Statistical Addendum for
A Cradle-to-Gate Life Cycle Assessment of Ready-Mixed Concrete Manufactured by NRMCA Members – Version 3.2

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1. Abbreviated Terms

EPA Environmental Protection Agency
EPD Environmental Product Declaration
FHWA Federal Highways Administration
GSA Government Services Administration
GWP Global Warming Potential
IRA Inflation Reduction Act
ISO International Organization for Standardization
LCA Life Cycle Assessment
LCI Life Cycle Inventory
LCIA Life Cycle Impact Assessment
NETL National Energy Technology Laboratory
NRMCA National Ready Mix Concrete Association
NSSGA National Stone Sand and Gravel Association
PCR Product Category Rules
TRACI Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts

2. Summary

The objective of this study is to evaluate the exogenous, uncontrollable factors that influence the Global Warming Potential (GWP) of ready mix concrete production and to propose a phase-by-phase method for regionalized benchmarking. This approach is designed to ensure specifiers in all regions of the United States are fairly incentivized to transition to low carbon construction materials in accordance with the goals of the Inflation Reduction Act (IRA) (2022).

The proposed method uses a statistical assessment of GWP developed based on primary data gathered as part of the NRMCA industry regional benchmark LCA for each life cycle phase. Benchmarking by life cycle phase allows for the selection of lower carbon materials while ensuring equitable access to IRA funds despite factors outside a producer's control, such as agency-specific material specifications, local availability of materials, and regional climate. This is a departure from the current practice of using total GWP reported in EPDs to create blanket national thresholds, which can unfairly burden some regions of the country while advantaging others.

This report develops a method that allows agencies to establish concrete mixture GWP thresholds that account for regional variations and agency specifications by treating the life cycle phases (A1, A2, and A3) as independent components that, when combined, provide the relevant 20th percentile, 40th percentile, 50th percentile, and average GWP values for similar products. The combined thresholds can provide a single embodied carbon number more representative of the region and material specification.

This report recommends the following:

- **Use Impact Factors for A1 Impacts:** A1 impacts are calculated based on plant-specific GWP impact factors for cement as well as industry average factors for other mix ingredient types (e.g. fly ash, aggregate, etc.) to set A1 GWP values.
- **Use Regional Trends for A2 Benchmarks:** The use of region-specific distribution-driven thresholds is recommended for the A2 life cycle phase. Impacts due to the transportation of materials are dictated by availability of materials locally.
- **Use Production Regions for A3 Benchmarks:** Impacts due to production vary to a smaller but statistically significant degree across different regions. While A3 impacts are within the control of material producers, the recommendation is to develop distribution-driven thresholds that account for regional operation differences.
- **Use the Sum of A1, A2, and A3 Benchmarks for Procurement:** By combining the local benchmark value for each of A1 (distribution), A2 (distribution), and A3 (distribution) an agency can identify a set of fair GWP thresholds that incentivize improvements in environmental performance.
- **Improve Sampling:** The analysis recommends the continued development of more representative data sets when establishing thresholds for procurement, driven by an intentional sampling process that targets states and regions with limited participation.

This report presents the development, justification, and implementation of this framework.

3. General Information

This study was commissioned by the National Ready Mix Concrete Association (NRMCA). This study uses data gathered as part of the A Cradle-to-Gate Life Cycle Assessment of Ready-Mixed Concrete Manufactured by NRMCA Members – Version 3.2. The LCA report was developed with the intent to support a sector or industry wide Environmental Product Declaration (EPD) for ready-mixed concrete as produced by participating National Ready Mixed Concrete Association (NRMCA) members in accordance with ISO 14025:2006 and the governing PCR. Development of regional benchmarks is also included so that benchmarking against region and strength-specific industry averages could be accomplished.

4. Scope of this Addendum

This LCA study was undertaken to establish a global warming potential (GWP) benchmarking methodology for concrete mixtures that accounts for the sensitivity of GWP to factors outside a producer's influence and to provide initial estimates of industry average GWPs for use in implementing Sections 60503 and 60506 of the IRA. The intended audience for this study is local, state, and Federal agencies that have set or are considering setting performance thresholds for concrete procurement, as well as concrete industry professionals seeking to understand the methodological approach and benchmark their own products against relevant industry averages. FHWA and other Federal agencies can use the report and calculations to be referenced by recipients of the Low Carbon Transportation Materials Program to identify substantially low carbon materials.

Sections 60503 and 60506 of the IRA provide funding to the General Services Administration (GSA) and Federal Highway Administration (FHWA) to pay for the differential cost or incentives for agencies to purchase construction materials with substantially lower embodied carbon as reported in EPDs than estimated industry averages. The material categories identified in the IRA and EPA Interim Determination include asphalt, concrete, flat glass, and steel. The EPA issued an interim determination in December 2022 establishing a cascading set of thresholds to define what it means to be "substantially lower" than industry averages. Under this rubric, the first threshold is materials that are the best performing 20% for GWP values. If not available locally, the next threshold is the best performing 40%. The EPAs determination goes on to state, "*If materials/products in the Top 40 percent are not available in a project's location, then a material/product qualifies for funding... if its GWP is better than the estimated industry average.*"

In supporting the goal of the IRA to incentivize the transition to low-carbon materials, this study assesses the extent to which exogenous factors (design and production parameters that producers cannot control) influence the GWP of concrete mixtures and proposes a phase-by-phase regionalized benchmarking approach that will ensure that market participants in all regions are appropriately incentivized to realize the intentions of the programs set forth in the IRA.

This study follows the ISO 21678 standard "*Sustainability in buildings and civil engineering works— Indicators and benchmarks — Principles, requirements and guidelines*."[1] Additionally the protocols outlined in the PCR document "*Product Category Rules (PCR) for Ready Mix Concrete*" for the calculation of GWP are adopted, specifically with respect to impact assessment methodology, allocation procedures, and the use of upstream inventories. These upstream datasets are specified by the NSF Concrete PCR and represent the best available data to model concrete product systems as determined by the PCR committee. Note that these data include both the USLCI database as well as ecoinvent data. The scope of this study is limited to only the GWP midpoint indicator, even though the methods outlined here can be extended to any of the other indicators as well.

[1] ISO, "ISO 21678."

ISO 21678 establishes four key benchmark values for defining thresholding policies (Figure 1). The thresholding technique adopted by EPA and GSA maps to these benchmark values in a straightforward fashion. The method we present in this document likewise maps to the benchmark types established in ISO 21678 but develops its benchmark values using a composite of regionalized benchmarks for each of A1, A2, and A3 as defined in Figure 2.

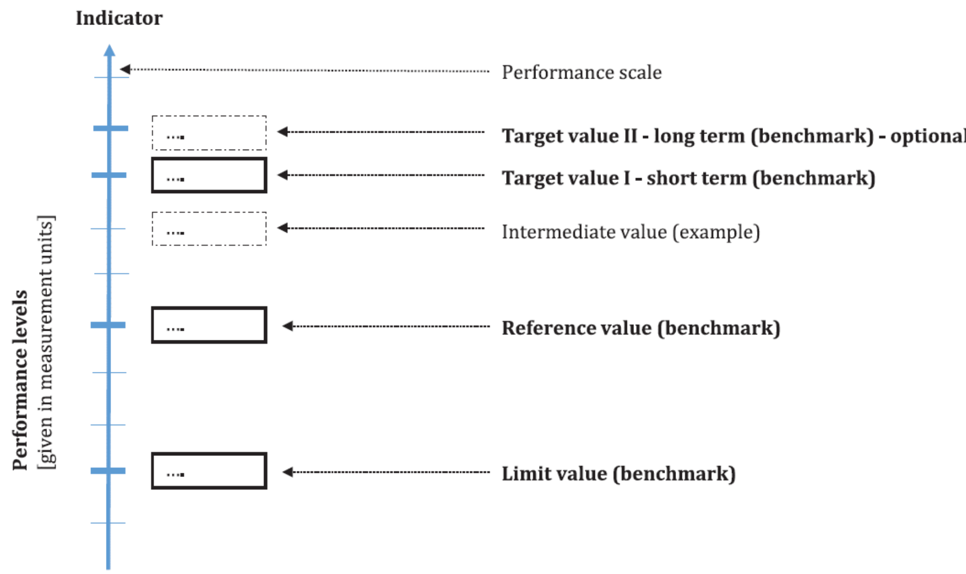

Figure 1. Limit, reference and target values representing benchmarks in the system of performance levels as part of a performance scale for one selected indicator (ref. ISO 21678:2020).

Construction Works Assessment Information														
Construction Works Life Cycle Information Within the System Boundary														Optional supplementary information beyond the system boundary
A1-A3			A4-A5		B1-B7					C1-C4				D
Production Stage			Construction Stage		Use Stage					End-Of-Life Stage				
A1	A2	A3	A4	A5	B1	B2	B3	B4[a]	B5	C1	C2	C3	C4	
Extractional upstream production	Transport to factory	Manufacturing	Transport to site	Installation	Use	Maintenance (incl. production, transport, and disposal of necessary materials)	Repair (incl. production, transport, and disposal of necessary materials)	Replacement (incl. Production, transport, and disposal of necessary materials)	Refurbishment (incl. Production, transport, and disposal of necessary materials)	Deconstruction / Demolition	Transport to waste processing or disposal	Waste processing	Disposal of waste	Potential net benefits from reuse, recycling, and/or energy recovery beyond the system boundary
			Scenario	Scenario	Scenario	Scenario	Scenario	Scenario	Scenario	Scenario	Scenario	Scenario	Scenario	Scenario
					B6 Operational Energy Use Scenario									
					B7 Operational Water Use Scenario									

[a] Replacement information module (B4) not applicable at the product level

Figure 2: ISO 12930 system boundary declaration from the Concrete Mixtures PCR

5. Background

The GSA's document "Interim IRA Low Embodied Carbon Material Requirements" released May 16, 2023[2] establishes thresholds for ready mix concrete based on the methodology outlined in the EPA documents "Interim Determination on Low Carbon Materials under IRA 60503 and 60506" and "COVER MEMO - EPA's Interim Determination for GSA & DOT/FHWA on low greenhouse gas construction materials under IRA Sections 60503 and 60506" released December 22, 2022.[3,4] The GSA thresholds are shown in Figure 3.

	GSA IRA Limits for Low Embodied Carbon Concrete - May 16, 2023 (EPD-Reported GWPs, in kilograms of carbon dioxide equivalent per cubic meter - $kgCO_2e/m^3$)		
Specified concrete strength class (compressive strength [f'c] in pounds per square inch [PSI])	**Top 20% Limit**	**Top 40% Limit**	**Better Than Average Limit**
≤2499	228	261	277
3000	257	291	318
4000	284	326	352
5000	305	357	382
6000	319	374	407
≥7200	321	362	402
Add 30% to these numbers for GWP limits where high early strength[1] concrete mixes are required for technical reasons.			

Figure 3. GSA's GWP limits as published. [5]

An accompanying FAQ identifies the data sources used for these thresholds: "GSA's GWP limits were developed based on industry average EPDs and actual products publicly available EPD data, filtered by material type, PCR(s) specified in GSA's requirements, North American geographical scope and current validity."[6]

The EPA Interim Determination provides the following calculation guidance:

> *"materials/products qualify if their product-specific GWP is in the best performing 20 percent (Top 20 percent or lowest 20 percent in embodied greenhouse-gas emissions), when compared to similar materials/products (for example, materials/products within the*

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[2] "U.S. General Services Administration Interim IRA Low Embodied Carbon Material Requirements." https://www.gsa.gov/system/files/Interim%20IRA%20LEC%20Material%20Requirements%20-%20used%20in%20Pilot%20May%202023%2005162023.pdf

[3] "Interim Determination on Low Carbon Materials under IRA 60503 and 60506." https://www.epa.gov/system/files/documents/2023-01/2022.12.22%20Interim%20Determination%20on%20Low%20Carbon%20Materials%20under%20IRA%2060503%20and%2060506_508.pdf

[4] "COVER MEMO - EPA's Interim Determination for GSA & DOT/FHWA on low greenhouse gas construction materials under IRA Sections 60503 and 60506." US Environmental Protection Agency, December 22, 2022. https://www.epa.gov/system/files/documents/2023-01/2022.12.22%20COVER%20MEMO%20Interim%20Determination%20under%20IRA%20Sections%2060503%20and%2060506_508.pdf

[5] "FAQs: GSA Interim IRA Low Embodied Carbon Material Requirements Pilot." https://www.gsa.gov/system/files/FAQs-on-GSAs-IRA-LEC-Material-Requirements.pdf

[6] "FAQs: GSA Interim IRA Low Embodied Carbon Material Requirements Pilot." https://www.gsa.gov/system/files/FAQs-on-GSAs-IRA-LEC-Material-Requirements.pdf

same product category that meet the same functional requirements). If materials/products in the Top 20 percent are not available in a project's location, then a material/product qualifies per this determination if its GWP is in the Top 40 percent (lowest 40 percent in embodied greenhouse gas emissions). If materials/products in the Top 40 percent are not available in a project's location, then a material/product qualifies per this determination if its ***GWP is better than the estimated industry average (emphasis added)****."*

The document goes on to discuss data sets that may be used in threshold calculation:

"<u>Estimating the best performing 20 percent and 40 percent and industry averages.</u> Agencies shall estimate the GWP at the 20th and 40th percentiles and the industry average, as needed, for each material/product category using data from a verified source (e.g., an open source EPD database, industrywide EPDs or a 3rd party verified LCA developed using the relevant PCR). In addition, agencies shall disclose the GWPs, the methodology for determining the percentiles and averages, the source(s) used for each material/product, and the parameters (including performance specification) that can be used to set the GWP."

The Interim Determination – while an important and significant step in furthering sustainable public procurement – presents the following opportunities for further investigation:

- First, the EPA determination does not describe a particular calculation method for determining the 20%, 40%, and estimated industry average. For example, it is unclear whether the average is intended as an arithmetic mean, or as the median.

- In the absence of available industry averages, GSA has used publicly available databases as a source for EPDs. While these databases serve as a useful industry resource, they are not third party verified for correctness or representativeness.

Using the above as points of departure, this study intends to analytically support the process that EPA and GSA have set forth, as follows:

- Developing an analysis framework for characterizing the sensitivity of the GWP metric to different drivers of uncertainty using industry specific data. Concrete mixture production is a distributed, local production process that is highly sensitive to uncertainties arising from exogenous regional factors through each of the A1, A2, and A3 life cycle phases such that using a nationwide, region-invariant benchmark to drive procurement can unfairly disadvantage some producers or more importantly make it impossible for concrete producers to meet the benchmarks on projects in locations where certain materials (blended cements, supplementary cementitious materials, etc.) are not available. Assessing the sensitivity of GWP to exogenous factors will support thresholds that do not unfairly limit contractors from accessing the IRA funding intended to help them reduce their emissions.

- Establishing a set of statistical approaches that, while simple, provide a formal approach that can be applied consistently to generate thresholds. This includes but is not limited to clarifying the ramifications of using either arithmetic mean or median as alternative definitions of average.

- Establishing separate categorization-driven benchmarking techniques for each of these phases as a candidate alternative to the existing single-valued cradle-to-gate approach covering A1-A3.

This study builds on the work done by EPA and GSA by establishing a larger dataset and examining multiple sources of uncertainty for each of A1, A2, and A3 phases of the concrete mixture life cycle.

6. Methodological Framework

The methodological framework is organized by sub-objectives that support the overall objective of developing industry benchmarks that account for the sensitivity of the GWP metric to various exogenous factors. The two primary sub-objectives are as follows:

O1: Uncertainty Characterization:

- Identify the exogenic actors, or categories by which the GWP can be classified, for example, climate, geography, availability of cementitious materials, and material specification, among others.

- Characterize the extent to which GWP of concrete mixtures is influenced by each of the categories and test for statistical significance.

- Establish a list of statistical tests used for making comparisons.

O2: Proposed Benchmark Calculation Method:

- Devise a method that agencies can use to assist decision-making.

- Establish a defensible set of coefficients/formulas based in LCA outcomes to calculate benchmarks.

Uncertainty Characterization

Bhat & Mukherjee (2019)[7] discuss the different kinds of uncertainty that influence the GWP measure. The first is referred to as aleatory uncertainty, or uncertainty arising from factors that can be characterized as random variables. Aleatory uncertainty describes the stochasticity in or due to exogenous factors *from outside the system boundaries*. In the context of GWP, aleatory uncertainties influence the foreground LCA parameters that distinguish one facility and product specific EPD from another. As the source of these uncertainties are due to factors outside the system boundary, and beyond the control of the contractor (e.g. climate), they can be modeled using random variables. In this document aleatory uncertainty is referred to as parametric uncertainty.

The second source of uncertainty is epistemic uncertainty, or uncertainty arising from gaps in knowledge about a system and/or data gaps. Epistemic uncertainty can arise due to incompleteness or limited quality of background LCI, or due to inconsistencies in LCA modeling approaches. As epistemic uncertainties are within the system boundaries, a purely statistical approach to characterizing their impact on GWP can be difficult, especially given the additional confounding influence of parametric uncertainty. Therefore, every attempt should be made to isolate epistemic uncertainties and evaluate them as alternative cases when investigating

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[7] Bhat, C. G., & Mukherjee, A. (2019) Sensitivity of Life-Cycle Assessment Outcomes to Parameter Uncertainty: Implications for Material Procurement Decision-Making, Transportation Research Record, Journal of the Transportation Research Board of the National Academies, 2673(3) 106:114.

parametric uncertainties. For example, given two sets of EPDs where one set was calculated using background database *A* and the other with background database *B*, each would undergo a separate analysis of the parameters, controlling for the use of different databases. Such a conditional analysis of GWP would ensure that the benchmarking is a function of statistical parametric uncertainty and not choice of background data. Typically, a PCR can be written to manage for epistemic uncertainty by specifying background datasets, selection of proxies for data gaps, and modeling approaches. In the case of the concrete industry, epistemic uncertainties due to data gaps have been reduced by model and background data specification in the PCR.

It is important that the uncertainty being characterized can be associated with known factors. Hence, the first step is to classify the data into independent categories. Classification allows assessment of uncertainties arising from each category independently one at a time holding all the other categories constant, thus eliminating confounding interactions between multiple variables.

For example, climate, an exogenous factor, impacts energy requirements during concrete facility operations (A3), and geology, another exogenous factor, impacts material availability and therefore travel distance (A2). Hence, the sensitivity of GWP to travel distances should be assessed across each climate zone separately, requiring a classification of the EPD data by climate. The classifiers used in this study are as follows:

1. Regional factors
    a. Variations in local operations
    b. Variations in local availability of materials
2. Technological factors
    a. Plant efficiency
    b. Plant type
3. Calculation factors
    a. Data entry errors
    b. Modeling approaches
    c. Choice of life cycle inventory
4. Political / economic factors
    a. Local mixture specifications
    b. Variations in regional availability of fuel sources
    c. Variations in local power grids

It is important to recognize that each of the above factors impact the GWP in different ways; some through parametric uncertainty or epistemic uncertainty (e.g., items 3 and 4). Items 1 and 2 directly influence foreground parameters such as plant energy use and travel distances. Classifying the data provides the opportunity to individually characterize the impact of each factor and enable the estimation of context specific thresholds with a higher level of confidence. Specifically, our choice of classifiers focuses on factors that are outside the control of a concrete producer.

Classification by Climate Regions

The NRMCA industry wide and benchmarking LCA provides regional LCA results for eight production regions plus a national average.

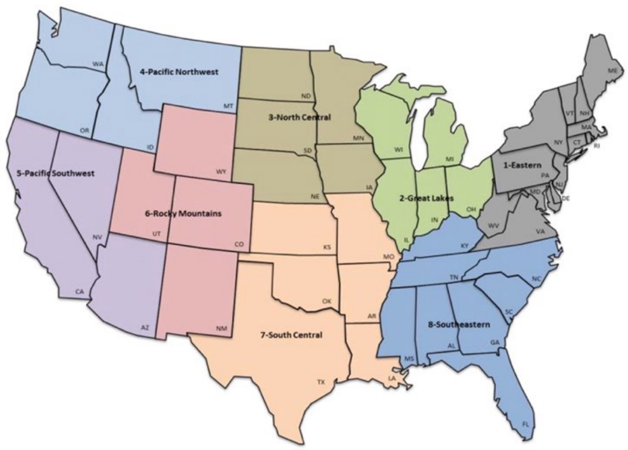

Figure 4. NRMCA Production Regions

1. Eastern Region
2. Great Lakes Midwest Region
3. North Central Region
4. Pacific Northwest Region
5. Pacific Southwest Region
6. Rocky Mountains Region
7. South Central Region
8. South Eastern Region

These regions represent a range of regional climate variations that affect A3 operational energy use.

Epistemic Uncertainty

The PCR for Ready Mix Concrete prescribes all background LCI datasets using the USLCI and ecoinvent except where there is a data gap.

This prescriptive approach to background data sets eliminates the potential for uncertainty due to differences in background data set choices. All calculated GWP indicators in this study use the same background data sets, leaving foreground or parametric data as the main source of uncertainty. Any uncertainty or error in the LCI used to estimate the A1 impacts will uniformly impact the estimation of GWP for all concrete mixtures and not advantage or disadvantage any mix evaluated under this system.

Uncertainty Assessment Method

The EPA's Interim Determination and the GSA's quintile-based threshold[8] is referenced in this study. As originally conceived, this method was intended to account for uncertainty in GWP reporting. The method proposed here better accounts for uncertainty through more accurate modeling of the concrete mixture supply chain. This contrasts with the method originally proposed by the GSA which prescribed modification of GWP values reported in EPDs by applying an arbitrary "uncertainty factor" to the GWP.

In this study, we develop a metric for identifying "substantially lower" levels of embodied carbon through application of the EPA quantile method to each life cycle phase. This phase-by-phase application of the method allows the development of regionalized benchmarks such that materials are judged as "substantially lower" levels of embodied carbon as compared to those designed and produced under similar geographic and technological circumstances.

Following the system established by GSA, the average, median, 40th percentile, and 20th percentile GWP were calculated for each region or category. In all cases for A2 and A3, states or regions with fewer than 5 participating sites or 3 participating organizations were excluded from reporting and identified as high priority for additional data gathering. The 20% thresholds were calculated via the quintile measurement, such that if 100 values are reported, the lowest 20 data points would be included, and the value of the 21st number is the threshold. The 40% thresholds are then the 41st number in this example. The 50% thresholds reported follow this method and are also the mathematical median. Finally, arithmetic means were calculated and are reported as averages.

While it is unclear if the GSA threshold for the "Better Than Average Limit" is based on arithmetic mean or median, this study assumes that the GSA used the arithmetic mean. This report includes both mean and median values whenever presenting 20%, 40%, and "Better Than Average" benchmarks for ease of comparison.

To characterize the causes of uncertainty, the GWP values for A2 and A3 were calculated for the participating locations in the benchmarking data.

A1 uncertainty analysis for the full spectrum of upstream suppliers and mixture designs was not conducted. However, we were able to calculate plant-specific cement GWP factors based on primary cement plant data.

O3: Proposed Benchmark Calculation Method

This report seeks to establish the use of a per-phase categorization and analysis framework based on the mathematical structure of EPD reporting:

$$GWP_{bench} = A1 + A2 + A3$$

[8] "U.S. General Services Administration Interim IRA Low Embodied Carbon Material Requirements." US General Services Administration, May 16, 2023. https://www.gsa.gov/system/files/Interim%20IRA%20LEC%20Material%20Requirements%20-%20used%20in%20Pilot%20May%202023%2005162023.pdf

Equation 1: Breaking out A1 from cradle-to-gate GWP calculation.

$$s.t. \sum_{i=1}^{n} x_i = 1\ tonne$$

Equation 2: Mass-based constraint on Equation 1

Where:

- GWP_{bench} = Total reported A1-A3 life cycle impacts
- x_i = Total amount of ingredient i in tonnes per cubic meter of mix
- $A1$ = Total A1 GWP
- $A2$ = Total A2 GWP
- $A3$ = Total A3 GWP

The separation of the benchmark by the three phases A1, A2 and A3, allows the individual characterization of uncertainty in phases A1, A2 and A3. Note that this "Statistical Addendum" maintains the eight NRMCA production regions that were assessed in the industry wide LCA study.

The following classification system has been used to categorize mixture types and establish candidate regionalization schemes:

A1 category impacts were established for 6 normal weight benchmark ready mixed concrete products by compressive strength (2,500 psi, 3,000 psi, 4,000 psi, 5,000 psi, 6,000 psi, and 8,000 psi) as well as 3 lightweight compressive strengths (3,000 psi lightweight, 4,000 psi lightweight, and 5,000 psi lightweight). The mixture proportions of each concrete product and methodology for establishing benchmark mix designs are presented in detail in the aforementioned Industry Wide LCA in Appendix C.

A2 categories were established by analyzing response data on a regional basis. A2 GWP impacts were calculated based on the combined transport impacts of aggregate, cement, SCMs, and admixtures.

A3 categories were also established by analyzing response data on a regional basis. A3 GWP impacts were calculated based on the average facility operations that includes electricity, natural gas, and other GWP causing activities.

a. Process for Future Updates

Updates to the benchmarks at a minimum will be in concurrence with PCR updates to reflect any significant changes in the PCR, which happens at least every five years. Updates can occur more frequently when market conditions allow or interim updates to the PCR drive the need for new revised data. Preferably these updates will occur as often as possible while balancing the burden of data collection and reporting, with the goal of continually increasing participation. Updates may provide value to the industry by including more specific climate region data, updates to primary energy use, or reflect efforts by industry to reduce impacts.

7. Industry Average Benchmark

This study reports a single indicator, GWP. Results based on the methodology described above for each of A1, A2, and A3 are presented below.

The A1 regional benchmarks were calculated in three steps. These steps are summarized in Figure 5 below.

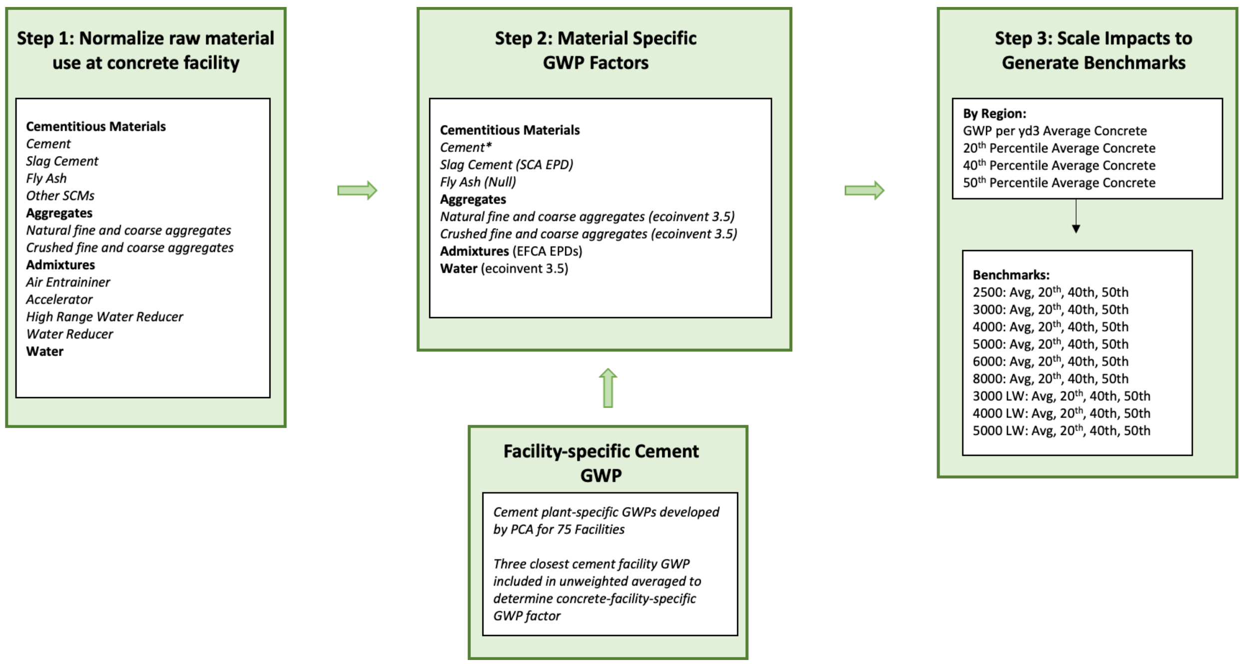

Figure 5. A1 benchmark calculation steps.

- Step 1: The first step was to calculate the use of different material ingredients at each plant. The result of this step was plant-specific use of cement, SCMs, aggregate, and other materials per cubic meter of concrete. This material use was then normalized by the total concrete volume produced at each facility to calculate the use of each raw material per volume (yd^3 and m^3) of concrete produced.

- Step 2: The second step was to apply GWP intensity factors for each of the ingredients found in Step 1 to calculate the plant-specific GWP for the average concrete mix produced at each facility. The GWP factors for all ingredients except cement were drawn from the default A1 datasources as specified in the NSF Concrete PCR. The citations for these data sources as well as a data quality assessment is provided in A Cradle-to-Gate Life Cycle Assessment of Ready-Mixed Concrete Manufactured by NRMCA Members – Version 3.2.

  The cement GWP intensity was calculated on a per-facility basis based on cement facility-specific data provided by PCA. We then mapped the three nearest cement facilities to each concrete plant to establish the concrete plant-specific GWP factors. Table 1 below provides the regional average cement GWP per metric and short ton that was utilized in this assessment. Figure 6 provides the distribution of average A1 GWP for an average product.

- Step 3: The third step was to scale the average concrete mix GWP by the material used in different concrete mix strength classes to calculate the range of regional benchmarks. To accomplish this, the average concrete product GWP in each region was scaled based on the GWP of the various products covered in the IW-LCA. The result of this scaling are the A1 benchmarks presented in Table 2 (yd^3) and Table 3 (yd^3).

Table 1. Top quintiles and averages in the benchmarking of cement (m. ton and sh. ton).

Cement Regional Benchmarks	Eastern kg CO2 e. /m. ton (kg CO2 e. sh. ton)	Great Lakes Midwest kg CO2 e. /m. ton (kg CO2 e. sh. ton)	North Central kg CO2 e. /m. ton (kg CO2 e. sh. ton)	Pacific Northwest kg CO2 e. /m. ton (kg CO2 e. sh. ton)	Pacific Southwest kg CO2 e. /m. ton (kg CO2 e. sh. ton)	Rocky Mountains kg CO2 e. /m. ton (kg CO2 e. sh. ton)	South Central kg CO2 e. /m. ton (kg CO2 e. sh. ton)	South Eastern kg CO2 e. /m. ton (kg CO2 e. sh. ton)
20%	916 831	1026 930	796 722	840 762	826 749	893 810	905 821	861 781
40%	918 833	1122 1018	916 831	877 795	880 798	953 864	976 886	902 818
50%	918 833	1122 1018	916 831	881 799	880 798	972 882	987 895	904 820
Average	918 833	1095 993	892 809	869 788	879 798	955 866	969 879	905 821

Figure 7 provides the distribution of A2 GWP across the participating concrete facilities. Table 4 shows the A2 GWP impacts by production region, including top 20% and 40% benchmarks, and are given in a per cubic meter (per cubic yard) basis.

Figure 8 provides the distribution of A3 GWP across the participating concrete facilities. The A3 GWP impacts by production region, including top 20% and 40% benchmarks, are given in a per cubic meter (per cubic yard) basis in Table 5.

This method has limitations in that these thresholds do not account for application or use the concrete materials. Ideally, thresholds can be developed based on state specific concrete classes as outlined in DOT materials and construction specifications which provide an indication of the application or use of the material and captures other performance characteristics like durability requirements. States considering the development of their own thresholds should begin collecting facility and product specific EPDs that capture the supply chain impacts of the constitent materials and parse the data based on appropriate climatic and/or geologic regions and differentiate by application when possible.

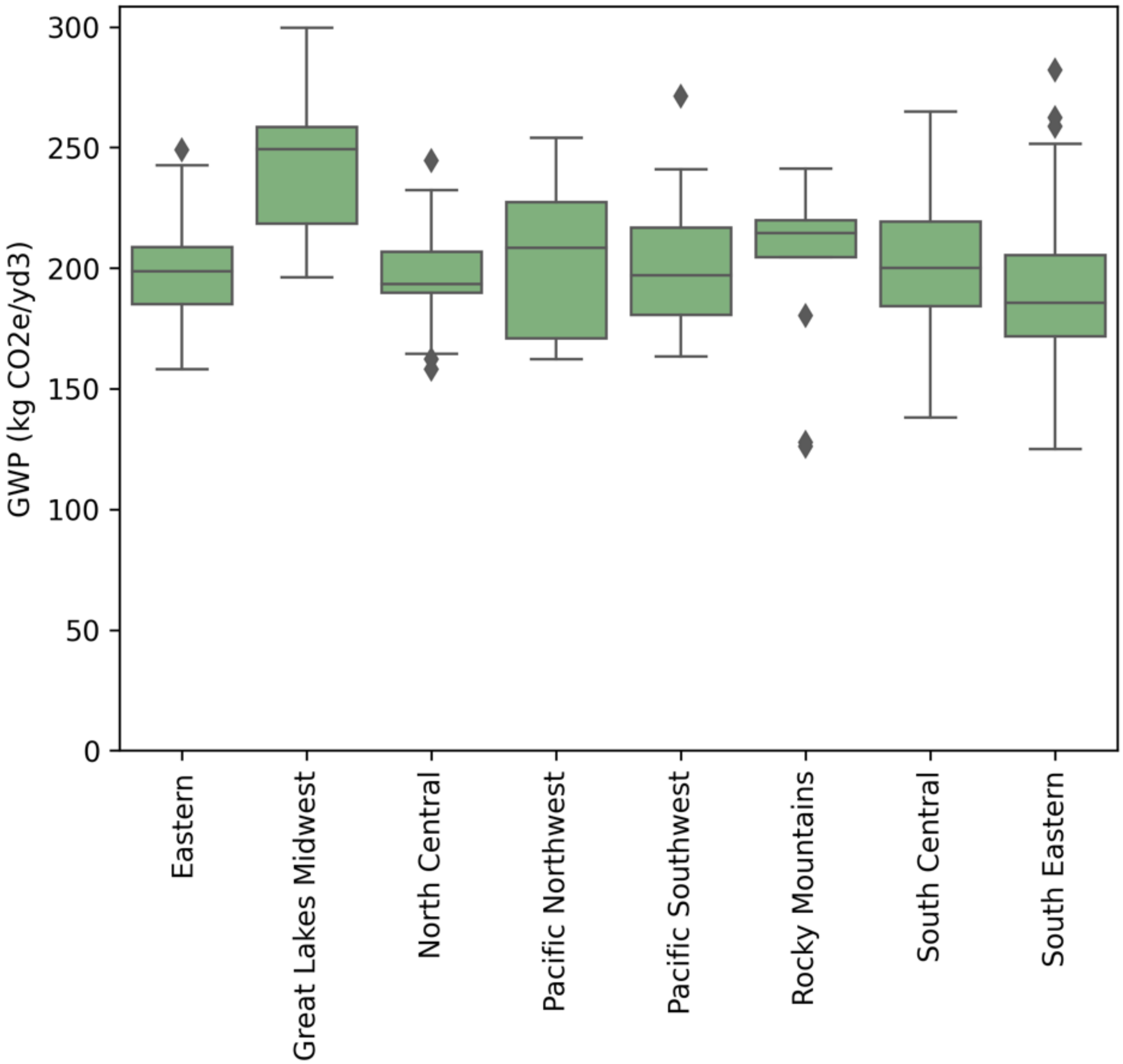

Figure 6. A1 GWP distribution by plant and NRMCA region.

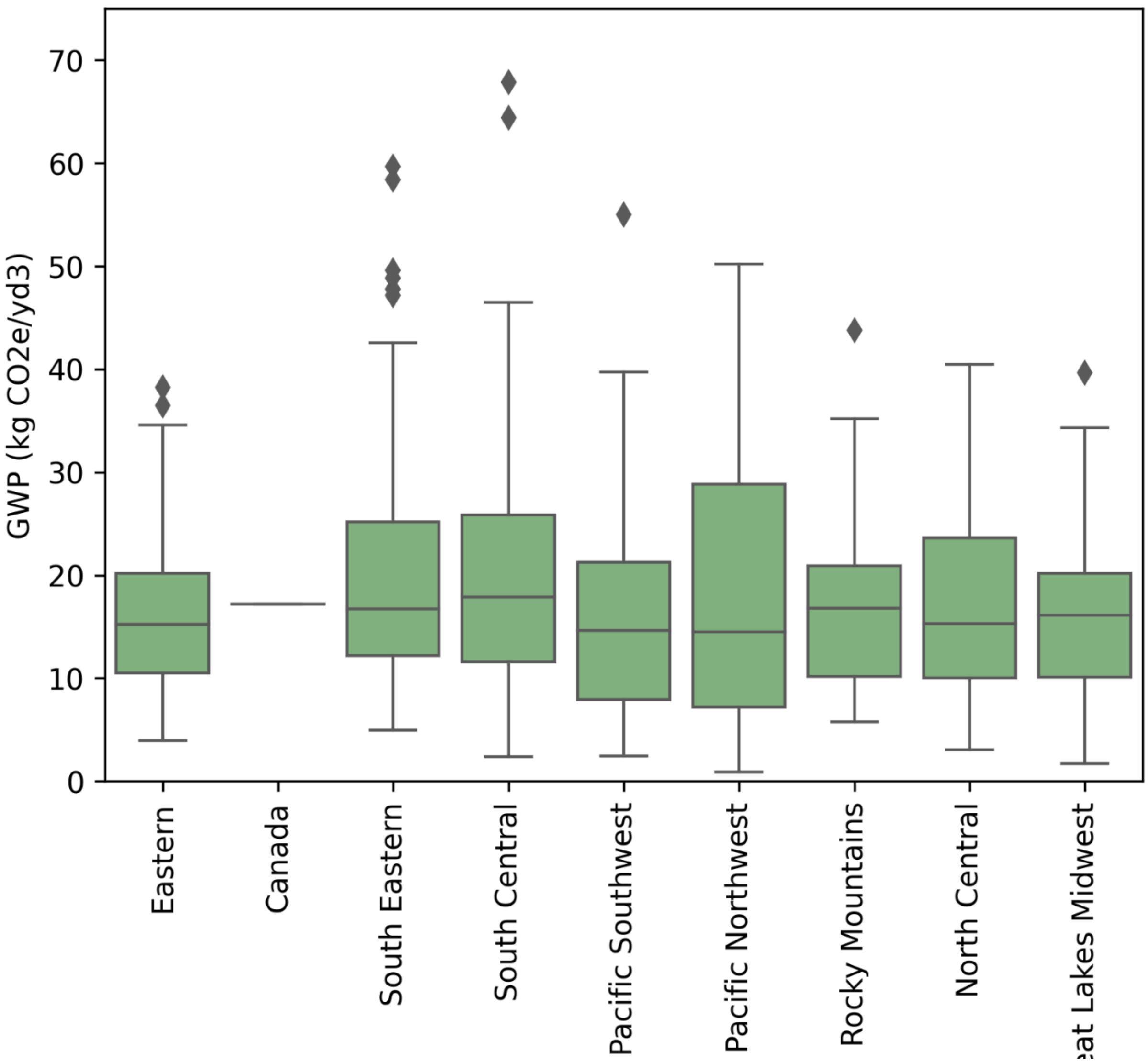

Figure 7. A2 GWP distribution by plant and NRMCA region.

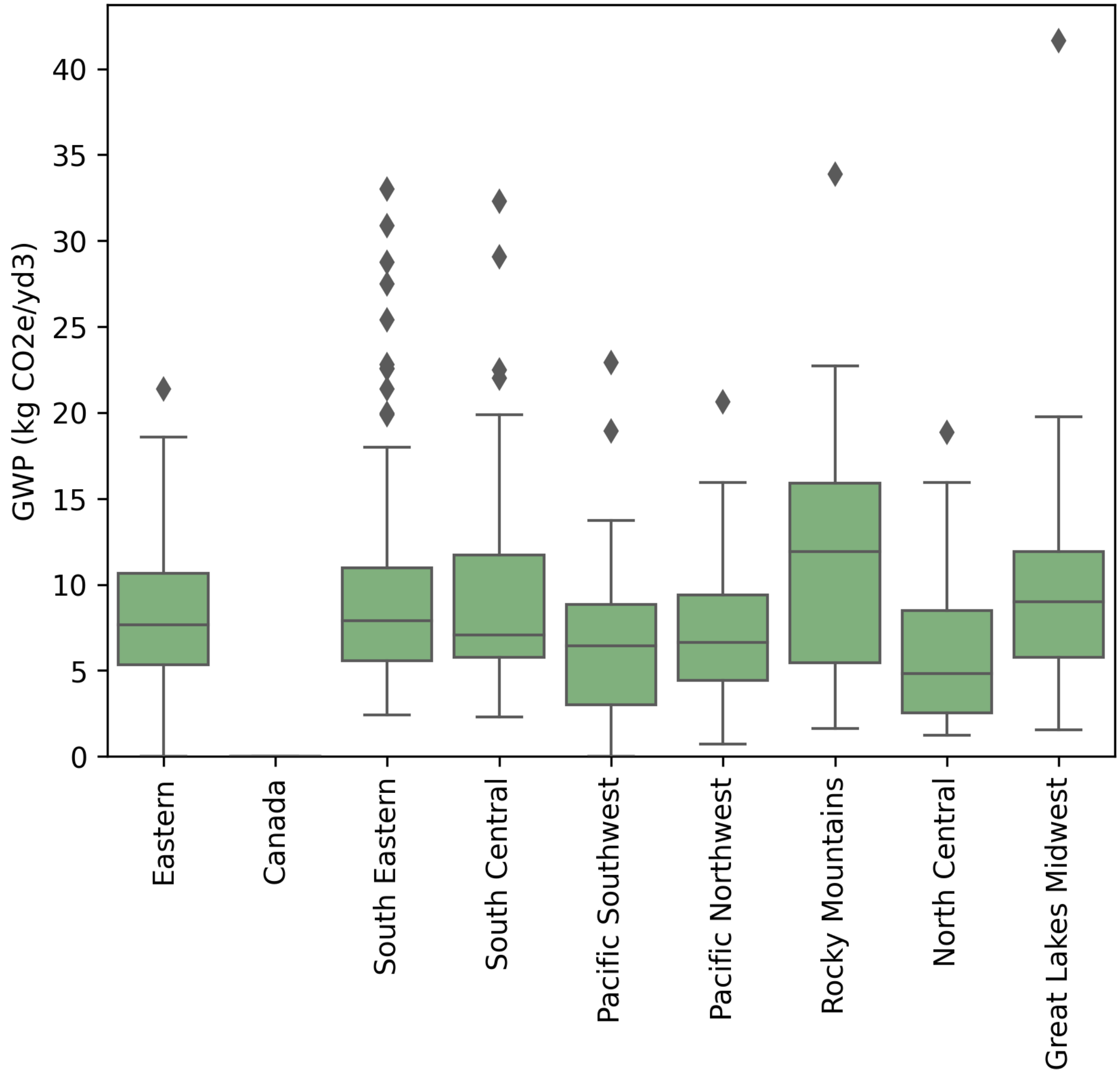

Figure 8. A3 GWP distribution by plant and NRMCA region.

Table 2: Top quintiles and averages in the benchmarking study of A1 GWP by region (per m³)

A1 Regional Benchmarks (m³)		2500	3000	4000	5000	6000	8000	3000LW	4000LW	5000LW
Eastern	Average	207.33	230.42	279.43	341.34	361.33	431.31	462.29	516.20	569.76
	20th Percentile	186.46	207.23	251.32	307.00	324.97	387.92	415.78	464.26	512.43
	40th Percentile	203.63	226.31	274.45	335.25	354.88	423.62	454.04	506.99	559.59
	50th Percentile	206.60	229.61	278.46	340.15	360.07	429.81	460.68	514.40	567.77
Great Lakes Midwest	Average	203.02	225.27	272.46	332.11	351.55	418.76	467.58	519.30	570.48
	20th Percentile	181.64	201.87	244.81	299.05	316.56	377.87	405.02	452.24	499.17
	40th Percentile	198.91	221.06	268.09	327.49	346.66	413.80	443.53	495.25	546.63
	50th Percentile	212.86	236.57	286.89	350.45	370.97	442.82	474.63	529.98	584.97
North Central	Average	207.99	229.62	274.74	331.01	351.08	412.56	456.12	503.37	553.73
	20th Percentile	187.13	207.97	252.21	308.09	326.13	389.30	417.26	465.91	514.26
	40th Percentile	201.38	223.81	271.42	331.55	350.97	418.94	449.04	501.40	553.42
	50th Percentile	203.18	225.81	273.84	334.51	354.10	422.68	453.04	505.87	558.36
Pacific Northwest	Average	208.13	232.56	284.42	350.11	370.54	445.38	484.62	538.30	592.09
	20th Percentile	182.82	203.18	246.40	300.99	318.61	380.32	407.64	455.18	502.40
	40th Percentile	199.64	221.88	269.08	328.69	347.93	415.32	445.16	497.06	548.64
	50th Percentile	202.56	225.12	273.01	333.50	353.02	421.40	451.66	504.33	556.66
Pacific Southwest	Average	218.91	240.50	283.83	337.09	358.57	413.03	453.57	498.91	545.71
	20th Percentile	182.69	203.04	246.23	300.79	318.40	380.07	407.37	454.87	502.07
	40th Percentile	197.68	219.70	266.43	325.46	344.52	411.24	440.78	492.18	543.25
	50th Percentile	204.89	227.71	276.16	337.34	357.09	426.25	456.87	510.14	563.08
Rocky Mountains	Average	208.02	229.89	275.00	331.08	351.38	411.77	461.00	508.26	555.91
	20th Percentile	184.88	205.47	249.18	304.39	322.21	384.62	412.24	460.31	508.08
	40th Percentile	212.13	235.76	285.91	349.25	369.70	441.30	473.00	528.16	582.96
	50th Percentile	219.79	244.27	296.23	361.86	383.05	457.24	490.08	547.23	604.01
South Central	Average	192.46	212.02	251.93	301.57	320.12	372.54	438.66	480.64	525.01
	20th Percentile	184.89	205.48	249.19	304.40	322.22	384.63	412.26	460.33	508.10
	40th Percentile	199.00	221.17	268.22	327.64	346.83	414.00	443.74	495.48	546.89
	50th Percentile	206.43	229.43	278.23	339.88	359.78	429.46	460.31	513.98	567.31
South Eastern	Average	209.46	229.56	270.14	319.92	340.17	391.25	442.31	484.61	523.75
	20th Percentile	182.05	202.33	245.37	299.73	317.28	378.73	405.93	453.27	500.30
	40th Percentile	196.72	218.63	265.14	323.88	342.84	409.24	438.64	489.79	540.61
	50th Percentile	204.60	227.39	275.76	336.86	356.58	425.64	456.22	509.42	562.27

Table 3. Top quintiles and averages in the benchmarking study of A1 GWP by region (per yd^3).

A1 Regional Benchmarks (yd^3)		2500	3000	4000	5000	6000	8000	3000LW	4000LW	5000LW
Eastern	Average	158.51	176.17	213.64	260.98	276.26	329.76	353.45	394.66	435.61
	20th Percentile	142.56	158.44	192.15	234.72	248.46	296.58	317.89	354.95	391.78
	40th Percentile	155.68	173.02	209.83	256.32	271.32	323.88	347.14	387.62	427.84
	50th Percentile	157.96	175.55	212.90	260.07	275.29	328.61	352.22	393.29	434.09
Great Lakes Midwest	Average	155.22	172.23	208.31	253.92	268.78	320.17	357.49	397.03	436.16
	20th Percentile	138.87	154.34	187.17	228.64	242.03	288.91	309.66	345.76	381.64
	40th Percentile	152.08	169.02	204.97	250.38	265.04	316.38	339.10	378.64	417.93
	50th Percentile	162.74	180.87	219.34	267.94	283.63	338.56	362.88	405.20	447.24
North Central	Average	159.02	175.56	210.05	253.07	268.42	315.42	348.73	384.85	423.35
	20th Percentile	143.07	159.01	192.83	235.55	249.34	297.64	319.02	356.22	393.18
	40th Percentile	153.97	171.12	207.52	253.49	268.33	320.31	343.31	383.35	423.12
	50th Percentile	155.34	172.64	209.37	255.75	270.73	323.16	346.38	386.77	426.90
Pacific Northwest	Average	159.13	177.80	217.46	267.68	283.30	340.52	370.52	411.56	452.69
	20th Percentile	139.77	155.34	188.39	230.12	243.60	290.78	311.66	348.01	384.12
	40th Percentile	152.64	169.64	205.72	251.30	266.01	317.54	340.35	380.03	419.47
	50th Percentile	154.87	172.12	208.73	254.98	269.90	322.18	345.32	385.59	425.60
Pacific Southwest	Average	167.37	183.88	217.00	257.72	274.15	315.78	346.78	381.44	417.23
	20th Percentile	139.68	155.24	188.26	229.97	243.43	290.58	311.45	347.77	383.86
	40th Percentile	151.14	167.97	203.70	248.83	263.40	314.42	337.00	376.30	415.35
	50th Percentile	156.65	174.10	211.14	257.91	273.01	325.89	349.30	390.03	430.50
Rocky Mountains	Average	159.04	175.76	210.25	253.13	268.65	314.82	352.46	388.60	425.02
	20th Percentile	141.35	157.09	190.51	232.72	246.35	294.06	315.18	351.94	388.45
	40th Percentile	162.18	180.25	218.59	267.02	282.66	337.40	361.64	403.81	445.71
	50th Percentile	168.04	186.76	226.49	276.66	292.86	349.58	374.70	418.39	461.80
South Central	Average	147.14	162.10	192.61	230.56	244.75	284.83	335.38	367.47	401.40
	20th Percentile	141.36	157.10	190.52	232.73	246.36	294.07	315.20	351.95	388.47
	40th Percentile	152.15	169.10	205.07	250.50	265.17	316.53	339.26	378.82	418.13
	50th Percentile	157.83	175.41	212.72	259.85	275.07	328.35	351.93	392.97	433.74
South Eastern	Average	160.14	175.51	206.54	244.60	260.08	299.13	338.17	370.51	400.43
	20th Percentile	139.19	154.69	187.60	229.16	242.57	289.56	310.36	346.55	382.50
	40th Percentile	150.40	167.15	202.71	247.62	262.12	312.89	335.36	374.47	413.32
	50th Percentile	156.43	173.85	210.84	257.55	272.62	325.43	348.80	389.48	429.89

Table 4. Top quintiles and averages in the benchmarking study of A2 GWP by region.

A2 Regional Benchmarks	Eastern kg CO2 e./m3 (kg CO2 e./ yd3)	Great Lakes Midwest kg CO2 e./m3 (kg CO2 e./ yd3)	North Central kg CO2 e./m3 (kg CO2 e./ yd3)	Pacific Northwest kg CO2 e./m3 (kg CO2 e./ yd3)	Pacific Southwest kg CO2 e./m3 (kg CO2 e./ yd3)	Rocky Mountains kg CO2 e./m3 (kg CO2 e./ yd3)	South Central kg CO2 e./m3 (kg CO2 e./ yd3)	South Eastern kg CO2 e./m3 (kg CO2 e./ yd3)
Average	21.94 (16.78)	21.91 (16.75)	22.13 (16.92)	23.72 (18.13)	26.19 (20.02)	24.07 (18.40)	26.33 (20.13)	26.06 (19.92)
20%	11.81 (9.03)	11.56 (8.84)	11.48 (8.77)	4.79 (3.66)	10.08 (7.70)	11.15 (8.52)	13.94 (10.66)	14.96 (11.44)
40%	16.99 (12.99)	18.16 (13.88)	16.74 (12.80)	16.13 (12.33)	16.09 (12.30)	14.99 (11.46)	19.60 (14.99)	19.93 (15.24)
50%	19.66 (15.03)	20.86 (15.95)	20.00 (15.29)	18.99 (14.52)	17.85 (13.65)	20.89 (15.97)	23.37 (17.87)	21.86 (16.71)

Table 5. Top quintiles and averages in the benchmarking study of A3 GWP by region.

A3 Regional Benchmarks	Eastern kg CO2 e./m3 (kg CO2 e./ yd3)	Great Lakes Midwest kg CO2 e./m3 (kg CO2 e./ yd3)	North Central kg CO2 e./m3 (kg CO2 e./ yd3)	Pacific Northwest kg CO2 e./m3 (kg CO2 e./ yd3)	Pacific Southwest kg CO2 e./m3 (kg CO2 e./ yd3)	Rocky Mountains kg CO2 e./m3 (kg CO2 e./ yd3)	South Central kg CO2 e./m3 (kg CO2 e./ yd3)	South Eastern kg CO2 e./m3 (kg CO2 e./ yd3)
Average	11.29 (8.63)	12.44 (9.51)	8.15 (6.23)	9.55 (7.30)	8.70 (6.65)	16.07 (12.29)	12.18 (9.31)	12.21 (9.33)
20%	6.95 (5.32)	6.50 (4.97)	2.82 (2.16)	3.53 (2.70)	3.58 (2.73)	3.73 (2.85)	7.16 (5.47)	6.21 (4.75)
40%	8.75 (6.69)	9.42 (7.20)	3.74 (2.86)	7.43 (5.68)	6.43 (4.92)	12.02 (9.19)	8.49 (6.49)	9.01 (6.89)
50%	10.27 (7.85)	11.76 (8.99)	6.31 (4.83)	8.21 (6.28)	8.61 (6.58)	14.46 (11.06)	9.21 (7.04)	10.30 (7.87)

8. Using Benchmarks in Public Procurement Scenarios

The benchmarks in this study are intended to allow agencies to account for variabilities in climate, geology, and agency specifications when determining whether a specific concrete mixture has substantially lower embodied carbon than estimated industry averages. A crucial takeaway of this study is that a national average benchmark cannot be used in procurement scenarios without accounting for differences in regional factors and practices that are beyond a contractor's control. Hence, the benchmarks are broken into life cycle phases to reduce confounding factors and can be summed to make a set of GWP values at the 20^{th} percentile, 40^{th} percentile, 50^{th} percentile, and average, that is regionally appropriate for agency-defined mix types.

Take the example of an agency in Pennsylvania setting benchmarks for a 3,000 psi mix. This agency would use the Eastern region 3,000 psi benchmark mixture values from Table 1 for A1, add the Eastern regional average values for A2 (Table 3), and add the Eastern regional values for A3 (Table 4). This approach is shown in Table 5. Each column provides the values used for each phase.

Working from the left, the A1 column has the 20% / 40% / 50% / Avg calculated value for the 3,000 psi mixture for the Eastern Region. The next column are the Eastern regional 20% / 40% / 50% / Avg benchmark values established in this study for A2, followed by the column showing the 20% / 40% / 50% / Avg benchmark values for the Eastern region. The next column, **in bold**, sums the prior columns, creating the final values for benchmarking this mixture in Pennsylvania. The GSA thresholds are provided for clarity.

Table 6: Benchmark for 3,000 psi mixture in Pennsylvania

[all values in kg CO2e / m3]	A1 (Eastern)	A2 (Eastern)	A3 (Eastern)	A1-A3 Total (Proposed Method)	Current A1-A3 GSA Thresholds
20%	207	12	7	**226**	257
40%	226	17	9	**252**	291
50%	229	20	10	**259**	x
Average	230	22	11	**263**	318

This method produces a GWP benchmark that is somewhat lower than to the GSA thresholds for this mix.

9. Summary and Recommendations

Using the current set of published EPDs to create national thresholds without regard for regional differences or material specifications results in GWP limits that unfairly burden some regions of the country. This approach should be avoided until EPD creation has happened at a large enough scale to fully represent the industry.

Agencies looking to procure low embodied carbon concrete mixtures under Sections 60503 and 60506 of the IRA should establish thresholds for each life cycle phase (A1, A2, and A3) that are appropriate for the agency's geographic location and material specifications. These thresholds can be added up for each agency mix type to give a single set of embodied carbon thresholds at the 20th percentile, 40th percentile, and average levels that is appropriate to the region, state, and mixture design specifications. Benchmarking by life cycle phase allows for selection of lower carbon materials while not preventing a region or state from accessing IRA funds because of the influence of factors such as agency specifications, geology, and climate, that are beyond the control of the contractor.

a. Limitations of this study

This study is a first attempt at establishing regionalized benchmarks for the ready mix concrete industry. The emphasis and primary takeaway from this report is the proposed underlying methodology that serves as a first step and is expected to evolve over time as the use of EPDs mature in the industry and more insights are gained on their role in public procurement. Hence, the limitations discussed in this section are also possible next steps in improving the benchmarking process. In discussing the limitations, the underlying principle is articulated to provide context for future steps.

The primary limitations can be discussed as follows:

- In this methodology, A1, for materials other than cement, has been modeled based on industry average data for the primary material inputs. As EPDs for specific upstream suppliers become more available, this approach will need an amendment. As a principle, it will still be true that the upstream impacts (A1) are a definite and calculable quantity given the design and selection of materials. Indeed, for a given mixture design, a contractor can intentionally select between two producers based on their EPDs to deliver a mixture with target GWP.

- In effect, the A1 GWP component is likely to reduce over time as upstream suppliers, especially cement develop new products and processes. The future benchmarking process will have to account for availability of supply chain specific EPDs for different upstream materials to develop intervals for A1 benchmarks. The fundamental principles of (i) allowing contractors the ability to compete based on selection of supply chain partners, and (ii) recognizing that A1 impacts are an outcome of choice that should not be treated as a random variable will still apply.

- Finally, the benchmarking process is driven by EPA's Interim Determination that only accounts for A1-A3 GWP values and does not explicitly account for performance outcomes. Clearly, the materials procured will have to meet design requirements, negating the possibility of a race to the bottom and selection of mixtures that are competitive on GWP only. However, the current framework with its emphasis on selecting lower GWPs discourages contractors from using additives and other material science innovations that deliver significant performance improvement with potentially higher GWPs. Future work will have to account for a benchmarking framework that accounts for GWP in addition to mixture performance properties.

b. Conclusions and recommendations for future work

Based on the analysis this report recommends the following:

- Impacts of upstream materials are dependent on mixture design specifications that are often outside the control of concrete mix producers. Hence, the use of a baseline mixture with constituent-specific adjustment factors is another means for estimating A1 impacts. The impacts of material choices are clearly communicated using this method while also reflecting sensitivities of a mixture's GWP to locally specified mixture design.

- Impacts due to the transportation of materials are dictated by availability of materials locally which in turn is a function of local geology.

- Impacts due to production vary to a smaller but statistically significant degree across different production regions. While A3 impacts are within the control of material producers, the recommendation is to develop thresholds that account for climatic variations.

- The analysis recommends the use of a representative data set when establishing thresholds for procurement, including an intentional sampling process that targets defined climates, geologies, population densities, or regions with significant impacts to thresholds. If sufficient EPDs are available in a state or region, these facility and product specific EPDs may be used to develop these procurement thresholds.

- For high-early strength concrete, the current recommendation is to use a GWP limit (benchmark) which is 30% (or more) higher than the 28-day compressive strength. For example, if the specified compressive strength is 5,000 psi at 28 days, but there is also a specification requirement to meet 3,500 psi at 3 days, it is recommended to multiply the 3,500 psi by 2.5 (since concrete generally reaches 40% of its strength at 3 days) which equals 8,750 psi. That would suggest using the benchmarks for 8,000 psi at 28 days. It is recommended that State DOTs and other entities that develop more localized benchmarks account for specialty mixtures like high-early strength, lightweight, self-consolidating, pervious, and roller-compacted concrete, among others, to differentiate these from conventional structural concrete that is more commonly used.

- NRMCA's current benchmarks were based on 2019 data when the majority (over 95%) of concrete was made with Portland Cement ASTM C150 Type I/II. Since that time, the use of ASTM C595 Blended Cement Type IL has increased to about 55%. Updated benchmarks intended to be published by NRMCA in early 2025 will capture much of this increased use of Type IL but not all, since the benchmark data will be based on 2023 ready mix operations. NRMCA intends to publish benchmarks for national and at least 8 regions but will break out additional regions (potentially up to 30 regions), depending on the data collected. NRMCA requires 4-5 companies reporting to generate a benchmark for a region such as a state or municipal region. Cement companies are working on developing Type IT cements now and likely that will be captured in future NRMCA benchmark surveys, although it's unclear if that will reduce the overall carbon footprint of concrete or simply shift the SCMs used by producers to cement manufacturers who will blend the SCMs into the cement. It will likely be 2028 before NRMCA updates the next benchmarking survey.

The contribution of the benchmarking framework discussed in this study is that it can be scaled to include additional regions and can be updated over time to reflect changes in technology and other factors.

10. Appendix: Statistical summaries & test outcomes

The typical summary statistics of mean, standard deviation, and confidence interval (on the mean) for each grouping discussed in this report are reported in Tables 6-8. The tables also contain the outcomes of the statistical tests performed (not including initial screening level analysis). All comparisons were performed using a two-tailed t-test. P-values are reported where $p < 0.05$ was considered significant.

Table 7. Summary statistics of benchmarking A1 data, production regions (all values in kg CO2e / cubic meter).

Category	Eastern	Great Lakes Midwest	North Central	Pacific Northwest	Pacific Southwest	Rocky Mountains	South Central	Southeastern
Count (N)	65	69	28	32	51	22	91	131
Standard Deviation	10.72%	10.98%	10.60%	15.07%	12.41%	18.09%	13.26%	15.67%
Confidence Interval	3.57%	4.26%	3.89%	8.03%	4.20%	10.93%	3.55%	2.92%

Table 8. Summary statistics of benchmarking A2 data, production regions (all values in kg CO2e / cubic meter).

Category	Eastern	Great Lakes Midwest	North Central	Pacific Northwest	Pacific Southwest	Rocky Mountains	South Central	Southeastern
Count (N)	65	69	28	32	51	22	91	131
Standard Deviation	10.85%	12.07%	12.02%	17.93%	35.28%	14.44%	16.53%	14.24%
Confidence Interval	3.08%	3.86%	4.26%	8.39%	10.73%	7.69%	4.16%	2.30%

Table 9. Summary statistics of benchmarking A3 data, production regions (all values in kg CO2e/ cubic meter).

Category	Eastern	Great Lakes Midwest	North Central	Pacific Northwest	Pacific Southwest	Rocky Mountains	South Central	Southeastern
Count (N)	65	69	28	32	51	22	91	131
Standard Deviation	47.21%	64.31%	77.18%	70.47%	66.09%	70.38%	61.74%	60.11%
Confidence Interval	12.05%	17.93%	27.36%	32.04%	18.28%	37.52%	13.71%	9.42%

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