increases in students' knowledge, confidence, and usefulness for all topics except for in two categories:

usefulness of the engineering design process and professionalism, where students' scores remained the same (average results are high at 2.78 and 3.00, respectively). Students demonstrated average increases in score of 1 or greater in five concepts: their knowledge and confidence of Industrial Ecology, constructability, service-learning, vermi-composting topics, and their LCAs. Industrial Ecology is an essential concept for sustainability-focused engineers and has even been defined as "the science of sustainability"[236]. LCAs are an integral part of the field of Industrial Ecology and is defined by the International Organization for Standardization (ISO) 14040 as "the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle"[237]. Despite noting an average usefulness score of 2.00 for Industrial Ecology before the course started, at that time, students did not feel knowledgeable or confident on topics related to Industrial Ecology (average scores of 0.56 and 0.56, respectively).

During the course, lectures, in-class activities, and homework assignments were used to allow the students to practice remembering, understanding, applying, and analyzing results from an LCA. By the end of the course period, the Industrial Ecology knowledge and confidence scores were 2.00 and 2.56, respectively. Similar trends were noted for other categories as well. For example, the usefulness scores for service-learning and vermi-composting were 1.67 and 1.00 at the onset of the course, but the students did not feel knowledgeable or confident (service-learning average score of 0.67 and 0.89, respectively and vermi-composting average score of 0.56 and 0.67, respectively). For these aspects of the course, students were given lectures, homework assignments, and the course project to allow for practice in remembering, understanding, applying, analyzing, evaluating, and creating solutions in these spaces. By the end of the course, the knowledge and confidence for service-learning increased to 2.22 and 2.44, respectively, and the knowledge and confidence for vermi-composting increased to 2.22 and 2.00, respectively. While these results would suggest the greatest relative change during the course we note that results are reflective in part of the small sample size in which a single respondent can greatly influence outcomes.

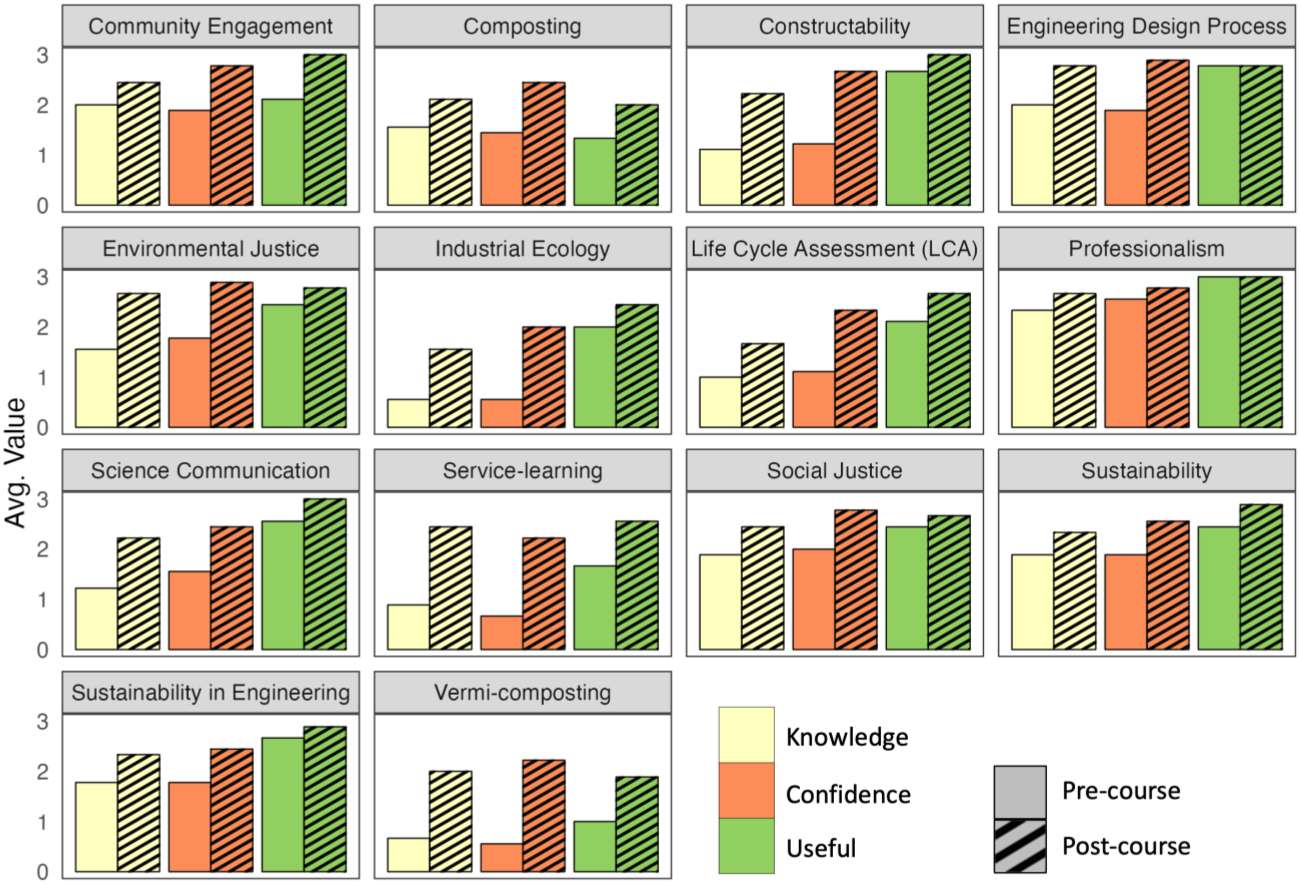

Figure 5.2. Average student response scores self-assessing their knowledge, confidence, and usefulness of a concept both before (pre-course) and after (post-course) instruction.

5.3.2 Qualitative Responses – Thematic Map

In addition to the quantitative results shown in Figure 5.2, qualitative results were collected through short answer survey questions. Effectively capturing results from a small sample size (i.e., 10 students) requires a detailed analysis of the nuanced thoughts and feelings of the student participants. As such, the qualitative results are discussed in terms of common themes among student responses and also through individual case studies. Figure 5.3 displays a thematic map of pre-course and post-course survey responses for each question. In this work, a "theme" is defined as a topic mentioned by two or more students and is depicted as a bubble connected to each question. The size of the bubble is determined by the frequency of the theme among student responses (i.e., the more often a theme came up in student responses, the larger the bubble). Since students can mention more than one theme in their responses, the frequency of themes will not always add up to 10. Question 1 asked students what year of schooling they are in, which is previously mentioned here and is not included in Figure 5.3.

Responses to Question 2

When asked “what was your motivation for selecting engineering as a major?” at the start of the course, the most frequent response was related to sustainability and climate change, mentioned by four students. Social impact, problem-solving, and the practicality of the discipline each received mention by three students. Two students mentioned creative aspects as their motivators.

At the end of the course, experience with hands-on skills arose as a new theme among three students as motivators for their careers. One student even mentioned applying the hands-on skills they learned from class into their personal life. This learning outcome can be directly attributed to the project that students co-designed and built with the community partner. The theme of social impact remained constant in frequency, but two of the students had not previously mentioned this in their pre-survey response. Further, one student detailed a broadening of their perspective through course concepts:

“I gained a much greater perspective on the impact my job as a (potential) engineer has on social and environmental issues. I think this course adjusted how I see my role and I recognize how there should be many considerations, in terms of the engineering design process, environmental justice, and community engagement, that I take into account when approaching work.”

Although practicality of the discipline decreased in frequency by one student, it remains an important theme.

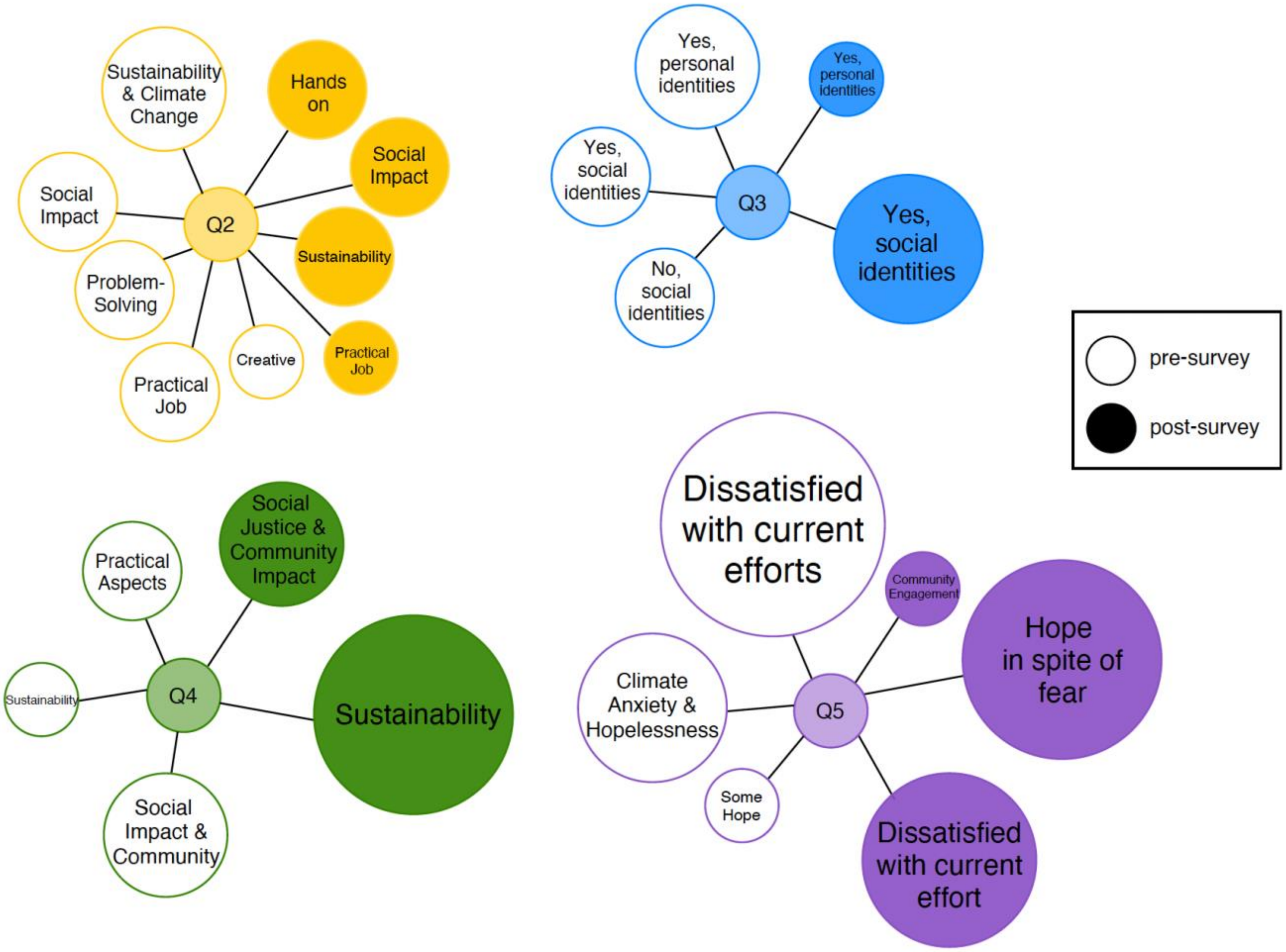

Figure 5.3. Map showing common themes among student qualitative responses to pre- and post- survey. **Question 2 (Q2):** What was your motivation for selecting engineering as your major? **Question 3 (Q3):** Do you believe that aspects of your personal/social identity (e.g., personality, hobbies, gender, ethnicity, sexual orientation, culture, ability status, socioeconomic status, religion/spirituality, nationality, etc.) are/will be valuable in your role as an engineer? If so, how? If not, why not? **Question 4 (Q4):** How do you envision using your engineering degree? **Question 5 (Q5):** Describe your thoughts and feelings about current sustainability challenges and our ability as a society to tackle them.
Note: Question 1 asked students what year of university they are in and is not included in this figure.

Responses to Question 3

When first asked, “Do you believe that aspects of your personal/social identity (e.g., personality, hobbies, gender, ethnicity, sexual orientation, culture, ability status, socioeconomic status, religion/spirituality, nationality, etc.) are/will be valuable in your role as an engineer? If so, how? If not, why not?”, seven students answered yes. Of the yes responses, four mentions of personal identities, such as personality and hobbies, and three mentions of social identities, such as race, gender, and religion were discussed. Two excerpts from student responses are provided below.

- *"Yes, I am curious about how things work and why things are the way they are. I think this thinking is helpful for engineering."*
- *"Yes, this summer I did an internship in Dallas, Texas and since one of my hobbies is line dancing, I felt like I was able to fit in from the start. I also feel like personality plays a role in what company you will choose. Also, ethnicity plays apart in Construction Management and as a Latina I was able to make a connection with the field guys easier than some of my coworkers."*

Three students responded no to this question, noting their social identities such as sexual-orientation, ability/disability, race, and gender as not being valued in their discipline. Three excerpts from student response are provided below.

- *"No. We don't really live in a society to accommodate or allow queer, colored, or disabled people to flourish. I have to constantly put myself down because of my capabilities and sexual orientation. Engineering culture especially is very "in the box" in terms of how everyone likes to think of things. I really dislike the engineering department and culture."*
- *"I think for the most part, engineering is really technical and doesn't leave much room for embracing personal/social identity."*
- *"I don't know how aspects of my identity could be useful as an engineer. Engineering seems disconnected from my identity. I guess after this class maybe I'll have a different perspective, if I can see more of the human side of the field."*

After the class, students' responses shifted from focuses on personal identities to emphasizing their social identities. Hobbies and personality are mentioned again, twice. Five students elaborated on how they feel their social identities are valuable in-spite of engineering not yet being a field that values these identities. Through the course, students connected with their own social identities and now recognize how these identities can be strengths in their future careers.

- *"I believe my background does play a role in engineering because our lived experiences can shed light on aspects and after-effects of engineering projects. Through this class, I was really able to empathize with marginalized groups who were negatively impacted by engineering projects. I recognize the duty we have as engineers to consider diverse perspectives in our work now more than ever."*
- *"Yes, I think my background and identity have impacted the way I view society and the world. I believe this is valuable as an engineer because I can represent many minorities."*

It is important to note that one student mentioned no change in their feelings, noting they do not believe their social identities are valued in engineering. Because only one student mentioned this, it is not displayed as a theme in Figure 5.3.

Responses to Question 4

The most frequent (four mentions) pre-course survey response to the question, "How do you envision using your engineering degree?", involved some kind of social impact and community. For example, some student responses include:

- *"I hope to use my degree to create and design things that help in any aspect whether that be the world, a community, etc."*
- *"The things I learn in school will help me make more decisions about what will be best for my community."*

Three students mentioned practical aspects like designing high rise buildings or construction management for as their career vision. Two students mentioned sustainability efforts as an area they envision their degree being used.

The mention of sustainability increased from two students in the pre-course survey to seven students indicating it as paramount to their future careers in the post-course survey. Students discussed specific concepts from the course such as Industrial Ecology and LCAs as tools they plan to use in their careers. Although students maintained their vision of social impact, their responses shifted from broad phrases like “help” and “taking care” to mention of specific concepts like social justice and community engagement. One student plans to embody a core principle of community engagement, recognizing community expertise and knowledge, which should be taken into account during the inception of any project[238]:

“…I also want to be an engineer that uplifts the community and I hope to take into account all sorts of community/social impacts before moving forward with any projects. “

<u>*Responses to Question 5*</u>

The themes in question 5 received the highest frequency of responses from students compared to all other questions. This outcome indicates there is consensus among students when it comes to their feelings to the prompt, “Describe your thoughts and feelings about current sustainability challenges and our ability as a society to tackle them.” Eight students mentioned a notable level of dissatisfaction with current sustainability efforts.

- *“I believe our society has a narrow-minded approach to many sustainability challenges. I want there to be more effort into exploring as many solutions as possible, whether it is policy or technology based.”*
- *“…it’s evident that those who are in positions to do anything about it choose not to. I also think that our education has failed us because sustainability issues and concepts are not taught generally speaking.”*
- *“I don’t believe our society is doing enough to reach net zero by 2050.”*
- *“Sometimes I feel like there’s a tendency to just try to find a technical solution to discrete environmental problems, like some innovation will magically solve just by existing. I think we need to engage communities more so that people actually use the innovations in a way that makes sense to them.”*

Among these responses, students alluded to or explicitly mentioned feeling a level of Climate Anxiety or hopelessness (five mentions). Climate Anxiety is an adaptive psychological response to the real threat of climate change[239]. Harmful impacts on physical health, mental health, and social relations have arisen as a result of the global climate crisis[240]. Worrying for future generations, apocalyptic futures, lack of adequate responses to climate change, and general feelings of helplessness and disempowerment are common themes among those who experience climate anxiety[241]. In addition to climate anxiety, children and young people are more susceptible to the direct health impacts of climate change as they experience them immediately and for the rest of their lives[242], which was reflected in some responses. Two students note maintaining hope in spite of the fear and anxiety surrounding sustainability and climate change.

After the course, the theme of hope in spite of fear grew and was mentioned in seven student responses. Students displayed a deeper understanding of the complexity surrounding climate change and sustainability in their responses, which yielded some optimism.

- *"It's tough to have hope with all the negatives of climate change that circulate the news, but I am trying to remain positive and look at the good that has been accomplished as well. I think we have the ability to tackle these issues but just need more people to care and understand that there is strength in numbers."*
- *"I think there may be many people who are apathetic to sustainability and are more concerned with short-term rewards. However, there are people who care and all we can do is work with others who find it a priority to make change and make sustainability a part of decision-making."*
- *"I think it would take a global collective effort. I think with continuing education and awareness there will slowly be improvements made."*

Even so, the general consensus of dissatisfaction with current sustainability efforts and climate action remained a major theme, with six mentions. Finally, a new theme emerged for two students regarding community engagement as a necessary component of addressing sustainability challenges, highlighting the influence of a Service-Learning approach to the class.

5.4 Conclusion

Engineering education must shift to meet the needs of a new generation. Engineering students increasingly come from diverse backgrounds and want to use their degrees to promote social change, engage with their communities, and take climate action. However, the current engineering curriculum is not prepared to provide students with the necessary knowledge and skills to do so with equity and inclusion in mind. One approach to address these aims is to incorporate the fundamental engineering principle of service, through community engagement, along with sustainability engineering topics. We provide an example of how Service-Learning and PBL approaches can work well together to address these desires. Through an analysis of student survey responses, we find these methods to deepen discipline-specific academic outcomes, while also increasing students' sense of belonging to their major and promoting problem solving spirit in spite of climate anxiety and dissatisfaction with current sustainability efforts. Due to the pilot nature of this course, this study was limited to 10 students. To deepen our understanding, additional student perspectives from larger class sizes are a necessary component of future work.

An unexpected takeaway from student responses is that they are experiencing climate anxiety. Worrying about the outcomes from climate change and environmental deterioration was mentioned by almost all students. And although they have contributed the least to the climate crisis, they are disproportionately impacted by it. Even so, young people are the ones leading climate action and activism, globally, in schools and within their communities. Schools and educators are uniquely positioned to support young people by providing the knowledge and skills to make students technically competent and personally empowered to take climate action. Engineering education must adapt to join in this educational and societal transformation to produce a technically rigorous, sustainability focused, and socially conscious engineering workforce.

6 Conclusion

This research presents an approach to advancing industrial decarbonization practices within the building materials industry that integrates factors tied to mitigating concomitant environmental impacts and fostering social equity. This work focuses primarily on cement and concrete for quantitative modeling of environmental impacts for varying concrete formulations. It provides a pathway to reaching net-zero GHG emissions for this critical class of infrastructure materials and the co-benefits and unintended consequences of those decarbonization methods on criteria air pollutants. Work is then expanded to address geographic-driven inequities in building materials manufacturing and engineering education transformation to integrate environmental justice and community engagement in curriculum for the next generation of engineers. Cumulatively, this work encompasses a multidisciplinary endeavor to equip the industry and future engineers with the insights and tools needed for holistic sustainable development.

6.1 Summary and Key Findings

Civil and environmental engineers require systematic and quantitative approaches to determine pathways towards climate damage mitigation goals, but simultaneously, they must address the complex interactions between materials production and society. Currently available methodologies fall short in providing robust analysis methods for these broad-reaching topics. As such, the field’s capacity to understand and effectively respond to the multifaceted challenges related to sustainability advancements is significantly hindered.

A key limitation in systematic assessment of decarbonization methods is the lack of transparent and publicly available models and data. The shortage in available models stifle the ability to avoid unintended consequences, tailor analyses, and consider the consequential social and health impacts on historically marginalized communities.

This deficit extends to the comprehensive measure of concomitant environmental impact categories and social burdens, and the integration of sustainability and social justice principles into engineering education. A crucial gap of prior research is the absence of an interdisciplinary approach that interweaves the quantitative assessment of emissions with the qualitative understanding of their impacts on local communities. These additional perspectives are vital for creating a more inclusive understanding of sustainability, ensuring that progress in one area does not lead to setbacks in another. They are especially critical for engineering education progress, where there is a pressing need to foster an ethos of sustainability and community engaged practice to meet current needs. In the face of existing challenges, educational institutions must equip future engineers with the tools necessary to navigate an increasingly complex world.

Chapter 2 introduces a key contribution of this research through the development of "OpenConcrete", which is a tool that provides an open-data platform for environmental impact assessment of cement-based materials. The data used and their sources as well as modeling assumptions are all published with the tool, enhancing transparency. Further, this tool goes beyond existing models to report on 11 environmental impact categories (e.g., GHG, NO_X, SO_X, $PM_{2.5}$, PM_{10}, VOC, CO, Pb, energy demand, water consumption, and water withdrawal). And the structure of the tool allows users to examine myriad concrete mixtures, processing conditions, and energy mixes, as well as adapt the model for additional material resources. This structure can support environmental-impact guided decision-making. To exemplify its outputs, the tool is applied to a scenario analysis of impacts to produce a representative concrete mixture across the United States, with results ranging from 189 kg CO_2-eq/m^3 of concrete (California) to 266 kg CO_2-eq/m^3 of concrete (West Virginia). The findings from this case study highlight the potential of OpenConcrete to not only measure GHG emissions but also to broaden the scope of environmental burdens considered in the production phase (i.e., to air pollutant emissions and resource consumption – namely energy and water resources).

Chapter 3 provides key insights into the various technologies that could be implemented to reduce emissions, their technology readiness and ability to scale, and the non-linear effects of using multiple emissions reduction strategies concurrently. Based on recent policy movements in California, evaluations of California's cement industry and its potential decarbonization are evaluated. Findings show the need for collective strategies to fully address GHG emissions as well as the potential for shifting environmental burdens (e.g., air pollutant emissions). The results suggest it is critical to measure influences on combined GHG emissions mitigation strategies as isolated examination may lead to over-estimations of efficacy. Moreover, this work underscores the necessity of collective action to realize regional and global climate targets. The pathway achieves a 96% reduction in GHG emissions by 2045, emphasizing the role of technologies within and beyond the cement sector and potentially integrating methods like Direct Air Capture (DAC) to overcome limitations in reaching net-zero emissions through cement decarbonization strategies alone.

Chapter 4 provides a framework for integrating various factors affecting neighboring communities based on geographic assessment, given that many quantitative assessments exploring environmental justice aspects of industrial production have focused on individual environmental impacts (e.g., air pollutants, chemical leachates). This work explores the intersection of industrial practices and environmental justice to provide a new method for assessing the disproportionate impacts on vulnerable communities as well as provides context for approaches to systematically understand potential drivers influencing those communities. The findings suggest that at the three spatial scales studied, construction and building material production facilities generally cause a geographic-based disproportionate impact (e.g., $I_d > 1$) relative to communities of color and considered low-income. This work serves as a catalyst for further research to refine these assessments, particularly within the context of environmental impact categories and social demographics often overlooked or under reported in census data.

Finally, Chapter 5 expands the methods derived to understand mechanisms that can better engage the next generation of engineers to tackle these complex challenges. A shift in engineering education towards Service-Learning and Problem-Based Learning (PBL) methodologies offers a transformative pathway to equip future engineers with the technical and social acumen required for climate action. The pilot study conducted in this research highlights the importance of educational reform in addressing the holistic needs of diverse student populations and fostering an empowered, sustainability-driven workforce. Furthermore, the findings suggest the pedagogical transformation resulted in deepened discipline-specific academic outcomes, with students reporting increases in their knowledge and confidence of all course topics after instruction. while also increasing students' confidence in their major and hope in spite of current climate anxiety.

6.2 Future Work

The research conducted herein creates a foundation for future study to better encapsulate the breadth of environmental impacts and social justice issues that should be considered in engineering decisions. Here, a few areas for future work that can directly build from this research are highlighted.

The OpenConcrete tool formulated in this research creates a strong steppingstone for future adaptations. Future research should expand upon OpenConcrete's initial system boundary, integrating construction, use phase, and end-of-life impacts to support whole life-cycle assessments. Exploration into region-specific conditions and the scalability of mitigation strategies across varying geographies would enhance the tool's practicality for global applications. Further, consideration for allocation of environmental impacts of industrial waste materials (e.g., fly ash) and eco-efficiency by including material performance metrics (e.g., compressive strength, durability) could also be addressed. Additionally, subsequent research may refine OpenConcrete's database accuracy, potentially integrating real-time data acquisition, uncertainty modeling, and machine learning models to predict and optimize the environmental impacts of concrete mix designs before they are implemented in industry. Finally, future work can investigate integrating circular economy principles into future tools' frameworks, assessing how material reuse and recycling within the construction industry can minimize waste and reduce environmental burdens.

To build on the progress of decarbonization pathways, future studies must also analyze the scalability and economic viability of emerging technologies, with a focus on integrating them into current industry practices. Additionally, future explorations into lifecycle costs and benefits of adaption and mitigation technologies should take place to better inform policy and investment decisions. Examinations of changes to labor markets, regional material availability, and competitiveness of industries will be critical to facilitate adoption of GHG emissions mitigations technologies. Quantitative and qualitative analyses should extend to assess the downstream effects of mitigation technologies, especially regarding their social and environmental trade-offs. Finally, future efforts should explore policy frameworks that incentive sustainable practices while minimizing disruptions to economies and local communities.

Barriers to a more holistic measurement come from a lack of standardized methodologies and comprehensive databases that encapsulate the full range of potential environmental and social repercussions. Environmental justice studies must strive for more granular data collection and interpretation, seeking to include vulnerable populations that are currently excluded in census data (e.g., migrant, and unhoused communities) in environmental assessments. Future work should aim to refine geographic-based indicators, include life-cycle inventories and environmental impact values in results, and develop more sensitive measures to capture the full spectrum of environmental injustice. It will be imperative for future research to go beyond traditional data sources and engage in Community-Based Participatory Research (CBPR), which can offer a deeper understanding of local environmental challenges. Moreover, there is a need for interdisciplinary approaches that fuse environmental science with social science methodologies to reveal the complex interactions between human health, social justice, and environmental sustainability.

In the field of engineering education, subsequent initiatives should broaden the implementation of Service-Learning courses, including larger and more diverse student cohorts to validate and extend the findings of this pilot study. This extension and expansion would support a curricular advancement that provides students with the key skills to pursue industrial decarbonization with context rooted in inclusive, just, and awareness of the multifaceted impact it has on both the environment and society as a whole. Continued dialogue and collaboration across disciplines will be essential in advancing the effectiveness of pedagogical shifts to meet the current challenges of our time. There is also a vital need to address climate anxiety in educational settings, guiding students to channel their concerns into positive climate action through technically rigorous, sustainability-focused, and socially responsible engineering solutions.

The insights gleaned from this dissertation lay the foundation for a holistic approach to industrial decarbonization, coupling technical innovation with a steadfast commitment to societal well-being. Building on this foundation, future research must extend to facilitate collaborative efforts among academia, industry, and policymakers, which is essential to drive adoption of low-carbon technologies while ensuring they are both economically viable and socially responsible. Additionally, there is a critical need to embed these sustainability concepts into engineering curriculum, empowering the next generation of engineers to use this new knowledge and social awareness in decision-making. Only with such forward-thinking and comprehensive strategy can we hope to meet the ambitious goals of environmental stewardship in the face of a rapidly changing global climate.

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Appendix A: Supplemental Materials for Chapter 1

OpenConcrete: An open-source tool for estimating the environmental impacts from concrete production

Supplementary Methods – OpenConcrete Sheets

OpenConcrete is an excel workbook, attached as a supporting file titled OpenConcrete_Tool.xlsx. It follows the user data flow diagram (Figure 2.2) and consists of 10 sheets detailed below.

Outline of Sheets

This sheet provides an outline and brief explanation of each sheet.

Inputs & Outputs

This sheet is the main interface for users. Cells highlighted in blue indicate input capability for the user. The user can determine the amount (kg or m^3) of and transportation distance (km) for each concrete constituent. The user can select from a drop-down menu (e.g., LC3, Portland limestone cement) or manually input the cement type (% proportions of clinker and gypsum). The user can also select or manually input the electricity mix (% by energy source) and fuel mix (% by energy source). The electricity mix can be selected from a drop-down menu among different states, the US average, or by manual entry. The thermal energy fuel mix can also be selected via drop-down with choices between the US average or by manual entry.

Cells highlighted in yellow indicate the outputs from the tool. The tool performs calculations to determine the environmental impact per m^3 of concrete (e.g., kg GHG/m^3 concrete) based on contributions from each stage, concrete constituent, and transportation distances set by the user. The calculations are live and update as the input data is changed.

Process Flow Diagram

This sheet contains a process flow diagram that outlines the scope of the assessments performed in OpenConcrete. Separate flows are marked for the inventory presented in the paper (Figure 1).

Inventories

This sheet contains inputs and outputs for each of the processes and concrete constituents in the tool. These flows include: (a) energy demand (MJ energy/kg constituent), including and electricity demands; (b) process and chemical derived CO_2, NO_X, SO_X, PM_{10}, $PM_{2.5}$, VOC, CO, Pb emissions factors (kg emissions/kg constituent); and (c) water demand (kg water consumption/kg constituent as well as kg water withdrawal/kg constituent). The inputs and outputs for these flows for batching (per m^3 of concrete) and transportation (per metric ton km (tkm) traveled) are also presented in this sheet.

References for each data source are provided within this sheet. The user can change any of the data sources within the inventories sheet as desired. For example, if the user wanted to update the energy demand for trucks to a more recent model, they would go to cell C41 (marked as the transportation energy demand for trucks) and update that value directly.

Thermal Energy

The greenhouse gas (GHG) and air pollutant emissions factors per MJ of thermal energy source (e.g., kg GHG/MJ of energy) as well as the water demand per MJ of thermal energy source (e.g., kg water consumption/MJ of energy) for different types of energy resources are presented in this sheet. Background calculations are performed here to incorporate the user-determined fuel mix proportions (%) to compute weighted average emission factors and demand factors based on the percentages of each fuel type. Note: this sheet contains a GHG emissions calculation using global warming potentials to assess CO_2-eq emissions based on CO_2, CH_4, and N_2O emissions, which can be updated by the user.

Electricity

The GHG and air pollutant emissions factors per MJ of electricity required (e.g., kg GHG/MJ of electricity) and water demand per MJ of electricity required (e.g., kg water consumption/MJ of electricity) for different energy resources are presented in this sheet. Background calculations are performed within this sheet to incorporate the user-determined electricity mix to compute weighted average emission factors and demand factors based on the percentages of each fuel type. Each state's electricity grid mix and the US average mix are provided on this sheet, with weighted averages computed based on electricity mix percentages from the US Environmental Protection Agency.[243] Note: this sheet contains a GHG emissions calculation using global warming potentials to assess CO_2-eq emissions based on CO_2, CH_4, and N_2O emissions, which can be updated by the user.

Kiln Efficiency Per State

For every state that produces cement, the kiln efficiency is determined by the proportion (%) of wet, dry, preheater and precalciner incorporation in the respective state cement kilns. The thermal and electricity demand are determined based on proportions of each type of kiln. For the states that do not produce cement, the US average kiln efficiency proportions are used. Note: the user may also specify their own ratios of kiln efficiency.

Constituents & Process Impacts

This sheet contains cells that perform calculations that determine emissions and water demand for concrete constituents and processes (in terms of kg environmental impact / kg constituent or process, e.g. kg NOx / kg fine aggregate), and for transportation (in terms of kg environmental impact/tkm traveled). This sheet also contains a graph which automatically updates to show the proportion of environmental impact (by % impact) by each concrete constituent; this chart updates based on the amount (kg or m^3) of each concrete constituent (Figure S2.2).

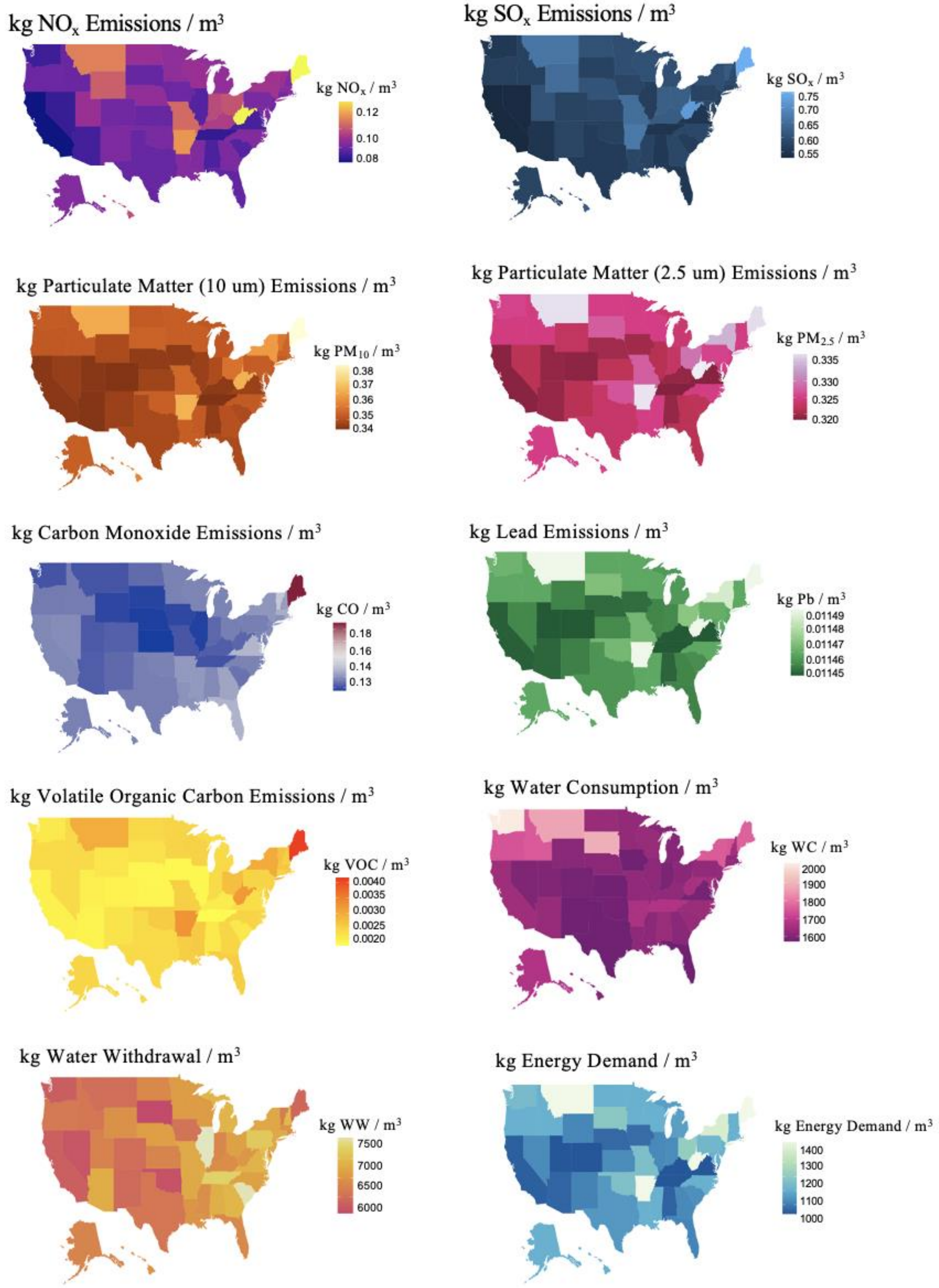
Transportation Distance

The total transportation-related GHG and air pollutant emissions (e.g., kg GHG, kg NO_X) as well as transportation-related water demand (e.g., kg water consumption) are calculated on this sheet. The transportation emissions factor from the Constituents & Process Impacts sheet is multiplied by the amount (metric ton) and distance (km) of each concrete constituent collected from the user-input data. The background calculations performed on this sheet incorporate the user-determined transportation distances to determine the transportation contribution to the emissions and water demand reported in the outputs section on the Inputs & Outputs sheet.

References

This sheet contains the references for data presented in the excel tool.

Supplementary Figures



kg NO_x Emissions / m^3

kg SO_x Emissions / m^3

kg Particulate Matter (10 um) Emissions / m^3

kg Particulate Matter (2.5 um) Emissions / m^3

kg Carbon Monoxide Emissions / m^3

kg Lead Emissions / m^3

kg Volatile Organic Carbon Emissions / m^3

kg Water Consumption / m^3

kg Water Withdrawal / m^3

kg Energy Demand / m^3

Figure S2.1. Heat maps of 10 environmental impact categories (NO_X, SO_X, VOCs, CO, PM_{10}, $PM_{2.5}$, Pb, water consumption, water withdrawals, energy demand) across US.

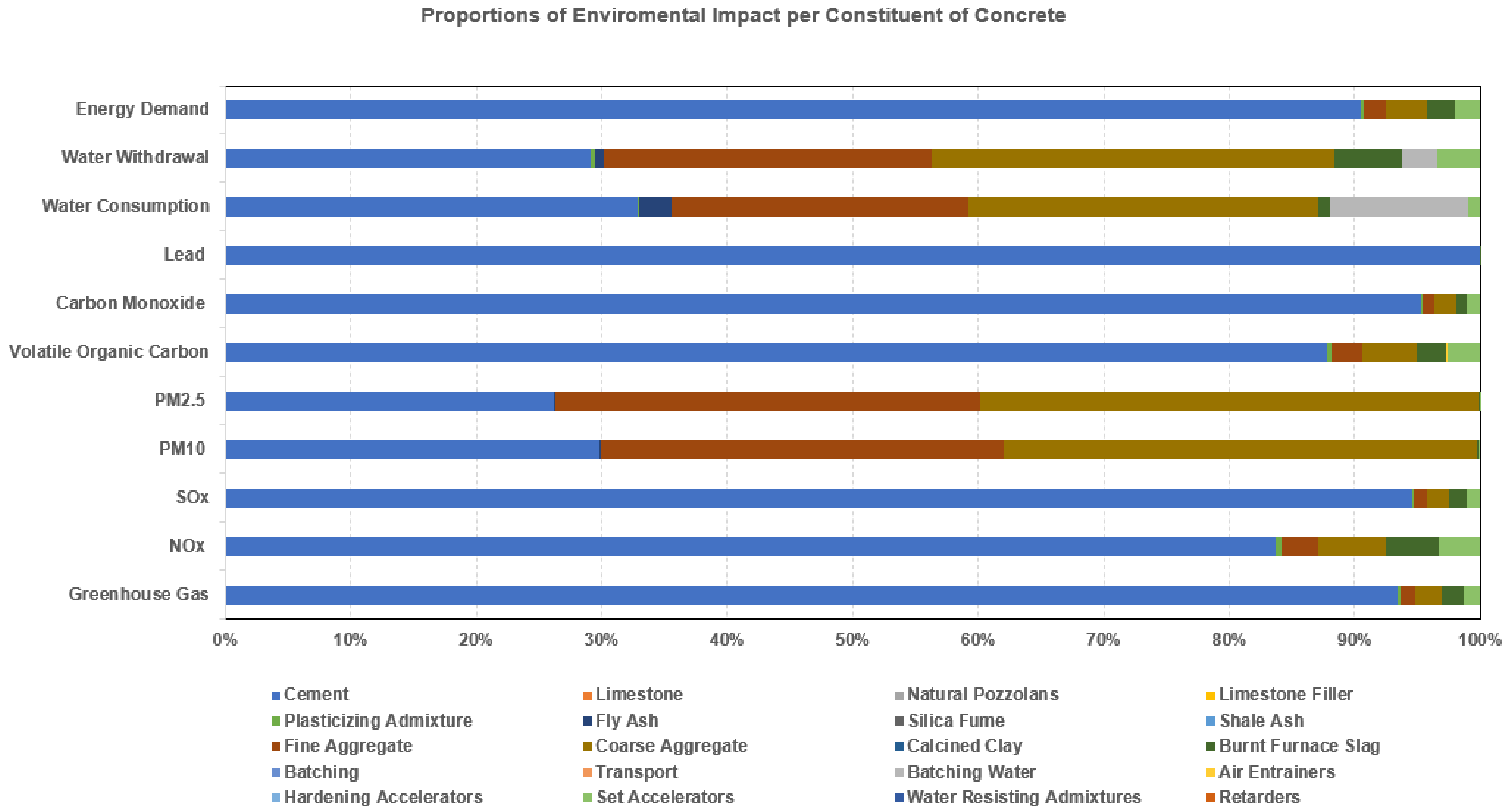


Figure S2.2. Proportions of cement production emissions based on contributions from different concrete constituents. This graph is using the same NRMCA concrete mixture[92] presented in Table 2

Supplementary Tables

Table S2.1. Environmental impacts, constituents, and life cycle phases considered in analysis of literature*.

	Environmental Impacts Analyzed					**Constituents Analyzed**				**Phases Analyzed**			
Article	**CO_2 and/or GHGs**	**NO_X or NO_2**	**SO_X or SO_2**	**PM**	**Other**	**Cement**	**SCMs**	**Aggregates**	**Other**	**Raw Material**	**Processing**	**Use**	**End of Life**
Celik *et al.* [35]	x	x	x	x	x	x	x		x	x	x		
Kajaste and Hurme [36]	x					x			x	x	x		
Chen *et al.* [39]	x	x	x	x	x	x	x				x		
Mikulcic *et al.* [44]	x					x	x						
Crossin [45]	x					x	x	x		x	x	x	x
Zhang *et al.* [46]	x												
Hossain *et al.* [48]	x			x	x			x		x	x	x	
Gursel *et al.*[49]	x	x	x	x	x	x	x	x	x	x	x	x	
Turk *et al.* [50]	x				x	x	x	x	x	x	x		
Tosic *et al.* [51]	x				x	x		x		x	x		
Allegrini *et al.* [47]	x					x	x	x	x	x	x		x
Pavlik *et al.* [52]	x	x	x			x			x	x			
Zhang and Wang [53]	x					x	x	x		x	x	x	x
Teixeira *et al.* [54]	x				x		x	x	x	x	x		
Butera *et al.* [55]	x			x	x			x		x	x		x
Dong and Ng [56]	x			x	x					x	x		
Feiz *et al.* [57]	x					x	x			x	x		
Serres *et al.* [58]	x				x	x		x	x	x	x		
Long *et al.* [37]	x				x	x	x	x	x	x	x		
Kurad *et al.* [244]	x					x	x	x	x	x	x		
Fouquet *et al.* [38]	x					x				x		x	x
Vargas and Halog [40]	x					x	x						
Teh *et al.* [41]	x					x	x		x	x	x		
Luo *et al.* [42]	x					x				x	x		
Anastasiou *et al.* [43]	x					x	x	x		x	x	x	x

*The literature review search was performed using Web of Science "Science Citation Index (SCI-EXPANDED) – 1990-present day" and keywords: (1) topic search: "Cement AND Life Cycle Assessment" OR topic search: "Cement and LCA"; and (2) topic search: "Concrete AND Life Cycle Assessment" OR topic search: "Concrete AND LCA".

Table S2.2. Review of Environmental Impact Accounting Tools.

Tool	Options for inputs	Environmental Impacts Outputs	Data Sources	Dedicated Concrete Tool?	Building/Project Specific?	Notes
OpenConcrete	Electricity grid mix, fuel mix, transportation mode & distance. Additional SCMs modeled: silica fume, shale ash	GWP, NOx, SOx, PM 10, PM 2.5, VOC, CO, Pb, Water Demand, Water Consumption, Energy Demand	Literature; customizable	Yes	No	
Green Concrete Tool[66]	Cement type, electricity grid mix, fuel mix, transportation mode & distance; can incorporate EPDs	resource use, fuel, electricity, water consumption, GWP, CO, NOx, Pb, PM10, SOx, VOC	Internal Database	Yes	No	Not an open-source tool.
GaBi[245]	Relies on user decision-making for system boundaries, materials selected, etc.	TRACI 2.0, CML 1996, 2001, and 2007),Ecoindicator 95 and 99, Ecological Scarcity Method (UBP), EDIP, USEtox, ReCiPe and many more you can add.	Multiple Databases	No	No	Relies on user decision-making for system boundaries, materials selected, etc.
SimaPro[246]	Relies on user decision-making for system boundaries, materials selected, etc.	CML, air, energy, GWP, water, many more	Multiple Databases	No	No	Relies on user decision-making for system boundaries, materials selected, etc.
OpenLCA[247]	Relies on user decision-making for system boundaries, materials selected, etc.	CML, ecoindicator 99, ReCiPe and many more you can add.	Multiple Databases	No	No	Relies on user decision-making for system boundaries, materials selected, etc.
Athena[248]	N/A	ISO 14040 and ISO 14044 standards TRACI impacts	N/A	No	Yes	Specific to pavement and buildings; project specific, ideal for use in construction. Unable to access to find inputs or data sources.
ELCAP[249]	Uses GaBi and models developed by UCPRC, can select specific construction equipment and pavement profiles; can incorporate EPDs	TRACI + primary energy demand broken out by raw materials, renewable and non renewable resources (combined), nonrenewable, renewable	GaBi and other databases	No	Yes	Currently in review with Caltrans. Software does not appear to be publicly available yet.
GCCA EPD Tool[67]	**N/A**	N/A	N/A	Yes, uses EPD data to make comparisons of concrete mixes, changing cement/clinker types	No	Unable to access without a GCCA account.
Umberto LCA+[250]	**N/A**	TRACI, ReCiPe, CML	Uses GaBi and ecoinvent	N/A	N/A	Unable to access to find inputs or data sources.

One Click LCA[251]	Ability to incorporate EPDs	TRACI, CML	Built-in database from multiple sources, climate earth, Ecoinvent.	No	Yes	Expert license is required to design specific concrete mixtures.
Tally[252]	N/A; can incorporate EPDs	N/A	N/A	No	Yes	This tool can be an add-in to BIM for use by designers. Created by an architecture firm. Unable to access to find inputs or data sources.
e-tool[253]	Concrete mixtures are preset and selected from drop down menu. Can incorporate EPDs	TRACI, CML, energy demand, mass of materials, DALY, Cost	N/A	No	Yes	Specific to designer/design stage and full buildings; free/open version of tool available.
Embodied Carbon in construction calculator (EC3) tool[254]	Categorizes materials based on CSI masterformat (e.g. concrete reinforcing: 032000) for selection. Can incorporate EPDs	Categories from EPDs	EPD database	No	Yes	Primary goal of tool is to incorporate EPD data to meet category goals and for material selection.
Climate Earth EPD[255]	N/A	TRACI, CML	EPD database	N/A	N/A	Provides the EPD data used in One click LCA. Partnered with one click LCA
BEES[256]	Ancillary materials, water, energy.	GWP, acidification, eutrophication, fossil fuel depletion, indoor air quality, habitat alteration, water intake, criteria air pollutants, human health, smog, ozone depletion, ecological toxicity.	Data repository from 230 building products; includes EPDs	No	Yes	Does not give the user much control for specific concrete mixtures.

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Appendix B: Supplemental Materials for Chapter 2

Meeting industrial decarbonization goals: a case study of and roadmap to a net-zero emissions cement industry in California

Supplementary Figures

The system boundary for conventional Portland cement production, which serves as the baseline for comparison of the key emissions mitigation strategies considered in our work, is shown in Figure S3.1.

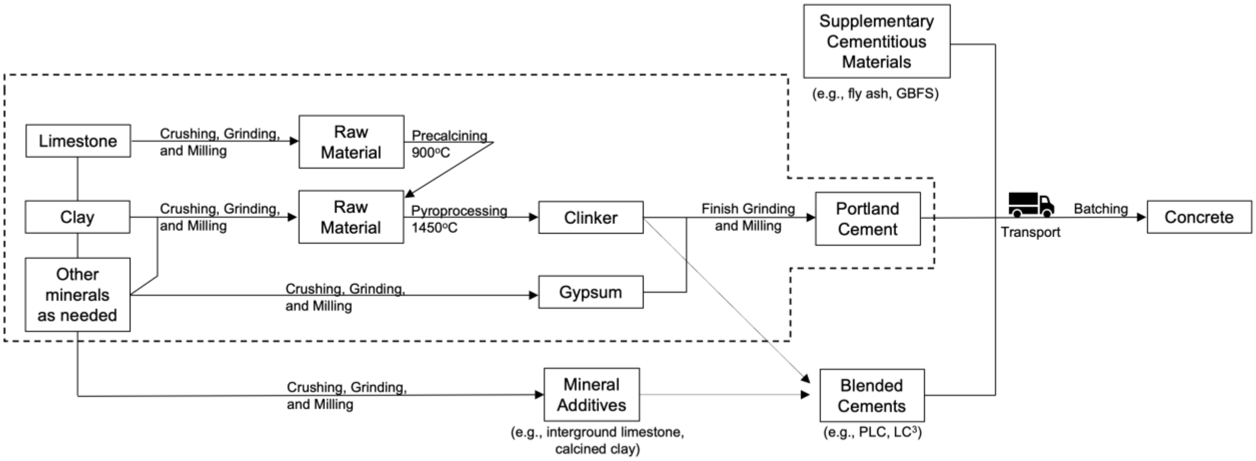


Figure S3.1. System boundary for comparison of greenhouse gas (GHG) mitigation strategy assessment to conventional Portland cement production.

Two additional roadmaps with different combinations of mitigation strategies are presented here: (a) low technology adoption roadmap (b) high technology adoption roadmap. Figure S3.2 presents the low technology adoption roadmap. This scenario reaches 90% reduction in 2045 and requires an electricity switch to 100% wind power, a kiln fuel switch to 100% natural gas, 100% of Portland cement to be made with CCS technologies, 5% of all cement to be clinkered alternative cements, and 5% of all cement to be alkali-activated materials. The supplementary cementitious materials (SCMs) modeled here include mineral additives in

Portland-Limestone cement (PLC) and calcined clay limestone cements (LC^3), which have higher GHG-intensities than fly ash that is modeled in Figure 3.3. Figure S3.3 presents the high technology adoption roadmap. This scenario reaches 100% reduction in 2045 and requires an electricity switch to 100% wind power, a kiln fuel switch to 100% renewable electricity, 100% of Portland cement to be made with high efficiency CCS technologies (note here, the CCS is modeled at 99% efficiency instead of 90% efficiency as modeled for Figure 3.3), 10% of all cement to be clinkered alternative cements, and 5% of all cement to be alkali activated materials. The medium efficiency CCS technology in 2035 models a 95% efficient system at collecting CO_2.

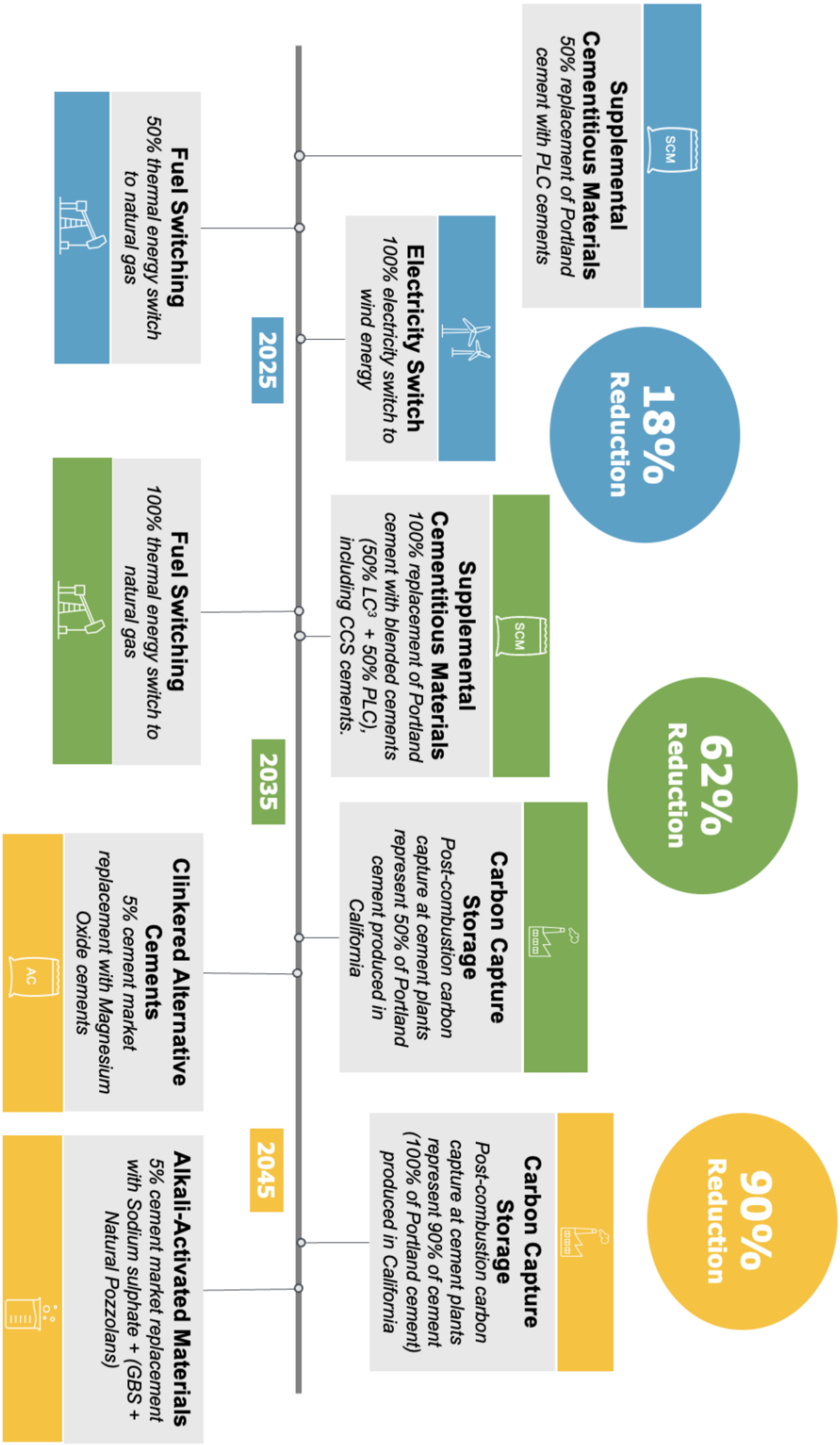
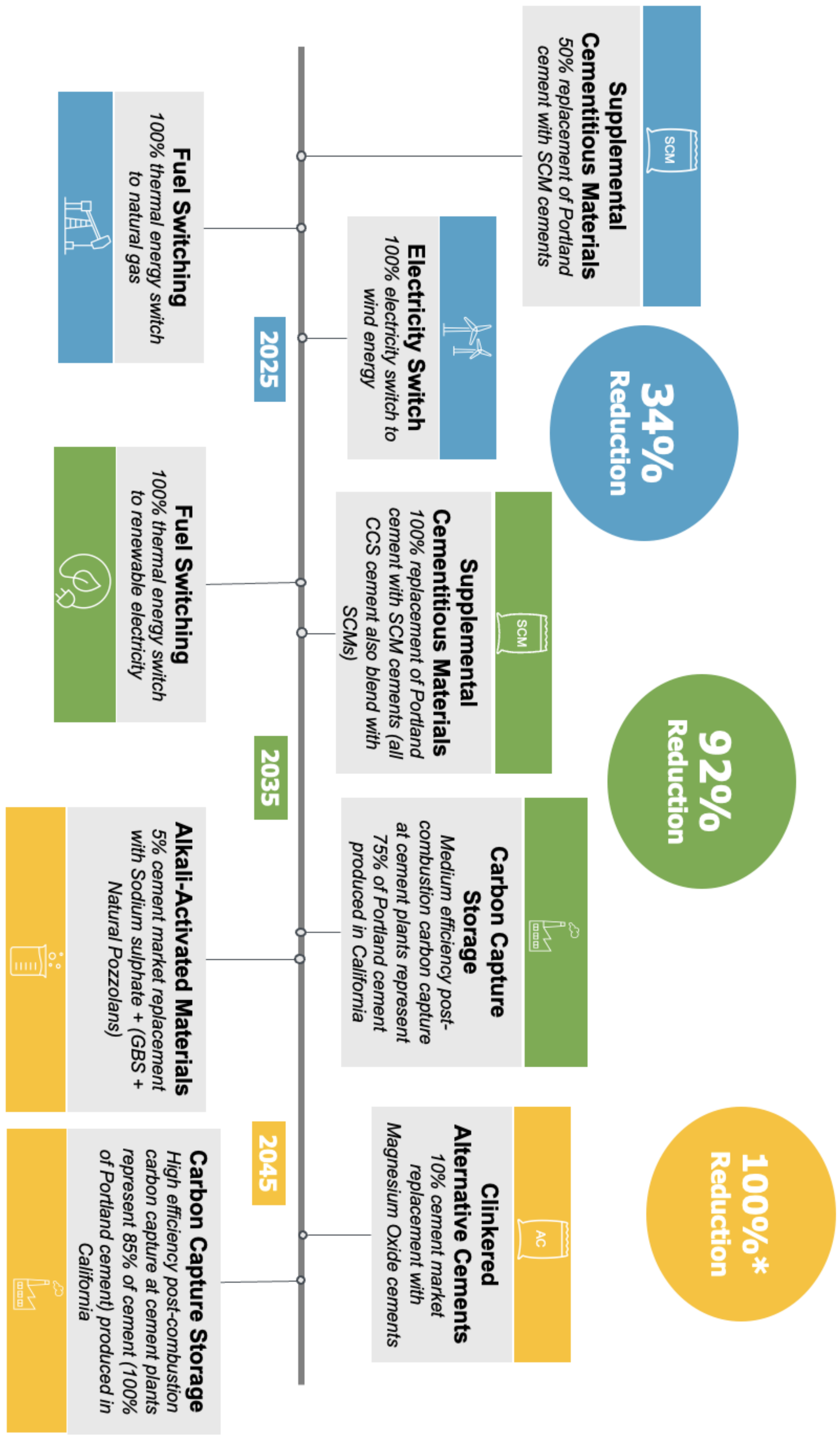


Figure S3.2. Technology roadmap – a low technology adoption scenario of greenhouse gas (GHG) emissions mitigation strategies for years 2025, 2035, 2045.



*in this scenario an even greater than 100% reduction can be achievable if the clinkered alternative cement modeled here solidify via carbonation, which if performed properly has the potential to contribute to a carbon sequestration mechanism.

Figure S3.3. Technology roadmap – a high technology adoption scenario of greenhouse gas (GHG) emissions mitigation strategies for years 2025, 2035, 2045.

Supplementary Tables

Depending on the mineral additive used, the levels of clinker replacement can range from 15-90% while still meeting performance requirements [114–119]. Table S1 displays the clinker replacement levels for the supplementary cementitious materials (SCMs) considered in this work.

Table S3.1. Supplementary Cementitious Material (SCM) clinker replacement percentages at concrete batching stage.

SCM	% Clinker Replacement
Limestone filler	15%
Calcined Clay	30%
Blast furnace slag	50%
Natural Pozzolans	20%
Fly Ash	35%

Table S3.2 summarizes the alkali-activated materials (AAMs) from our earlier work [33,124] and from the literature [125] that are considered in our study.

Table S3.2. Alkali-Activated Material (AAM) mixture proportions from the literature.

Author	Mixture Number	Solid precursors proportions				Alkaline activator proportions			
		GBFS	Natural Pozzolans	Calcined Clay	Limestone Filler	NaOH	Na_2CO_3	Na_2SO_4	Na_2SiO_3
Cunningham et al 2020	C1	46.7%	46.7%			6.7%			
Cunningham et al 2020	C2	48.7%	48.7%				2.6%		
Cunningham et al 2020	C3	49.5%	49.5%					1.0%	
Miller et al 2018	M1			86.0%	10.0%				4.0%
Robayo-Salazar et al 2019	RS1	21.0%	50.0%			5.0%			24.0%

Supplementary Methods

OpenConcrete

OpenConcrete is a quantitative tool created in our previous work [106] that contains relevant material, energy, and emissions data for each major step in cement and concrete production and facilitates environmental impact assessments, using life cycle assessment principles. This tool is designed for the analysis of cement-based composites, and it outputs emissions, energy demand, and water demand for user-specified mixtures, energy grids, kiln types, and more.

The results in our work utilize OpenConcrete, which reports GHG emissions in terms of CO_2-equivalents. In OpenConcrete, GHG emissions are calculated based on CO_2, CH_4, and N_2O emissions using Intergovernmental Panel on Climate Change (IPCC) second assessment report 100a global warming potentials, namely 21 and 310 for CH_4 and N_2O emissions, respectively. The method includes a cradle-to-gate assessment of cement production. The Portland cement is modeled with 95% clinker and 5% gypsum. The environmental impacts for electricity needed for cement production are based on values from the Argonne National Lab [257]. The baseline electricity mix for California is based on 2020 USEPA data [90]. The environmental impacts for the thermal demand in the cement kilns are compiled from a couple of USEPA data sources [74,258], and median values are taken based on distributions in our previous work [137].

Carbon Capture and Storage (CCS): Percent Reduction in GHG emissions vs. Percent Efficiency

The percent reduction of GHG emissions for CCS (87%) differs from the percent efficiency of the system (90%) because of difference in equations.

$$\% \boldsymbol{efficiency} = \mathbf{1} - \frac{\boldsymbol{new\ intensity}}{\boldsymbol{CCS\ baseline\ intensity}}; \quad \textbf{(Eq. 1)}$$

CCS baseline intensity = 1.12 kg GHG per kg cement

e.g., $\%\ efficiency = 0.9 = 1 - \frac{x}{1.12\text{ kg GHG per kg cement}}$

x = new intensity = 0.1 * (1.12 kg GHG per kg cement) = 0.112 kg GHG per kg cement

$$\% \boldsymbol{reduction} = \frac{(\boldsymbol{baseline\ intensity} - \boldsymbol{new\ intensity})}{\boldsymbol{baseline\ intensity}}; \quad \textbf{(Eq. 2)}$$

baseline intensity = 0.846 kg GHG per kg cement

e.g.,

$$\%\ reduction = \frac{(0.846 - 0.112) kg\ GHG\ per\ kg\ cement}{0.846\ kg\ GHG\ per\ kg\ cement} = 87\%$$

Alternative clinkers

The alternative clinkers in this work include: (1) Belite Ye'elimite Ferrite cement (BYF, phases: 46% belite, 17% ferrite, 35% ye'elimite, 2% interground gypsum); (2) Calcium Sulfoaluminate–belite Cement (C$AB, phases: 22% belite, 3% ferrite, 65% ye'elimite, 9); (3) Carbonatable Calcium Silicate Cement (CCSC, phases: 100% wollastonite); (4) Magnesium oxide cement from forsterite (MOMS, phases 100% periclase). These phases differ from those in ordinary Portland cement (63% alite, 15% belite, 8% aluminate, 9% ferrite, 5% interground gypsum).

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Appendix C: Supplemental Materials for Chapter 3

Supplementary Figures

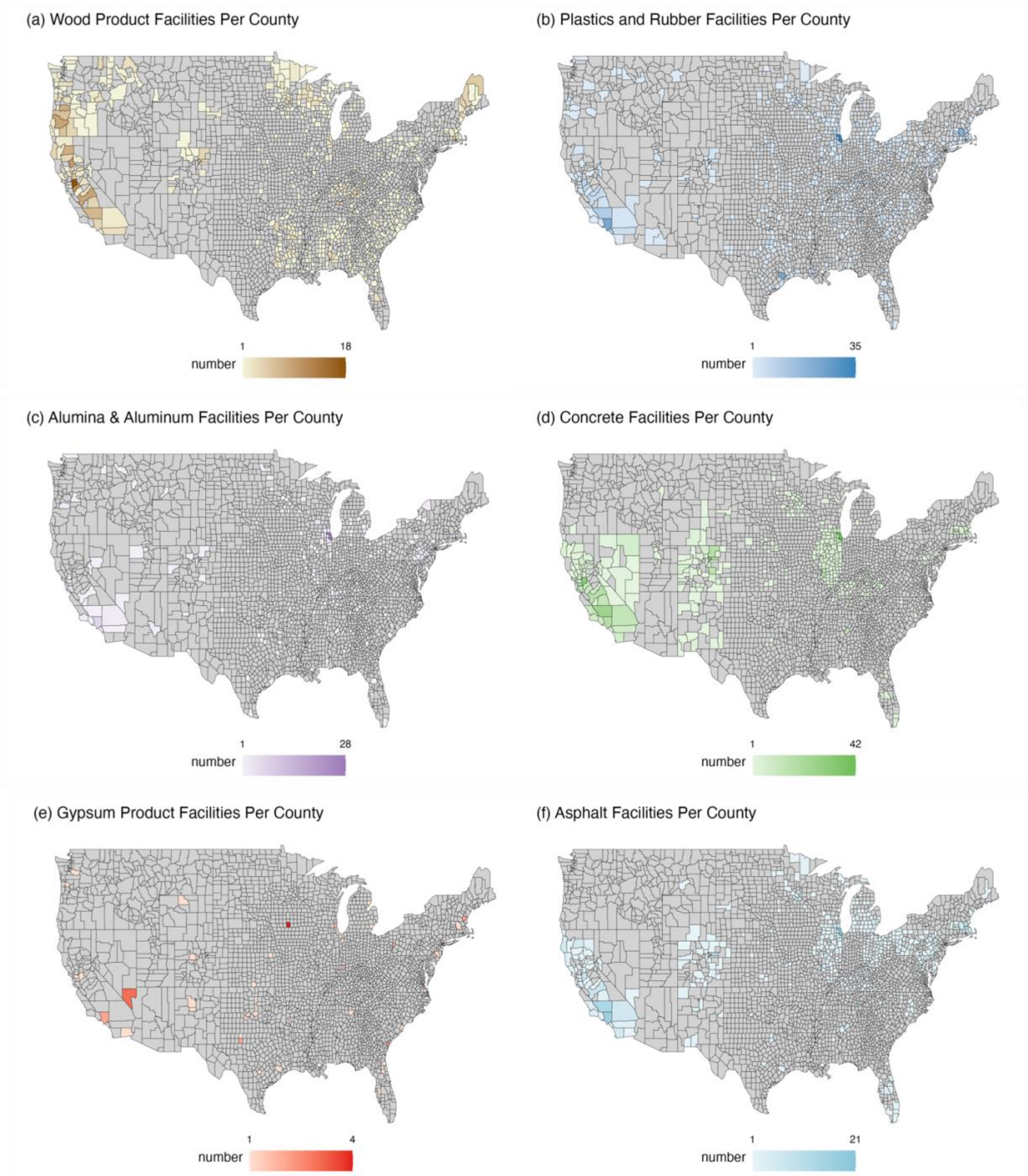

Figure S1. Count of Construction Building Materials (CBM) facilities per county for (a) Wood Products (b) Plastics and Rubber (c) Alumina & Aluminum (d) Concrete (e) Gypsum Products (f) Asphalt (g) Iron and Steel (h) Lime Products (i) Non-ferrous Metals (j) Glass (k) Cement (l)

Clay Products.

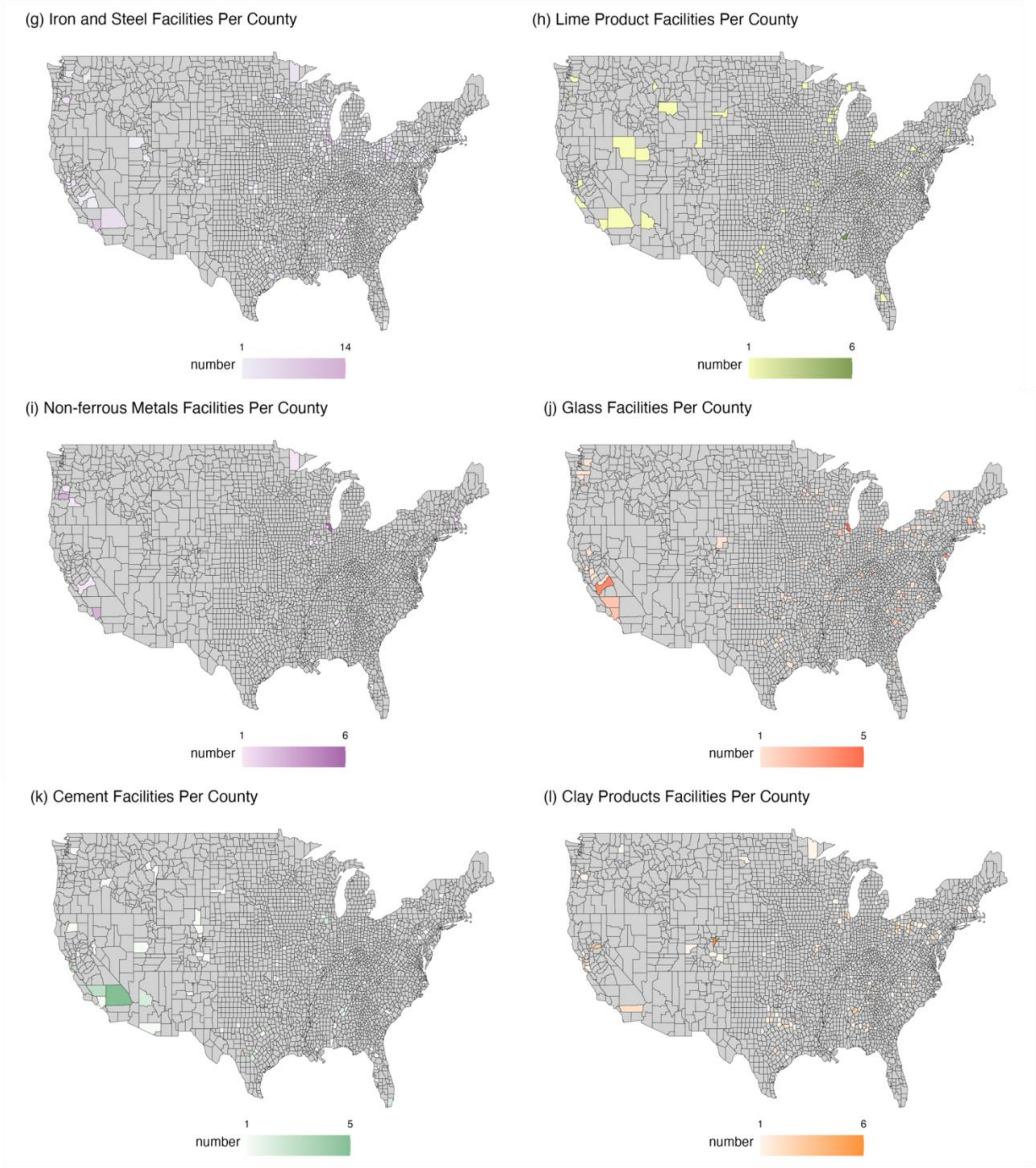

Figure S2. Count of Construction Building Materials (CBM) facilities per county for (g) Iron and Steel (h) Lime Products (i) Non-ferrous Metals (j) Glass (k) Cement (l) Clay Products.

Distribution of Disproportionate Impact (I_d) at three spatial scales

A comparison of the distributions of all CBM I_d values for the county, state, and nation level analyses are provided in **Figure S3**. The county and state level analyses exhibit a right-skewed distribution, meaning the majority of CBM facilities experience a disproportionate impact value near 1. Whereas, the national level analysis results in a normal distribution, centered around 48 (mean I_d value). The I_d values for county and state levels have low variance and are tightly clustered around their means.

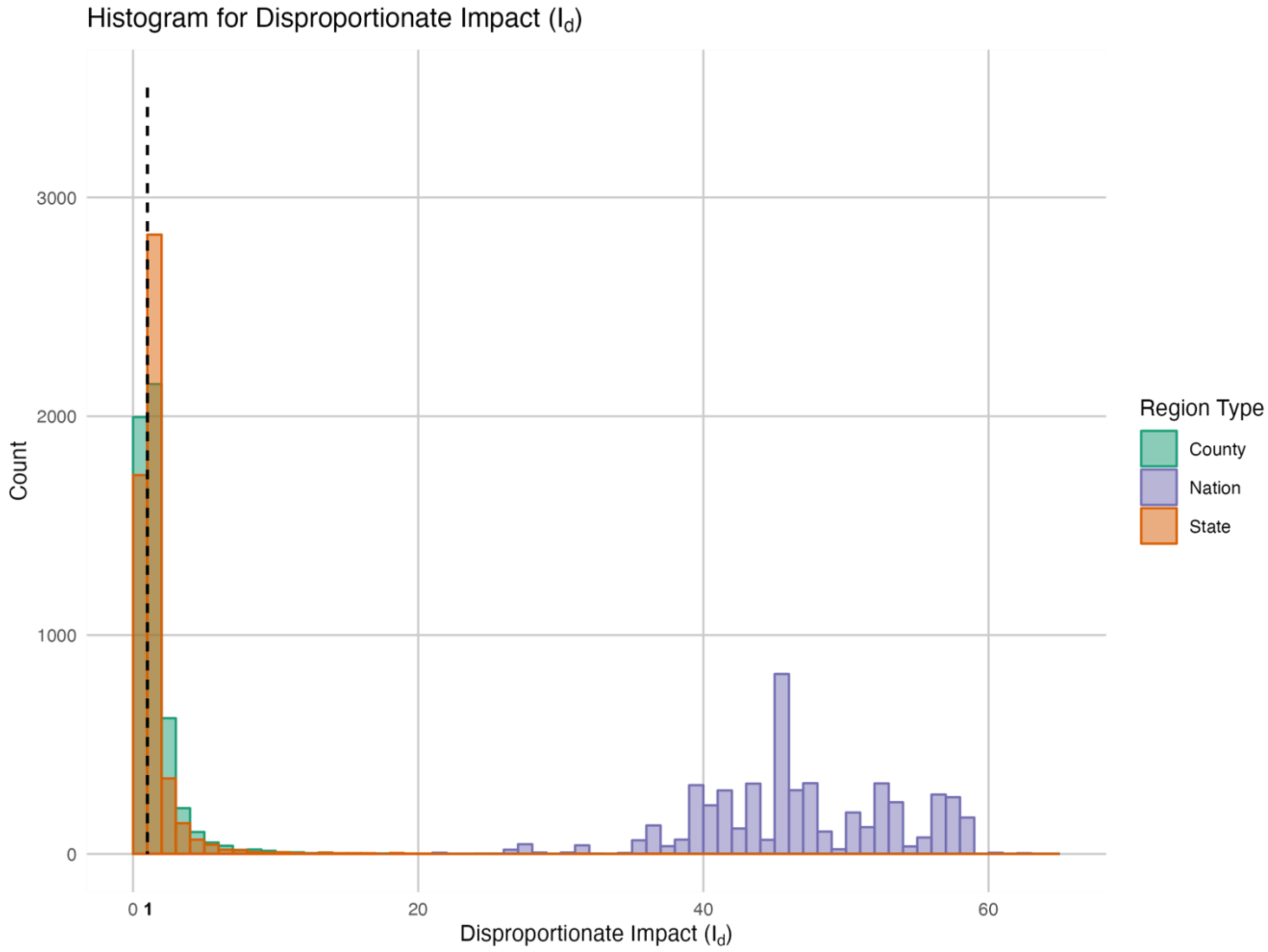

Figure S3. Distribution of Disproportionate Impact (Id) for all Construction Building Materials (CBMs) at all three spatial scales (e.g., county, state, nation).

Supplementary Methods

Industry Categories and their corresponding NAICS codes:

1. Wood Product Manufacturing
    a. All categories that begin with 321
2. Asphalt Paving and Roofing Manufacturing
    a. 32412, 324121, 324122
3. Plastics and Rubber Manufacturing
    a. All categories beginning with 326
    b. 3252, 32521, 325211, 325212
4. Clay Product Manufacturing and Building Materials
    a. 3271, 32711, 327110, 32712, 327120
5. Glass Products Manufacturing
    a. 3272, 32721, 327211, 327212, 327213, 327215
6. Cement Manufacturing
    a. 32731, 327310
7. Concrete Manufacturing
    a. 32732, 327320, 32733, 327331, 327332, 32739, 327390
8. Lime Manufacturing
    a. 32741, 327410
9. Gypsum Product Manufacturing
    a. 32742, 327420
10. Iron and Steel Manufacturing
    a. 3311, 33111, 331110, 3312, 33121, 331210, 33122, 331221, 331222, 331511, 331512, 331513, 33151
11. Alumina & Aluminum Manufacturing
    a. 3313, 33131, 331313, 331314, 331315, 331318, 3314, 33141, 331410, 33142, 331420, 33149, 331491, 331492, 3315, 33151, 331511, 331512, 331513, 33152, 331523, 331524
12. Non-ferrous metal manufacturing
    a. 3314, 33141, 331410, 33142, 331420, 33149, 331491, 331492, 3315, 33151, 331511, 331512, 331513, 33152, 331523, 331524, 331529

Appendix D: Supplemental Materials for Chapter 4

Integrating Service-Learning with Sustainability Engineering to Broaden Student Learning Outcomes

Pre- and Post- Survey

The pre- and post-course survey questions as presented to the students is provided below.

Knowledge, Confidence and Use Survey

All information will be treated as confidential. You will create a reproducible ID to link study measures, while maintaining your confidentiality. Please use the following to create your ID: use the last letter of your first name and the last four digits of your phone number (for example, Jane and 123-4567 = E4567). The results of this study may be used in dissertations, reports, presentations, or publications but your name will not be used. Results will be shared in the aggregate form.

ID:___________________________

Please rate the concepts and strategies listed below using the criteria provided. Decide how knowledgeable you are about each concept. Then rate how confident you are in your ability to teach someone to use or implement each concept. Finally, rate how useful each concept or strategy is for your future life and career in your disciplinary area.

Knowledge: 0 – I have no knowledge of this concept.
1 – I have some knowledge of this concept.
2 – I have more than average knowledge of this concept.
3 – I have a substantial amount of knowledge about this concept.

Confidence: 0 – I am not confident in my ability to apply this concept in my personal/academic life.
1 – I am somewhat confident in my ability to apply this concept in my personal/academic life.
2 – I am more confident than most in my ability to apply this concept in my personal/academic life.
3 – I am very confident in my ability to apply this concept in my personal/professional life.

Useful: 0 – This concept or strategy is neither useful nor relevant for my career aspirations.
1 – This concept or strategy is somewhat useful and/or relevant for career aspirations.
2 – This concept or strategy is useful and/or relevant for my career aspirations.
3 – This concept or strategy is very useful and/or relevant for my career aspirations.

Concepts	**Knowledge**	**Confidence**	**Useful**
Sustainability	0 1 2 3	0 1 2 3	0 1 2 3
Sustainability in Engineering	0 1 2 3	0 1 2 3	0 1 2 3
Community Engagement	0 1 2 3	0 1 2 3	0 1 2 3
Industrial Ecology	0 1 2 3	0 1 2 3	0 1 2 3
Life Cycle Assessment (LCA)	0 1 2 3	0 1 2 3	0 1 2 3
Environmental Justice	0 1 2 3	0 1 2 3	0 1 2 3
Social Justice	0 1 2 3	0 1 2 3	0 1 2 3
Constructability	0 1 2 3	0 1 2 3	0 1 2 3
Science Communication	0 1 2 3	0 1 2 3	0 1 2 3

Professionalism	0 1 2 3	0 1 2 3	0 1 2 3
Engineering Design Process	0 1 2 3	0 1 2 3	0 1 2 3
Service-learning	0 1 2 3	0 1 2 3	0 1 2 3
Composting	0 1 2 3	0 1 2 3	0 1 2 3
Vermi-composting	0 1 2 3	0 1 2 3	0 1 2 3

Above adapted from *Managing Challeging Behaviors in Schools: Resarch-Based Strategies That Work* by Kathleen Lynne Lane, Holly Mariah Menzies, Allison L. Bruhn, & Mary Crnobori. Copyright 2011 by the Gulford Press, New York, NY.

Free Response Questions

1. What year of college are you in? (circle one)

1st year 2nd year 3rd year 4th year 5th year other: ___________

2. What was your motivation for selecting engineering as your major? Please write in 2-3 sentences.

3. Do you believe that aspects of your personal/social identity (e.g., personality, hobbies, gender, ethnicity, sexual orientation, culture, ability status, socioeconomic status, religion/spirituality, nationality, etc.) are/will be valuable in your role as an engineer? If so, how? If not, why not? Please elaborate your response in 3-5 sentences. As a reminder, please only discuss things that you feel comfortable sharing.

4. How do you envision using your engineering degree? Please write in 2-3 sentences.

5. In 2-3 sentences describe your thoughts and feelings about current sustainability challenges and our ability as a society to tackle them.

6. As a final reminder, submitting your responses to this survey is optional. Please select one of the following options to indicate whether or not you consent to having your responses used anonymously in a research paper.

☐ Yes, you can use all my responses in a research paper.

☐ Yes, but you can only use my responses from the Knowledge, Confidence and Useful concepts section.

☐ Yes, but you can only use my responses in the free response questions.

☐ Yes, but (fill in the blank)____

☐ No, you may not use any of my responses in a research paper.