Washington State Industrial Emissions Analysis—Cement Case Study

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Introduction

Industry, especially "heavy" industry responsible for producing basic materials like metals, chemicals, and cement, tends to be highly carbon-intensive, generating high emissions per unit of economic value added. Emissions are typically associated with fossil fuel combustion, often for thermal energy needed to process raw materials, but also with chemical processes, such as the calcination of limestone for cement, that are an inherent part of production. Industry also tends to be capital-intensive, and many industries rely on fixed industrial "ecosystems" for energy and materials that lock in carbon-intensive methods of production. Moreover, basic material producers frequently compete in global markets, making costly transition efforts economically challenging.

Altogether, these characteristics make heavy industries "hard to abate." Decarbonizing these industries is not simply a matter of using cleaner fuels and improving efficiency, although these may be important strategies. The challenges are also technical and transformational: changing production systems, developing new infrastructure, and deploying new technologies to avoid or capture emissions in ways that are economically sustainable.

One implication is that, for many industries, decarbonizing is not a simple matter of choosing from a menu or cost curve of greenhouse gas emission abatement options. Instead, most studies look at industrial decarbonization "routes" or "pathways" that lay out a sequence of transformational steps needed to cost-effectively decarbonize over time, considering systemic interdependencies and scenarios for broader economic transformation, an example of which might be the development of a green hydrogen fuel economy.

The correct pathway for a particular industry will vary by its starting circumstances and geography. A basic prerequisite, therefore, is to understand in detail what these circumstances are. Key variables include energy intensities, types of fuel consumption, technical processes used, and structural interdependencies with other industries and value-chain partners.

The Washington State Department of Commerce contracted with the Clean Energy Transition Institute (CETI) to prepare a targeted analysis and case study on the potential for the manufacturing and use of green cement in Washington. The CETI, in collaboration with the Stockholm Environment Institute-US (SEI-US), developed the following paper in response to this request.

Case Study on Green Cement

Overview

Concrete is a ubiquitous and essential building material for much of modern infrastructure in the buildings, transportation, and industrial sectors. Although low-carbon substitutes for concrete exist in some applications (for example, wood for residential and other (typically smaller) types of buildings) concrete, in some form, will continue to be an essential building material even in a deeply decarbonized world.

Unfortunatley, cement, which is the binding agent in concrete and most mortars, is highly energy and carbon intensive. Cement is typically produced from a feedstock of limestone, clay, and sand. Cement production requires large amounts of both thermal energy and electricity, which are typically produced from carbon-emitting fossil fuels. However around two thirds of CO_2 emissions from global cement production comes from the calcination of limestone used as a raw material.[1] These emissions are inherent to the chemistry of current production processes, making full decarbonization of cement production technically challenging.

Globally, the production of cement contributes to around 7% of anthropogenic greenhouse gas emissions.[2] The industry's large carbon footprint, its importance to modern society, and the technical challenges involved in its decarbonization make it a poster child for "hard to abate" industries.[3] U.S. cement production stands out for having, on average, the highest carbon intensity in the world.[4] This is partly due to the high ratio of clinker used at U.S. cement plants (around 90%[5] of cement by mass, compared to 65%[6] globally). Clinker is the product of limestone calcination and is the material that gives cement its binding properties.

Standard "Portland cement" consists of about 95% clinker. Blending of Portland cement with other, "supplementary cementitious materials" (SCM) can signficantly lower overall carbon intensity by displacing clinker. Unlike in other parts of the world, however, most blending in the United States occurs at concrete mixing plants rather than at cement plants. This highlights the importance of working with the *concrete* industry in Washington on any decarbonization strategy.

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[1] International Energy Agency and Cement Sustainability Initiative, "Technology Roadmap: Low-Carbon Transition in the Cement Industry" (Paris, France: International Energy Agency, March 2018), https://www.iea.org/reports/technology-roadmap-low-carbon-transition-in-the-cement-industry.

[2] Energy Transitions Commission, "Mission Possible Sectoral Focus: Cement" (Energy Transitions Commission, January 2019), https://www.energy-transitions.org/publications/mission-possible-sectoral-focus-cement/.

[3] Max Åhman, "Perspective: Unlocking the 'Hard to Abate' Sectors" (World Resources Institute, March 2020), https://files.wri.org/expert-perspective-ahman.pdf.

[4] Ali Hasanbeigi and Cecilia Springer, "California's Cement Industry: Failing the Climate Challenge" (San Francisco, California: Global Efficiency Intelligence, February 4, 2019), https://www.climateworks.org/report/californias-cement-industry-failing-the-climate-challenge/.

[5] Hasanbeigi and Springer.

[6] International Energy Agency and Cement Sustainability Initiative, "Technology Roadmap: Low-Carbon Transition in the Cement Industry."

The carbon intensity of U.S. cement production, however, is not solely due to lack of blending. A study of California's cement industry found that it is also highly energy intensive, using both more electricity and thermal energy per ton of produced cement and clinker compared to 12 separate countries that were reviewed.[7]

In Washington there is one cement kiln, operated by the Ash Grove Cement Company in Seattle.[8] Another facility in Bellingham, operated by Lehigh Hanson, grinds and blends clinker to produce cement, but does not operate a kiln. Note that the carbon intensity of the Ash Grove plant in Seattle appears considerably lower than the U.S. average – around 500 kg CO_2e/tonne of cement, compared to 800 kg CO_2e/tonne nationally.[9] This is likely because of its current fuel mix, which consisted of a combination of natural gas and used tire combustion between 2017 and 2019.[10] Prior to 2017, Ash Grove relied to varying extents on coal like many other U.S. cement producers.[11] The Ash Grove plant is also energy efficient; it has been consistently recognized as an ENERGY STAR certified facility by the U.S. Environmental Protection Agency.[12]

The production of cement involves four sequential production processes (a more granular visual breakdown is provided in Figure 1):[13]

- **Raw Material Extraction**, in which limestone and clay, sand, or other materials are quarried. As of 10 years ago, Washington cement kilns relied on limestone quarried from Texada Island in British Columbia, from which it was transported by barge.[14] It is not clear if this is still the case.[15]

- **Raw Material Preparation**, in which a raw mixture of limestone and other materials (e.g., clay, sand) are crushed and ground into a mixture. This step can occur either as a dry process, in which the product is a fine dry powder, or in a wet process, where the crushed material is mixed into a slurry prior to grinding. The Ash Grove plant in Seattle uses a dry process.[16]

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[7] Hasanbeigi and Springer, "California's Cement Industry: Failing the Climate Challenge."

[8] Ash Grove Cement, "Fact Sheet on Ash Grove Seattle Plant," ca 2018, https://static1.squarespace.com/static/5f39b10071a9b67f78f74a82/t/5fb962099876b8736cac88d1/1605984777890/2020-AG_FACT_SHEETS-SEATTLE.pdf.

[9] Calculated from Ash Grove reported 2019 CO_2e emissions of 366,000 tonnes (obtained from: http://ghgdata.epa.gov/ghgp/main.do) and reported clinker production of 750,000 tons per year (from: Ash Grove (ca. 2018)). Electricity-related emissions assumed to be zero based on Seattle City Light resource mix. U.S. average obtained from Hasanbeigi et. Al (2019).

[10] "EPA Facility Level GHG Emissions Data," United States Environmental Protection Agency, 2021, http://ghgdata.epa.gov/ghgp/main.do.

[11] "EPA Facility Level GHG Emissions Data."

[12] U.S. Environmental Protection Agency, "List of Certified Plants," 2021, https://www.energystar.gov/industrial_plants/earn-recognition/plant-certification/list_certified_plants.

[13] P Erickson and Michael Lazarus, "Issues and Options for Benchmarking Industrial GHG Emissions" (Stockholm Environment Institute (SEI), 2010), https://www.sei.org/publications/issues-options-benchmarking-industrial-ghg-emissions/.

[14] Erickson and Lazarus.

[15] In 2017, demolition of a Texada Island limestone quarry site was completed on behalf of Ash Grove Cement Company: https://www.nwdemolition.com/portfolio/texada-remote-island-dolomite-and-limestone-quarry/

[16] Puget Sound Clean Air Agency, "Statement of Basis for Ash Grove Cement Company, Inc.," June 13, 2018, https://pscleanair.gov/DocumentCenter/View/216/Statement-of-Basis-PDF?bidId=.

- **Clinker Production**, in which the fine powder or slurry is heated in a kiln. The heating first transforms the ground limestone ($CaCO_3$) into lime (CaO), releasing CO_2, in a process called calcination, and then into solid pellets called clinker, the material which gives cement its binding properties. In Washington, Ash Grove operates a rotary kiln, which in conjunction with using a dry preparation process, is relatively energy efficient compared to older technologies involving “vertical shaft” kilns and/or a wet process.

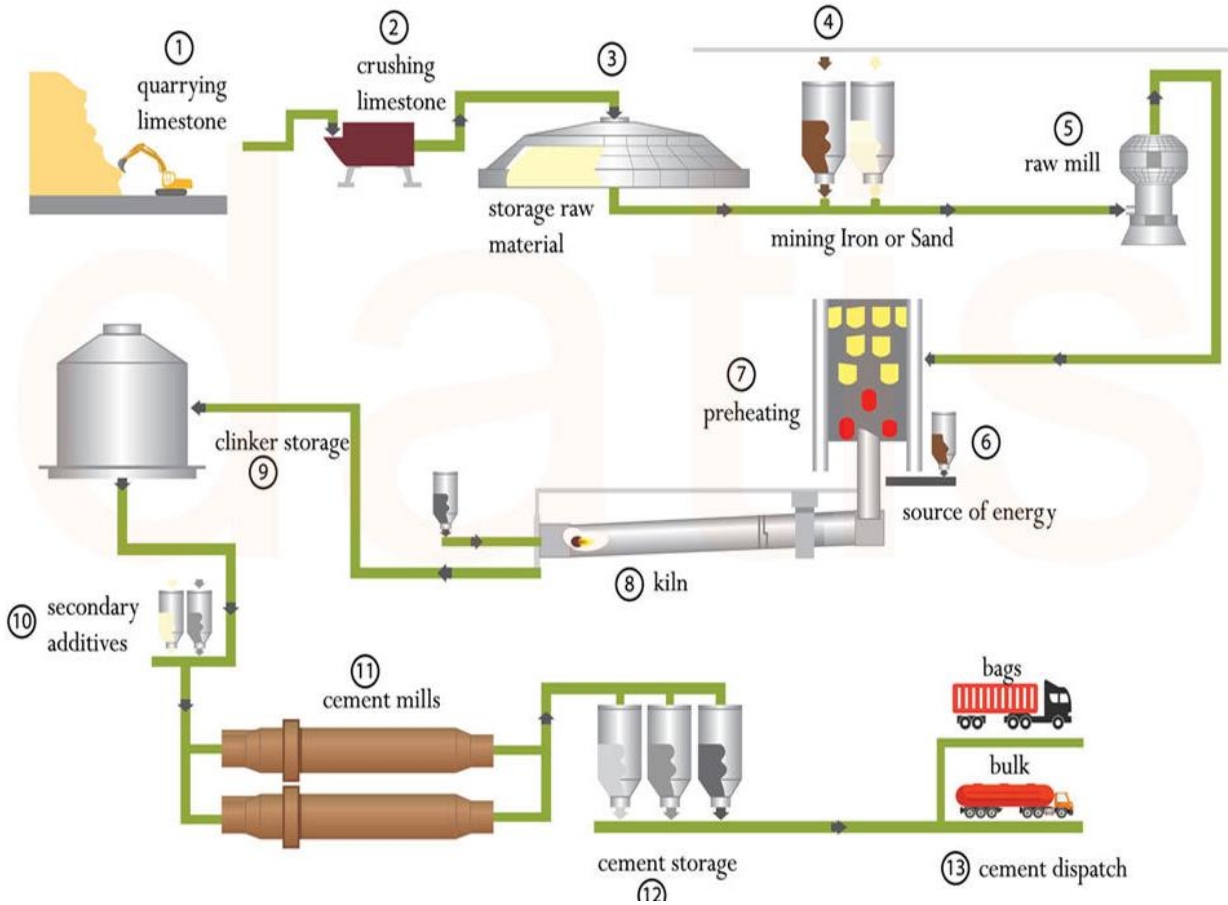
- **Cement Grinding and Blending**, in which clinker is mixed and ground in mills with other ingredients to produce cement. To make standard Portland cement, only about 5-10% gypsum and/or fine limestone is added.[17] Other “blended cements” can be made by mixing in other materials with cementitious properties, especially byproducts from other industries, such as fly ash from coal power plants or blast-furnace slags.[18] Lehigh, for example, indicates that it produces cement blends incorporating slag, fly ash, and (raw) limestone.[19]

[17] International Energy Agency and Cement Sustainability Initiative, “Technology Roadmap: Low-Carbon Transition in the Cement Industry.”

[18] Erickson and Lazarus, “Issues and Options for Benchmarking Industrial GHG Emissions.”

[19] “Lehigh Cement Company - Lehigh Hanson,” Lehigh Cement Company - Lehigh Hanson, accessed June 25, 2021, https://www.lehighhanson.com/sites/lehigh-cement-company.

Figure 1. Portland Cement Production Process



Source: Cement production line diagram available from Datis Export Group[20]

Cement itself is not an "end" product. Cement is used to produce concrete by mixing with water and aggregates, such as sand, gravel, or crushed stone. A chemical hydration process converts this mixture into hardened concrete. A concrete mix is typically about 10 to 15% cement, 60 to 75% aggregate, and 15 to 20% water by volume.[21]

Cement is also used to produce similar products, such as mortar, tile grout, and stucco. Most concrete (80%) is produced at "ready mix" plants, from where it is distributed to application sites (e.g., via concrete mixer trucks).[22] However, some is also produced at concrete product manufacturing facilities, where it is turned into a variety of premade products (e.g., masonry bricks or precast concrete). One Washington facility, James

[20] Datis Export Group, "What Is the Manufacturing Process of Portland Cement?," September 10, 2020, https://datis-inc.com/blog/what-is-the-manufacturing-process-of-portland-cement/.

[21] Hasanbeigi and Springer, "California's Cement Industry: Failing the Climate Challenge."

[22] Hasanbeigi and Springer.

Hardie Building Products in Tacoma, is a reporter under Ecology's GHGRP reporting program, emitting over 15,000 tCO_2e per year from stationary combustion.

Decarbonization Strategies

There is a growing body of literature examining decarbonization options for the "hard to abate" cement and concrete industry. This includes official decarbonization strategies developed by industry associations in specific countries (e.g., the United Kingdom), as well as global scenarios indicating how the sector could decarbonize in line with Paris Agreement goals (e.g., developed by the International Energy Agency). The following section is based primarily on three sources that provide overviews of what a "deep decarbonization" pathway for cement and concrete could look like:

- **A summary "roadmap" developed by UK Concrete, the industry association for concrete producers in the United Kingdom.**[23] This provides a short, high-level overview of how the UK cement and concrete industry could reach net-zero emissions by 2050, including the relative contribution of different kinds of measures to reducing greenhouse gas emissions (Figure 2). Notably, there is fairly heavy reliance on carbon capture utilization and storage (CCUS). As Figure 2 indicates, however, if the industry fully decarbonized, it could also play a role in achieving negative emissions, as concrete absorbs CO_2 through carbonation once it sets.[24] It may even be possible to enhance this carbonation process using novel techniques or cement chemistries.[25]

- **A "technology roadmap" study by the International Energy Agency (IEA) for low-carbon transitions in the global cement industry.**[26] This study presents a detailed scenario for how the global cement and concrete industry could decarbonize in line with efforts to limit warming to no more than 2°C. It describes a range of technologies and practices that could be deployed – some commercially available, other still speculative – along with their abatement potentials and relative costs. It focuses primarily on cement and concrete manufacturing (production phase) rather than upstream or downstream solutions. Note that it is *not* a full decarbonization scenario; rather, it models how the direct CO_2 intensity of cement production could be reduced by 32% by 2050.

- **A study of options for decarbonizing the cement industry by the Energy Transitions Commission.**[27] This study's recommendations mirror much of what the IEA and UK Concrete present in their roadmaps, but with a stronger focus on reducing emissions through cement demand management – exploring, for example, opportunities for "circular economy" approaches to cement use in the

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[23] MPA UK Concrete, "UK Concrete and Cement Industry Roadmap to beyond Net Zero" (London, United Kingdom: UK Concrete / Mineral Products Association, 2020), https://www.mineralproducts.org/Sustainability/Net-Zero-Carbon.aspx.

[24] Fengming Xi et al., "Substantial Global Carbon Uptake by Cement Carbonation," *Nature Geoscience* 9, no. 12 (December 2016): 880–83, https://doi.org/10.1038/ngeo2840.

[25] Note: the UK Concrete roadmap also identifies "thermal mass" energy savings as part of its contribution to achieving net zero emissions. Although this could be one advantage of continued use of concrete for buildings (reducing demand for heat energy), we do not include it here as it is more of an external co-benefit of concrete use rather than a core decarbonization strategy.

[26] International Energy Agency and Cement Sustainability Initiative, "Technology Roadmap: Low-Carbon Transition in the Cement Industry."

[27] Energy Transitions Commission, "Mission Possible Sectoral Focus: Cement."

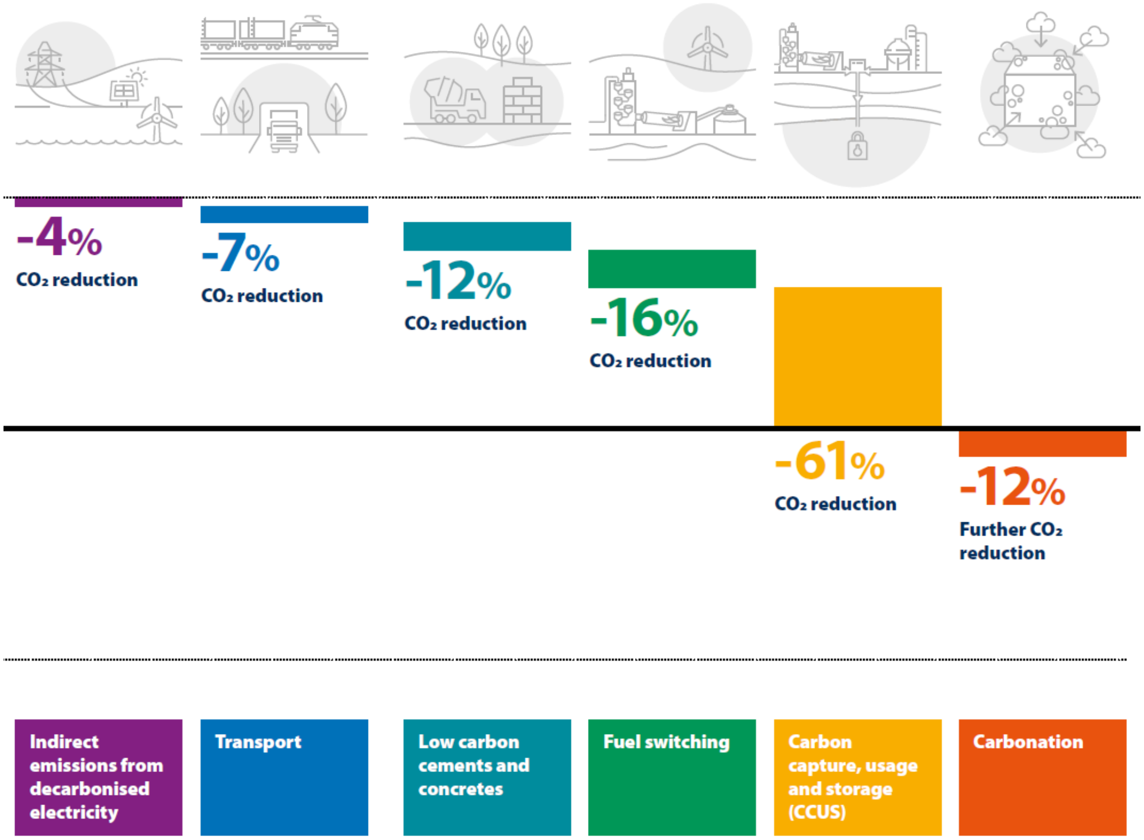
buildings sector. It also focuses, as does the UK Concrete roadmap, on how to achieve *full* decarbonization of cement production.

The remainder of this section is organized around six core abatement strategies for cement and concrete production identifed in the UK concrete roadmap (Figure 2) and additional upstream and downstream "concrete demand management" measures that could be considered as part of a comprehensive industry strategy:

- Energy efficiency, electrification, and electricity decarbonization
- Decarbonizing the transportation of cement and concrete
- Use of low-carbon cements and concretes
- Fuel switching
- Carbon capture and utilization or storage
- Enhanced carbonation of concrete
- Reducing upstream emissions
- Downstream "cement demand management" strategies

For each section, data needs related to each measure are identified along with known or possible sources for those data in Washington State.

Figure 2. Estimated Effect of Decarbonization Measures for the UK Concrete and Cement Industry



Source: MPA UK Concrete (2020)[28]

Energy Efficiency, Electrification, and Electricity Decarbonization

Improved thermal and electrical energy efficiency measures at cement plants offer some of the most cost-effective near term greenhouse gas emissions abatement opportunities. However, the total abatement potential is small compared to other measures. The IEA estimates about 3% of cumulative emission reductions would come from efficiency improvements in a cement industry deep decarbonization scenario.[29] Nevertheless, efficiency is important to emphasize because many decarbonization measures, including use of SCMs, fuel switching, and adoption of CCUS, may lead to *greater* absolute energy demand.

Various measures to improve kiln combustion efficiency can be deployed to reduce emisisons. However, these measures require greater inputs of electricity (e.g., for grinding of mineralizers, installing precalciners, adding preheating stages, or upgrading clinker coolers).[30] Thus, these measures lead, in effect, to indirect

[28] MPA UK Concrete, “UK Concrete and Cement Industry Roadmap to beyond Net Zero.”

[29] International Energy Agency and Cement Sustainability Initiative, “Technology Roadmap: Low-Carbon Transition in the Cement Industry.”

[30] International Energy Agency and Cement Sustainability Initiative.

electrification of energy use. Extraction and use of SCMs may also increase electricity demand (at cement or concrete plants, or in their supply chains) – also a form of indirect electrification as energy demand is shifted from kilns to SCM production. Finally, direct electrifcation of kilns may be possible using plasma torches for heating; this would be particularly energy intensive, putting a premium on finding efficiency solutions throughout the entire cement production process.[31]

Because of the potential for increase electricity demand, decarbonization of electricity is also an important element of any deep decarbonization strategy for cement production. UK Concrete highlights electricity decarbonization (in combination with energy efficiency improvements) as the first element of its broader strategy (Figure 2).

Although Washington State is currently working toward carbon-free electricity statewide by 2045, cement plants themselves could be part of this solution, including through the use of excess heat recovery (EHR) to generate electricity onsite.[32] According to the U.S. Energy Information Administration, very little onsite cogeneration currently occurs at U.S. cement plants[33] (see the MECS onsite energy flow diagram for cement manufacturing in the accompanying *Washington Industrial Emissions Characterization Tables* spreadsheet).

Given the high energy intensity of current U.S. cement production (see overview), energy efficiency measures may be especially important to emphasize. Although cement sector energy efficiency has improved since the 1980s, recent gains have been less pronounced. A 2013 U.S. EPA Energy Star report for the cement manufacturers saw ample room for continued improvement, and identified over 50 energy-efficient technologies and measures that could be adopted at U.S. plants.[34]

Historically, one of the most effective ways to reduce the energy intensity of cement production was to switch from a "wet process" (involving the use of water in grinding and preparation of raw materials, which then need to be dried) to a "dry process" (using drying grinding and preparation methods).[35] Today, nearly all U.S. plants, including Ash Grove in Seattle, use a dry process. Nevertheless, there are numerous opportunities to reduce energy use further in dry kilns, including by introducing a heater to pre-heat raw materials prior to being fed into the kiln, as well as by the introducing a second combustion chamber between the pre-heater and the kiln.[36]

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[31] Tove Burman and Johanna Engvall, "Evaluation of Usage of Plasma Torches in Cement Production" (Masters Thesis, Gothenburg, Sweden, Chalmers University of Technology, 2019), https://publications.lib.chalmers.se/records/fulltext/257463/257463.pdf.

[32] International Energy Agency and Cement Sustainability Initiative, "Technology Roadmap: Low-Carbon Transition in the Cement Industry."

[33] U.S. Energy Information Administration, "2018 Manufacturing Energy Consumption Survey (MECS)," 2021, https://www.eia.gov/consumption/manufacturing/data/2018/.

[34] Ernst Worrell, Katerina Kermeli, and Christina Galitsky, "Energy Efficiency Improvement and Cost Saving Opportunities for Cement Making" (Washington D.C.: ENERGY STAR, August 2013), https://www.energystar.gov/buildings/tools-and-resources/energy-efficiency-improvement-and-cost-saving-opportunities-cement-making.

[35] Erickson and Lazarus, "Issues and Options for Benchmarking Industrial GHG Emissions."

[36] Worrell, Kermeli, and Galitsky, "Energy Efficiency Improvement and Cost Saving Opportunities for Cement Making."

Finally, opportunities may exist for energy efficiency improvements and electrification at concrete manufacturers. This segment of the industry is less explored in the literature, but solutions are likely to be more straightforward, with more feasible options to substitute electricity to meet energy needs.

Key Data Needs for Washington

A particular initial focus should be on understanding current technologies and processes used at the Ash Grove cement plant in Seattle, and on identifying opportunities for greater efficiency improvements, including EHR for onsite electricity production.

Data needs	Existing or potential sources
Current technologies and processes used at Ash Grove plant in Seattle (e.g., whether raw materials are preheated; whether a second combustion chamber is used; other efficiency measures; use of EHR; etc.)	▪ Direct inquiries to Ash Grove ▪ Possibly tax records or siting permits at Puget Sound Clean Air Agency
Electricity consumption at Ash Grove plant	▪ Future GHGRP reporting ▪ Utility (Seattle City Light) sales records
Electricity and fuel consumption at concrete plants Specific types of technologies or processes used and concrete plants	▪ Working with electric and natural gas utilities to obtain information on sales to commercial/industrial customers ▪ Consulting local air agencies to identify facilities based on permit data ▪ Interviewing the Washington Aggregates and Concrete Association[37] to obtain data on the number of in-state facilities and typical energy use[38] ▪ Combining data from the above sources with typical industry-wide energy consumption data from the EIA MECS ▪ Possibly consulting data on energy use and demand-side management programs

Decarbonizing the Transportation of Cement and Concrete

Although emission reductions in cement and concrete transportation are not identified as a core strategy by the IEA, UK Concrete's roadmap suggests that up to 7% of the industry's total carbon footprint could be reduced through measures that decarbonize the transportation of cement, e.g., from storage silos to concrete producers (see Figure 1) and of concrete (from concrete producers to end users).

As with electricity decarbonization, efforts to reduce transportation emissions could be considered part of broader economy-wide decarbonization measures. However, as the UK Concrete roadmap suggests, cement

[37] "Home," Washington Aggregates & Concrete Association, accessed July 6, 2021, https://www.washingtonconcrete.org/.

[38] Concrete producers may also list existing facilities on their websites. For example: https://www.lehighhanson.com/home/locations/view/lehigh-cement-company|lehigh-cement

and concrete producers could play an active role by electrifying their fleets; improving logistics and otherwise reducing vehicle-miles travelled; and shifting to more efficient modes (like rail).

Key Data Needs for Washington

To understand transportation-related emissions, basic estimates are probably sufficient. For decarbonization strategy purposes, key information would include the types of vehicles used in cement and concrete transportation and the most promising options for eliminating vehicle emissions. For example, concrete mixer trucks have high energy demands, so electrfication *could* be challenging (depending on technology development, typical distances traveled, etc.).

Data Needs	Existing or Potential Sources
Cement and concrete transportation-related GHG emissions	Estimate from quantities produced, typical distances traveled, and typical modes (could be calculated with assistance from Washington Aggregates and Concrete Association, for example)
Typical vehicle types and duty classes (along with potential for electrification (BEV or FCEV)	Inquiries with Ash Grove and concrete producers (e.g., Washington Aggregates and Concrete Association)

Use of Low-Carbon Cements and Concretes

Aside from energy efficiency measures, increased *blending* of cement with SCMs is easily the most cost-effective and immediate way to reduce the carbon intensity of cement and/or concrete production. Blending can occur at a cement plant or at concrete batch plants. If done at a cement plant, the product is typically called “blended cement,” while a blended product from concrete batch plants may be referred to as “SCM concrete.”[39] Either way, the result is to reduce the clinker-to-cement ratio of the final product, resulting in lower overall carbon intensity.

The IEA’s global decarbonization scenario models the average clinker-to-cement ratio declining from 0.65 in 2014 to 0.60 in 2050.[40] Although this is a relatively modest change in the blending ratio, it results in a 30% reduction in the CO_2 intensity of process (calcination) emissions from cement production. The ETC indicates that ratios as low as 0.50 may be possible with available technologies and pozzolan-based SCMs, resulting in CO_2 intensity reductions of up to 70%.[41]

The feasibility and cost of blending can depend on the types of SCM used and their availability. Currently, the most common SCMs are fly ash (a “pozzolanic” by-product of coal combustion in furnaces or power plants) or slag (a by-product of pig iron production). Although common and low-cost, these materials should become scarce as the economy increasingly decarbonizes. Silica fume, a by-product from the production of silicon

[39] Loreti Group, “Greenhouse Gas Emission Reductions from Blended Cement Production” (Climate Action Reserve, 2008), www.climateactionreserve.org/wp-content/uploads/2009/03/future-protocol-development_blended-cement.pdf.

[40] International Energy Agency and Cement Sustainability Initiative, “Technology Roadmap: Low-Carbon Transition in the Cement Industry.”

[41] Energy Transitions Commission, “Mission Possible Sectoral Focus: Cement.”

metals and alloys in electric arc furnaces, could be a more viable "waste product" option, but may have limited availability.[42]

Other pozzolanic materials include naturally occurring volcanic and sedimentary rocks (especially volcanic ash and pumices, which may be available in the Pacific Northwest), as well as ash from the combustion of organic materials like rice husks or hemp.[43] Availability of these materials will vary by region. In its decarbonization scenario, the IEA projects that the most common SCMs globally will be raw limestone (uncalcined, but finely ground for blending) and calcined clay, which are globally more available.[44]

Notably, blended cements and SCM concretes are typically *cheaper* than unblended alternatives using standard Portland cement. Barriers to widespread adoption include technical constraints (blended cements sometimes take longer to set, with implications for project schedules) and, in some regions, SCM availability.[45] However, the largest barrier by far is buyer "preference."

More specifically, in many jurisdictions, building standards or public procurement regulations dictate higher clinker-to-cement ratios. Although these specifications are nominally based on safety and health concerns, many studies have found that increased blending does not sacrifice safety and can meet required properties for a variety of construction uses, including *greater* strength and durability.[46] Many observers therefore emphasize the need for "buy clean" standards in public procurement, along with updating of building standards, to encourage greater use of blended cements in the United States.[47]

A final opportunity for reducing the process carbon intensity of cement involves innovations in cement binding materials. New cement chemistries could reduce, or even eliminate, process CO_2 emissions by reducing or eliminating the carbon content of minerals used as raw materials.[48] Instead of limestone, for example, binding materials based on magnesium-silicates, pozzolans, and other compounds could be used.[49]

A large variety of potential new chemistries is being explored, ranging from commercially available alternatives (e.g., belite clinker, which could reduce process carbon emissions by 6%) to those undergoing research and

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[42] "Blended Cement," Lehigh Hanson, Inc., accessed June 29, 2021, https://www.lehighhanson.com/products/cement/blended; International Energy Agency and Cement Sustainability Initiative, "Technology Roadmap: Low-Carbon Transition in the Cement Industry."

[43] International Energy Agency and Cement Sustainability Initiative, "Technology Roadmap: Low-Carbon Transition in the Cement Industry"; The Manh Dinh et al., *Hemp Concrete Using Innovative Pozzolanic Binder* (Clermon-Ferrand, France: First International Conference on Bio-based Building Materials, 2012), https://www.researchgate.net/publication/279851063_Hemp_concrete_using_innovative_pozzolanic_binder.

[44] International Energy Agency and Cement Sustainability Initiative, "Technology Roadmap: Low-Carbon Transition in the Cement Industry."

[45] Loreti Group, "Greenhouse Gas Emission Reductions from Blended Cement Production."

[46] Loreti Group; "Blended Cement."

[47] Rebecca Dell, "Build Clean: Industrial Policy for Climate and Justice" (San Francisco: ClimateWorks Foundation, December 2020), https://www.climateworks.org/report/build-clean-industrial-policy-for-climate-and-justice/; Hasanbeigi and Springer, "California's Cement Industry: Failing the Climate Challenge."

[48] Energy Transitions Commission, "Mission Possible Sectoral Focus: Cement."

[49] Energy Transitions Commission; International Energy Agency and Cement Sustainability Initiative, "Technology Roadmap: Low-Carbon Transition in the Cement Industry."

development (e.g., magnesium silicates, which could in principle eliminate carbon process emissions altogether).[50] New concrete chemistries are also being developed, which have the potential to reduce clinker use and possibly eliminate proces carbon emissions in the long run.[51]

Key Data Needs for Washington

In developing a decarbonization strategy for Washington's cement industry, it will be critical to understand the potential for producing and developing low-carbon cements and concretes. Key variables to understand would include the following.

Data Needs	Existing or Potential Sources
Typical blending ratios and types of SCMs used	Unless Ash Grove is exceptional, blending in Washington is likely to occur at concrete batch plants. Consulting with major concrete producer (e.g., Lehigh) or the Washington Aggregates and Concrete Association could indicate what typical blends are. On its website, Lehigh suggests that most current blends are based on slag, fly ash, and limestone.[52]
Who are the major concrete producers	Consult the Washington Aggregates and Concrete Association members list[53]
Cost and (potential) availability of alternative SCMs, including alternative pozzolan sources such volcanic rocks or hemp	Washington Aggregates and Concrete Association Academic institutions studying construction materials and/or alternative cements and concretes?
Existing building standard requirements, and procurement policies/specifications for concrete in public buildings and infrastructure	Washington State Building Code Council Washington Department of Transportation

Fuel Switching

Although efficiency and use of low-carbon cement blends could significantly lower emissions, large thermal energy demands for making cement are largely unavoidable. Cement kilns must typically heat raw materials to over 2,500°F. Achieving these temperatures is (currently) not practical using electrical energy sources, so fully decarbonizing cement production will likely require alternative fuels or technologies to replace the use of fossil fuels.

[50] International Energy Agency and Cement Sustainability Initiative, "Technology Roadmap: Low-Carbon Transition in the Cement Industry."

[51] Energy Transitions Commission, "Mission Possible Sectoral Focus: Cement."

[52] "Lehigh Cement Company - Lehigh Hanson."

[53] "Membership List - Public," Washington Aggregates & Concrete Association, accessed July 6, 2021, https://www.washingtonconcrete.org/member-list-public.

Current literature suggests several options with varying degrees of cost and feasibility – some commercially available, some more speculative. The most immediate options could be use of biogenic fuels (biomass or biogas) or waste fuels (like municipal solid waste (MSW) or tire-derived fuel, such as what Ash Grove is using). The IEA's deep decarbonization scenario models much greater use of these fuels in cement production globally in the future.[54] There are limits to their application, however.

Most waste fuels – such as tires or MSW – are not low-carbon (although they may displace direct use of fossil fuels); sewage sludge is the one major exception. Globally, availability of biofuels could be a constraining factor.[55] Renewable natural gas, for example, may be available only in limited amounts, although the cement sector could be a prime candidate for having access to what supply is available. This is in part because cement kilns have requirements for the minimum calorific value of fuels that exceed the calorific value of most organic materials.[56]

Other options include use of green hydrogen fuel (produced by electrolysis from zero-carbon electricity)[57] or the use of plasma torches or arc reactors.[58] The former option would require development of green hydrogen infrastructure. In addition, unlike biofuels, use of hydrogen would require significant design modifications to existing kilns because of its combustion properties.[59] Use of plasma torch technology is still in its infancy, and far from full industrial-scale deployment in the cement sector.

Key Data Needs for Washington

Key questions revolve around the compatibility of Ash Grove's existing cement kiln with alternative fuels. Ash Grove's reported fuel mix over the past 10 years suggests that it has some flexibility,[60] including the capability to rely on waste fuels and natural gas. This could make biofuels, including renewable natural gas, feasible options. Looking further into the future, it may make sense to understand any technical and cost constraints around use of hydrogen or plasma technologies.

Data Needs	Existing or Potential Sources
Existing equipment and technologies used at Ash Grove cement kiln, and age of equipment (relevant for considering future retrofit of upgrade options)	Inquiries with Ash Grove staff Tax records Siting permits (e.g., filed with PSCAA)
Current and historical fuel mix	GHGRP reporting data

[54] International Energy Agency and Cement Sustainability Initiative, "Technology Roadmap: Low-Carbon Transition in the Cement Industry."

[55] Energy Transitions Commission, "Mission Possible Sectoral Focus: Cement."

[56] International Energy Agency and Cement Sustainability Initiative, "Technology Roadmap: Low-Carbon Transition in the Cement Industry."

[57] Energy Transitions Commission, "Mission Possible Sectoral Focus: Cement."

[58] Burman and Engvall, "Evaluation of Usage of Plasma Torches in Cement Production."

[59] Energy Transitions Commission, "Mission Possible Sectoral Focus: Cement."

[60] "EPA Facility Level GHG Emissions Data."

	Inquiries with Ash Grove staff (for specific fuel mix ratios, since currently fuel quantities are not reported)
Availability of alternative fuels	Washington State waste characterization studies Deep decarbonization pathway studies (e.g., for 2021 State Energy Strategy), including for future RNG or green hydrogen availability

Carbon Capture and Utilization or Storage

Even if thermal energy were fully decarbonized, cement production would still have a substantial carbon footprint due to process emissions from calcination. Therefore, unless radically new cement chemistries are developed and deployed, a core measure in any deep decarbonization strategy will be to capture, and utilize or store, CO_2 produced during cement production. Most studies suggest that carbon capture, utiltization, and storage (CCUS) will contribute a majority of expected emission reductions in the cement and concrete sector (see Figure 2, for example).[61]

Multiple technology options for CCUS are possible, including post-combustion technologies (chemical absorption, membranes, or calcium looping) and oxy-fuel capture technologies (burning fossil fuels in pure oxygen rather than air, thus increasing the percentage of CO_2 in heat-related emissions and enabling greater capture).[62] Other technologies are being explored as well. Post-combustion technologies – especially chemical absorption – are currently most advanced, though other options (like oxy-combustion) may ultimately offer cost advantages for capturing *process* emissions specifically.[63]

One challenge is that CCUS may be more expensive for cement than for other sectors,[64] although there are competing estimates for different technologies and many unknowns in assessing their cost.[65] One cost factor has to do with lack of proximity to potential users or transport options to storage reservoirs, since cement plants are often *not* clustered with other industries. This may not be an issue for Ash Grove, given its location

[61] MPA UK Concrete, "UK Concrete and Cement Industry Roadmap to beyond Net Zero"; International Energy Agency and Cement Sustainability Initiative, "Technology Roadmap: Low-Carbon Transition in the Cement Industry"; Energy Transitions Commission, "Mission Possible Sectoral Focus: Cement."

[62] International Energy Agency and Cement Sustainability Initiative, "Technology Roadmap: Low-Carbon Transition in the Cement Industry"; Energy Transitions Commission, "Mission Possible Sectoral Focus: Cement."

[63] International Energy Agency and Cement Sustainability Initiative, "Technology Roadmap: Low-Carbon Transition in the Cement Industry."

[64] Energy Transitions Commission, "Mission Possible Sectoral Focus: Cement."

[65] Peter C. Psarras et al., "Carbon Capture and Utilization in the Industrial Sector," *Environmental Science & Technology* 51, no. 19 (October 3, 2017): 11440–49, https://doi.org/10.1021/acs.est.7b01723; D. Leeson et al., "A Techno-Economic Analysis and Systematic Review of Carbon Capture and Storage (CCS) Applied to the Iron and Steel, Cement, Oil Refining and Pulp and Paper Industries, as Well as Other High Purity Sources," *International Journal of Greenhouse Gas Control* 61 (June 1, 2017): 71–84, https://doi.org/10.1016/j.ijggc.2017.03.020.

in Seattle. However, cost challenges are one reason why a focus on material efficiency and circular economy measures may ultimately be an important part of decarbonization strategies (see below).

Although utilization of captured CO_2 (e.g., for industrial applications or to produce synthetic fuels) can help make carbon capture more cost-effective, in the long run utilization is not consistent with full decarbonization. A key question, therefore, is how to *store* captured CO_2 in durable reservoirs. Options here include injection into geologic reservoirs, or mineralization and storage either in geologic reservoirs (underground) or in durable building materials.[66]

The latter may be a promising option; already one U.S. company (Carbon Cure[67]) has refitted around 50 concrete plants with technology that uses captured CO_2 to enhance carbonation in concrete production, improving the concrete's strength and durability.[68] Howver, other studies suggest the net benefits of this approach may be mixed.[69]

Key Data Needs for Washington

Key questions related to CCUS include what modifications would be required at Ash Grove's existing cement plan to implement different kinds of carbon capture technologies; access to possible markets for captured CO_2; and what the potential is for different carbon storage options in Washington or in the region (including availability of geologic reservoirs and possible transport options for either gaseous or mineralized carbon).

Data Needs	Existing or Potential Sources
Existing equipment and technologies used at Ash Grove cement kiln, and age of equipment (relevant for considering future retrofit of upgrade options)	Inquiries with Ash Grove staff Tax records Siting permits (e.g., filed with PSCAA)
Cost and feasibility of different capture, utilization, and storage options, including at Ash Grove and at concrete plants	This is largely outside the scope of our current project, which is focused on data related to energy use and current emissions and would need to be explored through further research. However, inquiries with the Washington Aggregates and Concrete Association may make sense as an initial step to understand whether existing concrete manufacturers may be candidates for – or are already using – Carbon Cure's technology, for example.

66 International Energy Agency and Cement Sustainability Initiative, "Technology Roadmap: Low-Carbon Transition in the Cement Industry."

67 "CarbonCure's Concrete Solution | Concrete Technology Reducing Carbon Impact," CarbonCure Technologies, accessed July 6, 2021, https://www.carboncure.com/.

68 Energy Transitions Commission, "Mission Possible Sectoral Focus: Cement."

69 Dwarakanath Ravikumar et al., "Carbon Dioxide Utilization in Concrete Curing or Mixing Might Not Produce a Net Climate Benefit," *Nature Communications* 12, no. 1 (February 8, 2021): 855, https://doi.org/10.1038/s41467-021-21148-w.

Enhanced Carbonation of Concrete

Concrete absorbs CO_2 from the atmosphere throughout its lifetime. Despite the current carbon intensity of concrete *production*, therefore, concrete has a potential role to play as a medium- to long-term carbon sink. Although concretes used today do not absorb nearly as much carbon as is produced in their manufacture (UK Concrete estimates about at 12% overall reduction in emissions – see Figure 2) there may be ways to enhance the carbon-absorbing properties of concrete even as the industry is increasingly decarbonized.

Future techniques may be able to enhance concrete carbonation (i.e., lifetime absorption of CO_2 in concrete, as oppose to direct incorporation of CO_2 when the concrete is produced, as in the Carbon Cure model). At this point the potential for such techniques is somewhat speculative (the most promising techniques may involve end-of-life treatment of concrete)[70] but could become part of a comprehensive strategy for the industry.

Key Data Needs for Washington

Data needs for a Washington-specific "enhanced carbonation" strategy would be a topic for further exploration and research. Key questions would be whether existing building codes, for example, could be modified to encourage use of concrete blends and applications that enhance CO_2 uptake conditions.[71] A review of common practice during building or infrastructure demolition might also indicate ways to encourage practices for enhancing CO_2 uptake (see "cement demand management" strategies, below).[72] Identifying related data needs would require further research to identify specific kinds of technologies and practices that could be promoted.

Reducing Upstream Emissions

Upstream emissions are likely to be a small component of the total "carbon footprint" of the cement industry. Emissions primarily come from extraction and transportation of raw materials, which could be addressed through broader measures targeting on- and off-road transportation. Key data needs would include identifying the sources of raw materials and modes of transportation.

Key Data Needs for Washington

Data needs	Existing or potential sources
Sources of raw materials used in WA cement plants and their locations Types of extraction equipment used at these locations and associated fuel consumption Distance raw materials are transported Modes of transportation	Interview Ash Grove staff to identify sources of raw material. Use general information (defaults) to estimate emissions.

[70] R. Andersson et al., "Carbonation as a Method to Improve Climate Performance for Cement Based Material," *Cement and Concrete Research* 124 (October 1, 2019): 105819, https://doi.org/10.1016/j.cemconres.2019.105819.

[71] Andersson et al.

[72] Andersson et al.

Downstream "Cement Demand Management" Strategies

Policies targeting the use, demolition, and recycling of cement and concrete could have a significant impact on the industry's greenhouse gas emissions. Cement "demand management" strategies could include:

- **Improving Material Efficiency in Buildings and Infrastructure.** More efficient building and infrastructure design (using less material), improving the durability and buildings and infrastructure, recycling of structural elements (which could be enabled through improved design), and using building space or infrastructure more intensively (reducing the demand for new construction) could significantly reduce demand for cement and concrete, leading to significant greenhouse gas emissions reductions and lowering the total cost of full decarbonization of cement and concrete production.[73] An IEA analysis suggests that these kinds of measures could lower demand for cement by between 15% and 24% globally (relative to baseline levels) by 2060 – producing similar levels of emission reductions.[74]

- **Recycling of Cement and Concrete.** Cement is not typically thought of as a recyclable material. However, there is potential to recycle un-hydrated cements if they are crushed and separated appropriately at end of life, and hydrated cements can be reused if they are reprocessed in kilns (where they will not produce process emissions because calcination already occurred during initial production).[75] Demolished concrete can also be reused, as aggregate in the production of new concrete, although the emissions benefits of doing so may be limited.[76]

- **Material Substitution.** Primarily, this would mean using more wood in building construction rather than concrete (which may be a particularly viable option for Washington).[77]

A study cited by ETC suggests that altogether these "circular economy" approaches could reduce cement emissions in Europe by up to 45%.[78] Similar levels of abatement could conceivably be achieved in the United States given the similar availability of recyclable cement and concrete from existing infrastructure.

[73] Energy Transitions Commission, "Mission Possible Sectoral Focus: Cement."

[74] Araceli Fernandez Pales et al., "Material Efficiency in Clean Energy Transitions" (International Energy Agency, March 2019), https://webstore.iea.org/material-efficiency-in-clean-energy-transitions.

[75] Energy Transitions Commission, "Mission Possible Sectoral Focus: Cement."

[76] Energy Transitions Commission.

[77] Energy Transitions Commission.

[78] Material Economics, "The Circular Economy - a Powerful Force for Climate Mitigation" (Stockholm: Material Economics, 2018), https://materialeconomics.com/publications/the-circular-economy-a-powerful-force-for-climate-mitigation-1.

Key Data Needs for Washington

Data needs	Existing or potential sources
Estimates of fossil fuel consumption in transportation & construction activities (demand management strategies could also affect these emissions)	Could be estimated from data on current concrete demand[79] and typical transportation modes
How efficiently concrete is used in buildings and infrastructure (based on design, durability, use intensity, etc.)	Would require further research on building codes and typical practices
Extent to which concrete and cement recycling already occur in WA	Washington State Department of Transportation [State law (ESHB 1695, passed in 2015) requires WSDOT to develop strategies for recycling and reuse of construction aggregate and concrete, and requires use of at least 25% recycled aggregates and concrete in WSDOT projects.][80]

[79] Available from sources such as the Portland Cement Association (e.g., https://www.cement.org/docs/default-source/ga-pdfs/cement-industry-by-state-2015/washington.pdf?sfvrsn=2&sfvrsn=2).

[80] Washington State Department of Transportation, "Recycled Concrete Usage in Aggregate Materials: 2019 Annual Report" (Olympia, WA: Washington State Department of Transportation, December 16, 2019), https://wsdot.wa.gov/sites/default/files/2019/12/19/RecycledConcrete2019.pdf.

Conclusion

The Washington 2021 State Energy Strategy recommended as a first step for determining how to decarbonize the state's industrial sector improving data collection to develop robust, Washington-specific decarbonization roadmaps for industry emissions. This in-depth Cement Case Study offers an example of analysis that could be performed next for each of the state's industries on the way toward creating a full set of deep decarbonization industrial pathways for the state.

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