Update to the Life Cycle Assessment for Asphalt Mixtures in Support of the Emerald Eco Label Environmental Product Declaration Program

June 2021

Amlan Mukherjee, PhD, PE

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For:

National Asphalt Pavement Association

6406 Ivy Lane, Suite 350

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July 26, 2021

Joseph Shacat
Director of Sustainable Pavements
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301-731-4748

National Asphalt Pavement Association
6406 Ivy Lane, Suite 350
Greenbelt, MD 20770-1441

Dear Mr. Shacat,

The National Asphalt Pavement Association (NAPA) commissioned John Beath Environmental, LLC (JBE) to conduct an external independent critical review of the non-comparative life cycle assessment (LCA) study, "Update to the Life Cycle Assessment for Asphalt Mixtures in Support of the Emerald Eco Label Environmental Product Declaration Program", from July 18, 2021. The study was conducted by Dr. Amlan Mukherjee on behalf of NAPA, the commissioning organization. The study's objective is to support the development of the "Product Category Rule for Asphalt Mixtures" for the environmental product declaration (EPD) program hosted by NAPA.

The review of the study was performed to demonstrate conformance with the following standards:

- ISO 14040:2006, Environmental management — Life cycle assessment — Principles and framework
- ISO 14044:2006, Environmental management — Life cycle assessment — Requirements and guidelines
- ISO/TS 14071:2014, Environmental management — Life cycle assessment — Critical review processes and reviewer competencies: Additional requirements and guidelines to ISO 14044:2006
- ISO 21930, Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services

The critical review was conducted by a single external expert, per ISO 14044, section 6.2, and was intended to ensure that:

- the methods used to carry out the LCA are consistent with this International Standard,
- the methods used to carry out the LCA are scientifically and technically valid,
- the data used are appropriate and reasonable in relation to the goal of the study,
- the interpretations reflect the limitations identified and the goal of the study, and
- the study report is transparent and consistent.

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The critical review took place at the end of the study. It excluded an assessment of the life cycle inventory model, but included a review of individual datasets used to conduct the analysis. The provided report was reviewed for conformance to the aforementioned ISO standards, and feedback sent to the practitioner via a comment matrix spreadsheet. Once the report was updated accordingly and responses entered into the spreadsheet, both the report and spreadsheet were returned to the reviewer for a second round of feedback. Ultimately, all comments were deemed to be adequately addressed by Dr. Mukherjee in the final version of the report.

Based on the independent review objectives, the study “Update to the Life Cycle Assessment for Asphalt Mixtures in Support of the Emerald Eco Label Environmental Product Declaration Program”, from July 18, 2021 is found to be in conformance with the applicable ISO standards referenced herein. The plausibility, quality, and accuracy of the LCA study results are confirmed.

Sincerely,

Trisha Montalbo

Trisha Montalbo, Sc.D.
Senior Consultant
John Beath Environmental

JOHN BEATH ENVIRONMENTAL, LLC
Striving to make something better every day

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Self-declaration of reviewer independence and competencies

Report title and date:

> Update to the Life Cycle Assessment for Asphalt Mixtures in Support of the Emerald Eco Label Environmental Product Declaration Program", from July 18, 2021, by Dr. Amlan Mukherjee on behalf of the National Asphalt Pavement Association (NAPA)

I, the signatory, hereby declare that:

- ✓ I am not a full-time or part-time employee of the commissioner or practitioner of the LCA study
- ✓ I have not been involved in defining the scope or carrying out any of the work to conduct the LCA study at hand
- ✓ I do not have vested financial, political or other interests in the outcome of the study

My competencies relevant to the critical review at hand include knowledge of and proficiency in:

- ✓ ISO 14040 and ISO 14044
- ✓ LCA methodology and practice
- ✓ Critical review practice
- ✓ Environmental, technical and other relevant performance aspects of the product system(s) assessed
- ✓ Language used for the study

I declare that the above statements are truthful and complete. I will immediately notify all parties involved (commissioner of the critical review, practitioner of the LCA study, reviewer(s)), as applicable, if the validity of any of these statements changes during the course of the review process.

Date: July 26, 2021

Name: Trisha Montalbo

Signature: Trisha Montalbo

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Glossary of Abbreviations and Terms

AASHTO: American Association of State Highway Transportation Officials

ABR: Asphalt binder replacement

AI: Asphalt Institute

Btu: British thermal unit

CO_2 Eq: Carbon dioxide equivalents

EPD: Environmental product declaration

FEDEFL: Federal Elementary Flow List

FLCAC: Federal Life Cycle Assessment Commons

GTR: Ground tire rubber

GWP: Global warming potential

kWh: Kilowatt-hour

LCA: Life cycle assessment

LAS: Liquid anti-strip

LCI: Life cycle inventory

LPG: Liquefied Petroleum Gases

Mcf: One thousand cubic feet

MMBtu: One million British thermal units

NAPA: National Asphalt Pavement Association

NO_x: Nitrogen oxides

NREL: National Renewable Energy Laboratory

PCA: Portland Cement Association

PCR: Product category rules

RAP: Reclaimed asphalt pavement

RAS: Recycled asphalt shingles

SBR: Styrene-butadiene Rubber

SSBS: Solution Styrene-butadiene Rubber

SBS: Styrene-butadiene-styrene

SO_x: Sulphur oxides

Ton: U.S. short ton (2,000 pounds)

TRACI: Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts

Goal and Scope

The goal of this life cycle assessment (LCA) is to support the Product Category Rule (PCR) for Asphalt Mixtures for the environmental product declaration (EPD) program hosted by the National Asphalt Pavement Association (NAPA). The PCR addresses United Nations Standard Products and Services Code (UNSPSC) 30111509: Asphalt Based Concrete. The PCR is expected to be compliant with International Organization for Standardization (ISO) core PCR ISO 21930.

The study was funded by the National Asphalt Pavement Association and conducted by Dr. Amlan Mukherjee, Professor in the Department of Civil, Environmental & Geospatial Engineering at Michigan Technological University. The study commenced in August 2020 and was completed in July 2021. The intended audience of the PCR includes the following stakeholders:

1. Asphalt mixture producers and producers of constituent materials such as aggregate, asphalt binder, polymers and various additives, who want to quantify and declare the environmental impacts of the mixtures they produce at their plants;
2. Members of the architect/engineering/contractor industry who are looking to purchase asphalt mixtures with an EPD to quantify the net life cycle impacts of their pavement construction processes;
3. Decision-makers and designers at local, state and federal transportation agencies who are seeking to quantify the environmental impacts of asphalt pavement designs; and
4. Any downstream users of products that contain asphalt mixtures seeking to conduct an LCA for their products and services.

Representatives from all the above stakeholder categories were included in and involved with the PCR committee that supported the development of the PCR.

After the PCR has been externally reviewed, the current EPD automation software system will be updated to reflect new datasets and the calculations presented in this LCA study. In keeping with the approach from the last five years, the datasets will support the software system and will allow for rapid EPD generation, allowing asphalt mixture producers to create and update their EPDs with ease. The software will be externally verified and validated to ensure that the underlying rigor of the LCA is not lost.

This LCA report achieved ISO14040/44 compliance in July 2021. The report was critically reviewed by a single reviewer. The purpose of the study is to support the PCR for asphalt mixtures and it is not intended for public comparative assertions. The analysis is intended to represent asphalt mixtures sold from stationary and portable plants through the period of validity of the updated PCR (2022-2027).

The primary changes in this LCA, compared to the existing LCA study are:

1. Improvements in recommended upstream datasets as follows:
    a. Inclusion of a variety of fuels sourced from the USLCI and other available public datasets,
    b. Electricity consumption data updated to reflect Department of Energy (NETL), electricity baseline inventories, regionalized to the level of balancing authority,

c. Inclusion of system level cradle-to-terminal inventory data from Sphera (2019) for asphalt binder, asphalt binder with varying amounts and types of polymer modifiers, and asphalt binder with 8% ground tire rubber (GTR),

d. Inclusion of EPA's transportation and heavy equipment life cycle inventory.

2. Inclusion of portable asphalt mixture plants.
3. Enhanced reporting of trends in life cycle impact assessment indicators based on foreground data collected through the NAPA EPD program since 2015.
4. Extended sensitivity analysis.

Declared Unit

The declared unit for this LCA is 1 U.S. short ton of asphalt mixture ***sold***, rather than tons produced, as the basis for calculating impacts on a per-ton basis. All mention of "ton" in this report refers to a U.S. short ton equivalent to 2,000 pounds or 0.907 metric tonne. In cases where the asphalt mixture is used in a pavement construction operation where the reference unit for the related pay item is in square yards (sq yd), then a conversion of approximately 110-113 lb/sq yd per inch of pavement can be used to estimate the tonnage of asphalt mixture used.

System Boundaries

The system boundaries for the study are established in Figure 1, Figure 2, and Figure 3, in increasing levels of detail. This LCA accounts for processes that are within the bounds of phases A1: Raw Material Supply; A2: Transport; and A3: Manufacturing (Figure 1: Life cycle stages from BS EN 15978:2011).

The scope of the underlying life cycle assessment of the asphalt mixture is strictly "cradle-to-gate" with the gate being defined as the point at which the asphalt mixture is transferred from the silo at an asphalt plant. This LCA supports a business-to-business (B2B) EPD program that aims to aid contractors in communicating the life cycle impacts of asphalt mixtures at the point of procurement.

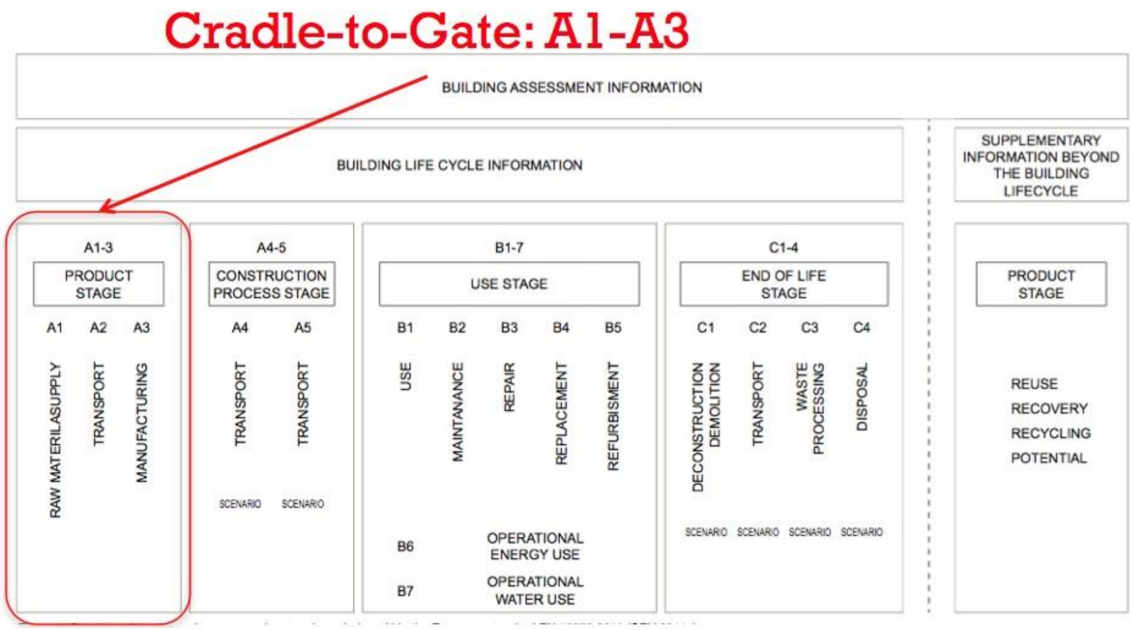


Figure 1: Diagram of Designations of Modular Information Used

After construction, the asphalt mixture becomes part of a pavement structure in combination with other construction elements. During the construction and use stages the environmental performance of a pavement is a function of Pavement Vehicle Interaction models and other pavement management considerations that involve the pavement as a system rather than just the asphalt mixture, an evolving topic of scholarship. It is expected that this limited scope cradle-to-gate LCA (and associated EPDs) will provide a building block to compute the complete life cycle impacts of a pavement system, while at present supporting contractors in meeting procurement related reporting requirements.

Product Scope

This LCA study supports a PCR for asphalt mixtures produced in stationary asphalt plants and on construction sites using portable plants. Moving forward, unless otherwise specified, the term "plant produced" will include mixtures from both stationary and portable plants. An asphalt mixture is defined as a plant-produced composite material of coarse aggregate, fine aggregate, and liquid asphalt binder. The mixture may contain varying quantities of recycled materials as a substitute for virgin materials, as well as chemical additives, as listed below:

1. The use of reclaimed asphalt pavement (RAP) and recycled asphalt shingles (RAS) as substitutes for aggregate and virgin asphalt binder;
2. Polymers added to modify the binder at the refinery/terminal before arrival to the plant;
3. Additives added to the binder at the plant including, but not limited to, fibers, crumb rubbers, liquid antistrips, rejuvenators, and stabilizers; and
4. Various warm-mix technologies and additives.

Items 2, 3 and 4 in the list above are considered part of the scope of the product for which the PCR is being developed. Complete data sets for items 1 and 2 have been included as discussed in a later section. Items 3 and 4, while considered a part of the system have not been included in this LCA. However, they will be included as inventories get updated and become available.

This program provides EPDs that are specific to a particular asphalt mixture from a specific asphalt plant. Hence, the design of the asphalt mixture is a necessary input to the EPD. However, for proprietary reasons, the design will not be provided in the EPD document. Instead, the performance specifications the mixture is intended to meet, per American Association of State Highway Transportation Officials (AASHTO) *M323-04 Standard Specification for Superpave Volumetric Design*, and the loading of the pavement for which the mixture is intended to be used will be provided in Equivalent Single Axel Loads (ESALs). For the sake of this study the Oregon Department of Transportation specification has been referenced (ODOT 2018). The LCA and all outcomes discussed here can be generalized across any specification as long as the mixture design is available by weight.

Purpose

The asphalt mixtures PCR, originally published in 2017 is being updated, to accommodate the use and implementation of EPDs that will provide a basis for comparing the cradle-to-gate environmental impacts of the production of asphalt mixtures. Per the recommendations of ISO 14025:2006, the environmental impacts of all asphalt mixtures that have an EPD compliant with this program can be compared. The key processes are illustrated in Figure 2. It is expected that the PCR will prescribe all life cycle inventory data to be used, effectively establishing a benchmark that will minimize variances resulting from differences in choice of upstream data. Therefore, EPDs compliant with the PCR will only reflect differences in plant energy use, material use, and plant emissions, as well as other collected foreground data, thus providing an effective means for comparing the environmental impact of the process used to produce an asphalt mixture. The impact of plant infrastructure is not included as these impacts are similar across all plants and can be considered as a common overhead. However, as well-maintained plants tend to be more energy efficient, the differences in plant energy use due to age and/or maintenance requirements are reflected in the process energy calculations.

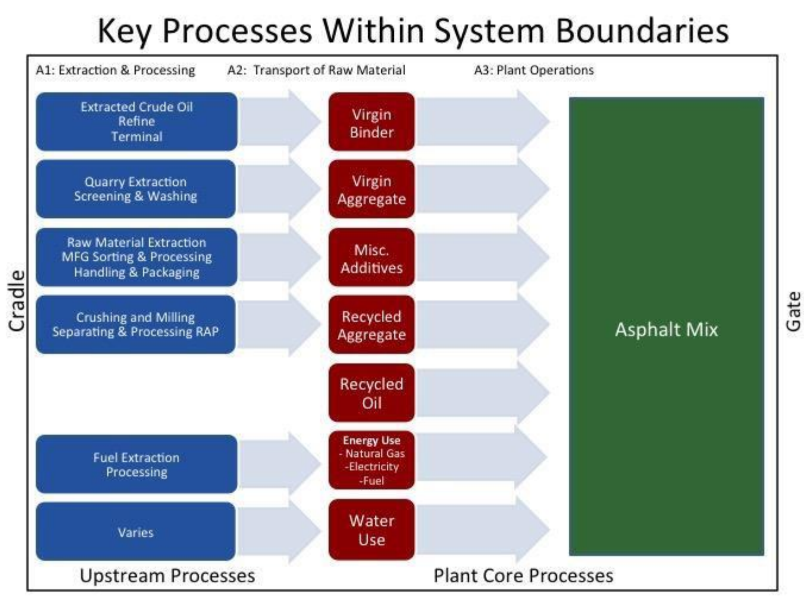


Figure 2: Diagram of the System Boundaries and Key Processes

Asphalt Production Temperature

In the PCR from 2017, no differentiation was made between a "hot" asphalt mixture and a "warm" asphalt mixture. Instead, for each asphalt mixture the plant production temperature will be declared in the EPD.

Reduced production temperature can reduce the energy requirements and thus lower the environmental impacts of asphalt production. Different plants achieve temperature reduction in different ways; however, the use of RAP and/or polymer-modified asphalts can place a limit to how far temperatures can be reduced. This creates significant variability in the actual temperatures at which asphalt mixtures are produced. Therefore, it is preferable if the EPD explicitly declares each mixture production temperature, along with a declaration of any pertinent warm-mix technology used to reduce temperatures. This topic is further discussed in a later section.

In this version of the PCR, producers will have the opportunity to voluntarily disclose any additives that are being used in the mixture (including water used for foaming) to reduce the temperature of the mixture. In addition, while the temperature for the mixture will continue to be reported, the producers will have the option to declare if they consider their mixture to be "Warm Mix Asphalt".

Processes Included in System Boundary

All inputs and outputs to a unit process shall be included in the calculation. For each of the items, the associated data sources have also been declared in a following section. The items are referenced using the phase and associated number on the list. Hence, A1:2 refers to item 2 in phase A1. The broken line envelopes indicate the sub-system boundaries of the specific inventories used. Figure 3 summarizes the key processes and how they relate across the different life cycle phases.

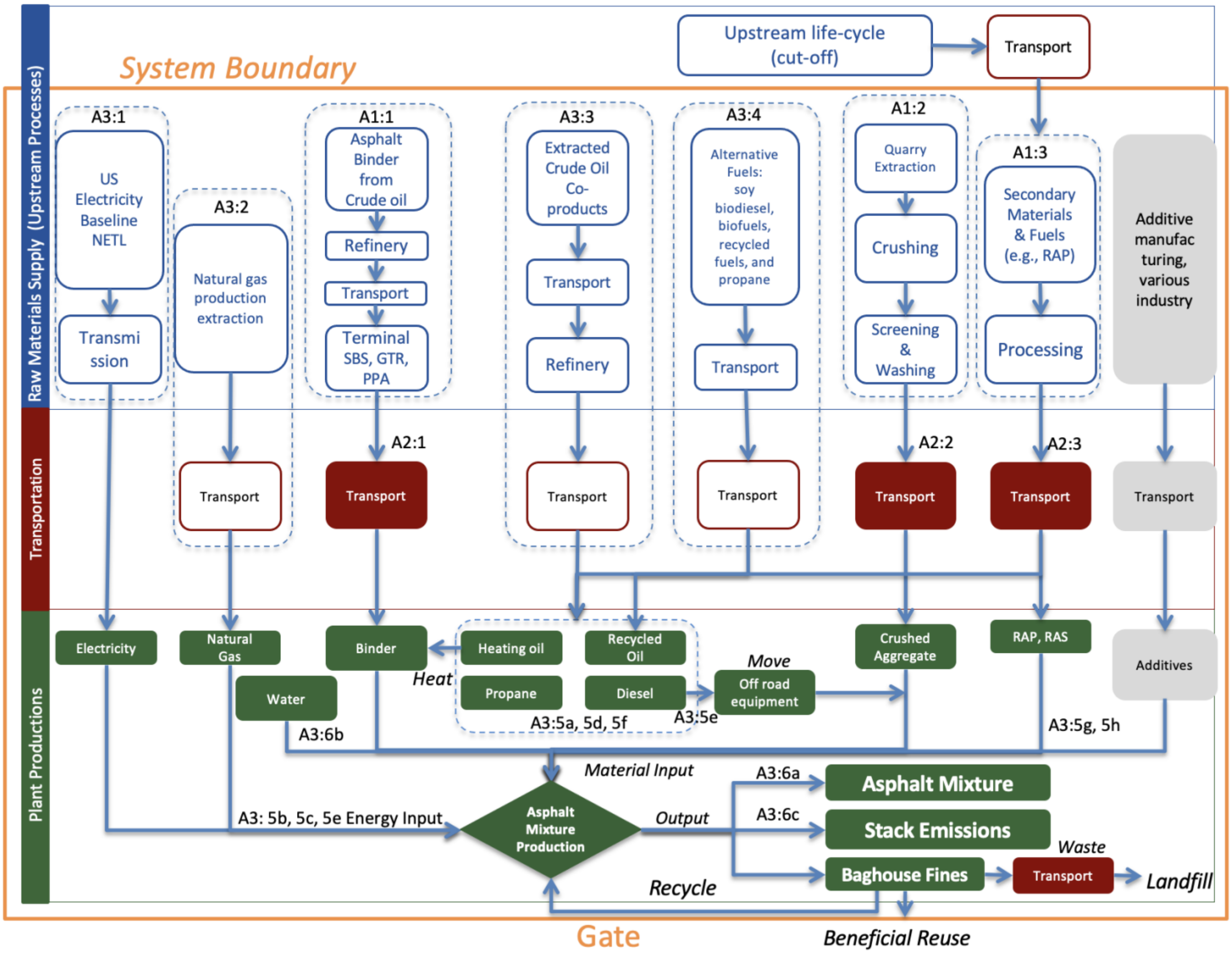


Figure 3: System Boundary Process Diagram

Processes in Phase A1: Material Supply, Mining, and Production

Data for all these processes will be based on background/upstream data sources, from existing public U.S. LCI data. The following are included:

1. Impacts associated with the extraction of crude oil, its refining and production of asphalt binder and transportation to terminal – this also includes the addition of various polymers and their transportation to the terminal. Fresh water consumption reported in upstream are included in the reporting (particularly relevant for asphalt binder). Waste (hazardous and non-hazardous) included in upstream databases is also reported.
2. Impacts associated with the mining, extraction, and production of aggregates.
3. Impacts associated with the secondary materials and fuels. See section on *Allocation.*

Processes in Phase A2: Transport to Plant

Transportation distances to the plant are considered to be foreground data. However, transportation distances that are part of upstream processes, involving transport of a raw material through the supply chain before it arrives to the plant, are considered as part of the upstream/background datasets as indicated by the metadata.

1. Transportation of liquid asphalt binder from the refinery to the asphalt plant. It is assumed that the liquid asphalt binder is directly sourced from a terminal. The LCI for asphalt binder being used includes transportation to terminal, but not to the asphalt plants. The distance traveled by the asphalt binder from the terminal to the plant will be part of foreground data collected for each plant. This is indicated by a solid box in Figure 3.
2. Transportation of virgin aggregate from source to the asphalt plant. This will be based on foreground data collected for each plant.
3. Transportation of recycled materials such as recycled oil, RAP, and RAS to the asphalt plant. This will be based on foreground data collected for each plant.
4. In situations where baghouse fines are not fully recycled internally, transportation from the plant to point of beneficial reuse or landfill.

Processes in phase A3: Plant Operations

All data collected for this part of the system will be directly based on plant operations and will be considered foreground data.

1. Impacts associated with the regionalized production of electricity and its transmission to the asphalt plant.
2. Impacts associated with the extraction, and production of natural gas for combustion in boiler and equipment, including compressed natural gas in heavy construction equipment. Includes transportation of natural gas to plant – typically via pipeline, included in upstream data sources, from existing public U.S. LCI data
3. Impacts of all fossil fuels such as coal and co-products of crude oil refining, including extraction, refining, and storage. The co-products of interest to this PCR include the following:

- For plant operations (stationary and portable): Coal (anthracite, bituminous and lignite), diesel, liquefied petroleum gas (propane), and residual fuel oil.
- For heavy construction equipment: diesel, gasoline, liquefied petroleum gas (propane).
- Includes transportation of crude oil from well to refinery and transportation of all co-products of refining (excepting for liquid asphalt binder) from the refinery to the asphalt plant. This will be based on upstream data sources, from public U.S. LCI data.

4. Impacts associated with alternative fuels such as soy biodiesel, biofuels, recycled fuels, and propane if used, at the plant. Includes transportation of soy biodiesel, biofuels, recycled fuels, and propane if used, at the plant. This will be based on upstream data sources, from public U.S. LCI data.
5. Energy (fuel and electricity) used at the plant for the mix production process, including:
   a. Off-road equipment used to move aggregate and other related mobile equipment used on site for production of asphalt mixtures;
   b. Burner used for drying aggregates;
   c. Burner used for secondary purposes, such as heating exhaust gases;
   d. Heating of liquid asphalt binder in storage tanks;
   e. Movement of aggregate and liquid asphalt binder through the plant and mixing process;
   f. Asphalt mixture storage in silos and liquid asphalt binder in tanks;
   g. Processing of RAP and RAS completed at the plant site; and
   h. Additive addition completed at the plant, i.e., chemical antistrip or hydrated lime, warm mix, rejuvenator, etc.

The above operations directly use upstream impacts associated with energy sources in items 1, 2, 3 and 4 in this list.

6. Outputs from plant, including:

a. Total amount of asphalt mixture sold at the plant. Production is defined by total tonnage of asphalt mixture sold;

b. Total amount of water used at the plant for dust control and/or as an additive for foaming. No differentiation is being made between water used for dust control and water used for foaming. However, water used for foaming will be noted in the section declaring production temperature and temperature-reduction methods;

c. Total plant emissions from stack; and

d. Total quantity of baghouse fines that are not closed-loop recycled 100% in the plant, is designated as either a material for recycling (beneficial re-use) or as a waste (to landfill). Mix producers will indicate the tonnage of baghouse fines exported from their plant, and whether they are exported as a waste material or for beneficial re-use.

Portable plants: not illustrated in the diagram, the portable plant operation is the same as in the stationary plant including the use of diesel and recycled fuel oil, and the following:

a. Total weight of aggregate, binder and other material components of asphalt mixtures (such as RAP and RAS) used in the portable plant, including distances travelled to plant for each of these items reported as foreground data.

b. Total distance travelled by the portable plant on an average in between construction sites, reported as foreground data.

Cutoff Criteria

All inputs and outputs to a unit process for which data are available have been included in the calculation. In case of insufficient input data or data gaps for a unit process, the cut-off criteria is limited to 1% of renewable and non-renewable energy usage and 1% of the total mass input of that unit process, unless a material has the potential of causing significant emissions into the air, water, or soil or is known to be resource-intensive. The total sum of neglected input flows is limited to 5% each of energy usage and mass.

Materials that are less than 1% of the total mass input but are considered environmentally relevant include chemical additives and polymers, such as:

1. Liquid antistrips, rejuvenators, recycling agents, emulsifying agents, and warm-mix chemical additives;
2. Ground tire rubber, energy used for recycling rubber; and
3. Polymers in binder, broken down into two classes of chemicals: Elastomers or rubbers, such as styrene-butadiene-styrene (SBS), and Plastomers.

Given the environmental significance of these materials, they are included as part of the product scope despite the small quantities involved. Upstream data Items 2 and 3 are available and have been included in the system boundary for this LCA, even though there is a data gap for cases when the GTR is not blended at the terminal and is instead added at the plant using the dry process. Significant data gaps also exist in upstream life cycle inventories for materials in Item 1. Items with data gaps will be included in the analysis when reliable and transparent sources become available.

Excluded from System Boundary

Upstream impacts of extraction, production, and manufacturing of any material not consumed in the production of the asphalt mixture is considered to be "part" of the plant infrastructure and is therefore explicitly excluded from the system boundary. These include:

1. The asphalt mixture production equipment and machinery, including lubricants and any other substance used to facilitate the smooth functioning of the plant;
2. Machinery for the recycling of RAP and RAS;
3. Machinery and equipment for blending GTR or other polymers
4. Any equipment used for on-site generation of electricity, heat, or mechanical power.
5. Any materials consumed by the general management, office, and headquarters operations.
6. Solar panels or any other alternative energy apparatus used to substitute traditional energy sources at the plant;
7. General management, office, and headquarter operations; and

8. Impacts from plant personnel, including their commuting to and from the plant.

It could be argued that components of a plant, such as lubricants and conveyor belts, undergo wear and tear and are consumed in the production of the asphalt mixture. The quantities of these components used, based on data reported by an asphalt plant producer, are:

1. Lubricant usage for a plant that produces 150,000 tons a year is approximately 200 gallons; i.e. 0.0013 gallons per ton per year, or 5.2×10^{-6} tons of lubricant per ton of asphalt mixture.
2. A plant that produces 150,000 tons a year, has 2,500 feet of conveyor belts, of which approximately 10-foot-long sections are replaced annually, if the belt breaks (conservative estimate), or approximately 6.67×10^{-5} feet per ton per year.

Based on the above estimates, these components were deemed to meet the cut-off criteria as they are less than 1% of the total mass input per ton of an asphalt mixture.

For all material that comes with packaging, e.g., additives, it is reasonably assumed that the impact of the packaging is included in the upstream inventories. In any case, given that additives are in the range of ~1% of the mix, the associated impacts due to packaging will likely fall within the cut-off threshold.

Finally, given the goal of the EPD program, to facilitate comparison of environmental impacts of products in the same category, infrastructure and consumables are excluded as asphalt producers use similar capital goods to produce the same product. Hence, capital goods are omitted from this study and are considered of limited relevance to the decisions that EPDs from this PCR are expected to support. This also includes consumables (lubricants and conveyor belts) used in operating and maintaining the equipment.

Life Cycle Assessment Inventory

This section outlines the processes that contribute to the asphalt mixture life cycle, classifying them as foreground and background/upstream data. Foreground data is defined as any data item whose sources have been directly observed and collected for the purpose of this study. Background/upstream data is defined as data inventories from other sources and that have not been directly observed for the sake of this study.

Foreground Data

The following must be considered as foreground data inputs for all EPDs certifying specific asphalt mixtures. Foreground data was collected over a 12-month period between August 2014 and June 2015, from 40 plants, as well as data that was collected by the EPD tool during the period 2017 - 2020. The instruments used for the data collection process has been included as Appendix A: Data Collection Instrument.

1. Total asphalt sold by the plant, reported in U.S. short tons
2. Total electricity: total kWh of energy consumed at plant with regional information
    a. Solar power generated on site in kWh if used
    b. Wind power generated on site in kWh if used.
3. Generator energy
    a. Diesel fuel in gallons

    b. Biofuels in gallons

4. Plant burner energy (primary and secondary) and hot oil heater energy
    a. Natural gas use in Mcf or MMBtu
    b. Propane used in gallons or in liters
    c. Diesel fuel in gallons or in liters
    d. Recycled fuel oil in gallons or in liters
    e. Biofuels in gallons or in liters
5. Mobile equipment energy
    a. Diesel fuel use in gallons or in liters
    b. Natural gas use in MCF or MMBtu
6. Aggregate used in production in U.S. short tons
7. Asphalt binder used in production in U.S. short tons
8. One-way distances travelled to plant for asphalt binder and aggregate (both virgin and recycled), expressed in U.S. short ton-miles.
9. Water used in gallons or in liters.
10. Stack emissions from plant in pounds. The most recent data should be reported in addition to emissions estimates as per the Environmental Protection Agency (EPA) AP-42 Compilation of Air Pollutant Emission Factors emissions estimation document.
11. Pre-determined scenarios: For the parameters that may be difficult to estimate or collect foreground data for, the following has been used.
    - Default energy requirements for processing of RAP/RAS is 0.1 gal of diesel per short ton or 0.4 kWh/short ton.
12. Distance travelled by RAP/RAS to plant: mix producers will report the distance from the RAP processing site to the plant (A2), and the EPD will include a recommended default distance in Module D to account for transport from milling to processing site that agencies can include as part of end-of-life transport. The default distance has been determined based on an industry survey that will determine the A2 distances. A default value for A2 RAP transport will be provided in the PCR.

The foreground data collection instrument has been provided as a supplement to this document (Appendix A: Data Collection Instrument). It is important to note that besides the above information, a significant amount of plant context information (including plant equipment type, age, date of most recent maintenance and location) was collected as supplementary information. The entire plant is considered as a single unit process, where raw materials, water, and energy are inputs and the asphalt mixture and emissions to air are the outputs.

There are no hazardous waste materials on site. No waste material is produced as all material at the plant is completely recycled. This includes the volume of mix that is rejected during start-up as well as the baghouse fines. The former is usually completely recycled and sent back to the RAP pile, the latter is also completely recycled within the process. In the case where baghouse fines are not completely recycled internally, asphalt plants will designate this material as either a material for external recycling (beneficial re-use) or as a waste (to landfill). Mix producers will indicate the tonnage of baghouse fines exported from their plant, and whether they are exported as a waste material or for beneficial re-use. As the cut-off method is being used for allocation, the downstream impacts or any benefits of the material are not included. Waste, both hazardous and nuclear, and non-hazardous as reported in upstream datasets is reported as available.

Allocation

This section considers how environmental impacts of upstream products, including recycled products and products that originate in processes with multiple co-products, are allocated to the asphalt mixture.

Recycled materials

The cut-off method is used for allocating upstream impacts for materials recycled or reclaimed from other processes. Recycled/reclaimed materials, such as Reclaimed Asphalt Pavement (RAP), Recycled Asphalt Shingles (RAS), ground tire rubber (GTR) and recycled fuel oil (RFO), will use the “cut-off method.”

1. The upstream impacts associated with recycled/reclaimed materials’ previous life cycles, including production/manufacturing, transport, and use are excluded from the system boundary.
2. Impacts associated with the processes involved in recycling the materials for use in the asphalt mixture are considered part of the system boundary. Hence, the included processes are:
    a. Impacts of crushing RAP/RAS in preparation for use in an asphalt mixture.
    b. Impacts of recycling motor and other non-traditional fuels, such as cooking oil and biofuels. An inventory for recycled fuel oil was developed based on a study by Geyer et al. (2013).
3. An economic allocation is not being used for materials like RAP because the supply of RAP is independent of the quantity used in an asphalt plant. Asphalt plants do not typically buy RAP — although infrequently, they do — and therefore they are not creating a demand for it. Typically, plants allow contractors to dump RAP at the plant site for free. In situations when the volume of RAP produced is much greater than what is used at a plant, plants sometimes charge contractors to dump RAP to help control the size of their stockpiles. It can be safely argued that RAP is not produced to meet a demand for it created by asphalt plants.
4. The distance travelled to plant sites by RAP is being estimated using an industry survey – this can be difficult to estimate because they often come from different construction sites. However, a defined distance based on typical market area is considered a reasonable estimate for the distance travelled by the recycled materials to plant.
5. GTR is processed into small granules or powder and either blended with asphalt binder at the terminal (terminal blend), blended with asphalt binder at the asphalt plant (wet method) or added directly at the asphalt plant (dry method). This processing is included.

6. All travel distances from point of reclamation to the point of processing are not included in this system boundary. However, travel distances from the point of processing to the point of production (asphalt plant) are included. This specifically applies to excluding the distance travelled by asphalt milling from a construction site to the point of processing.
7. For recycled fuel oil, an inventory was developed using a critically reviewed study by Geyer et al. (2013). The inventory includes the impacts due to collection and waste management (including truck and rail transport, hazardous waste landfilling, hazardous waste incineration, and waste water treatment) and reprocessing of used oil (including re-refining, distillation, and recycled fuel oil production). Combustion emission factors were used to estimate impact of use at the plant. Avoided burdens from the displaced use of primary products was not included in this accounting.

Materials from Processes with Multiple Co-Products

Asphalt mixtures use various materials that are co-products of multifunction processes. The most important of these materials is the liquid asphalt binder — a co-product of the petroleum refining process. Other products include chemical additives and polymers. A significant departure from the data being used in the EPD program is that a high-quality dataset is now available for asphalt binder (along with additives such as SBS, GTR and Polyphosphoric Acid), as an outcome of an LCA conducted by the Asphalt Institute and Sphera. A thermodynamics-based allocation is used to develop the asphalt binder inventory as a co-product of the petroleum refining process.

Blast furnace slag, a co-product of iron and steel production, may be used as aggregate in the asphalt mixture. Williams et al. (2019) reported that approximately 1% of the asphalt mixtures produced annually in the United States uses aggregate slag. The PCR for construction aggregates suggests the use of *economic allocation to allocate flows to the slag at the iron or steel production facility* (ASTM 2017). However, at this time no data is available for aggregate slag, and there are no guidelines to conduct the economic allocation appropriately. Therefore, the inventory for aggregate slag is being treated as a data gap. As a significant percentage of the mixture by mass is aggregate a complete LCA cannot be conducted for a mixture using aggregate slag. When slag is used as a supplementary cementitious material, i.e., as slag cement, it is considered to be a "recovered waste material" and according to the slag cement PCR, *only the materials, water, energy, emissions, and other elemental flows associated with reprocessing, handling, sorting, and transportation from the point of the generating industrial process to their use in the production process need to be considered* (ASTM 2014). Available industry average EPD data can be used for cement slag should it be used in an asphalt mixture as a replacement for fine aggregate.

The energy use and environmental impacts (including emissions and water use) at the plant is allocated to the asphalt mixture using a mass-based approach. For example, the gross electricity use over a twelve-month period reported in kilowatt-hour (kWh) is divided by the total tonnage of material sold to estimate the kWh/ton parameter used as an input. Similarly, the tonnage of aggregate (or asphalt binder, or any other component) used per ton of asphalt mixture is calculated based on the mass-based composition specified in the mix design.

Upstream/Background Data

The primary datasets, all of which can be directly accessed from the Federal Life Cycle Assessment Commons (FLCAC), that comprise the background datasets are as follows:

- The US Life Cycle Inventory (USLCI) from the National Renewable Energy Lab, using the Federal Elementary Flow List (FEDEFL)

- Publicly available electricity baseline inventories from the Department of Energy (NETL), and
- Transportation and fuels inventories developed by the Environmental Protection Agency (EPA)
- Inventories developed from publicly available reports and EPDs.

All the following datasets are available in OpenLCA format and are TRACI 2.1 compatible for producing mid-point indicators, as well as the Cumulative Energy Demand (CED) method. They are also compatible with the FEDEFL nomenclature. A complete dataset will be made available with this LCA study and can be used in any LCA platform that can import it in the JSON-LD format. A detailed list of the inventories are as follows:

Fossil Fuels

The following inventories are being used to assess the upstream life cycle impacts of the fuels. In addition, combustion emissions at plant are being collected as foreground data, either reported through direct measurement or estimated as described in Item 10 of *Foreground Data*.

Diesel

- Diesel, combusted in industrial boiler (Source)
- Diesel, combusted in industrial equipment (Source)

Gasoline

- Gasoline, combusted in industrial equipment (Source)

Liquefied Petroleum Gas (Propane)

- Liquefied petroleum gas, combusted in industrial boiler (Source)

Residual Fuel Oil

- Residual fuel oil, combusted in industrial boiler (Source)

Coal

- Anthracite coal, combusted in industrial boiler (Source)
- Bituminous coal, combusted in industrial boiler (Source)
- Lignite coal, combusted in industrial boiler (Source)

Natural Gas

- Natural Gas, combusted in industrial boiler (Source)

Soy Biodiesel

- Soy biodiesel, production, at plant (Source)
- Biodiesel combustion data compliments the "production, at plant" inventory using data for combustion emissions in *firetube boiler designed for use in institutional, commercial, and light industrial applications* Miller (2008) [Source: Table 6, 7], also see further discussion in the section *Use of Bio-Fuels*.

Recycled Fuel Oil

- Recycled fuel oil, combusted in industrial boiler: developed from Data developed from Geyer et al. (2013) [Source: Tables: 10,11, 26, 32, 33, 34, 41, 42.]

Electricity

Following technologies are relevant for the background data category "Electricity"

- Generation based
- Consumption-based

The life-cycle inventory data for consumption-based electricity is available from the National Energy Technology Laboratory (NETL) and the generation-based electricity is available from GREET as well as United States Lifecycle Inventories' (USLCI's) National Renewable Energy Laboratory (NREL). The LCA uses the consumption-based electricity (what electricity is consumed) from NETL, instead of production-based (what electricity is produced), as the default background data for electricity based on conversations with LCA Commons (Source).

Transportation

Natural Gas (Source)

- Transportation by pipeline, natural gas powered Diesel
- Transportation by barge, diesel powered
- Transportation by combination truck, diesel powered
- Transportation by ocean freighter, diesel powered
- Transportation by train, diesel powered
- Transport, refuse truck, diesel powered

Gasoline (Source)

- Transportation by combination truck, gasoline powered
- Transport, refuse truck, gasoline powered

Construction Materials

Asphalt Binder: The following inventories are available from this source.

- Asphalt binder, no additives, consumption mix, at terminal, from crude oil
- Asphalt binder, 0.5% polyphosphoric acid (PPA) (by weight of asphalt binder), consumption mix, at terminal, from crude oil (
- Asphalt binder, 3.5% styrene-butadiene-styrene (SBS) (by weight of asphalt binder), consumption mix, at terminal, from crude oil
- Asphalt binder, 8% ground rubber tire (GRT) (by weight of asphalt binder), consumption mix, at terminal, from crude oil

Aggregate – same as existing LCA

- Data sources from Life Cycle Inventory of Portland Cement Concrete, SN3011

- Impacts associated with the mining, extraction, and production of aggregate identified in publicly available EPDs, from Vulcan Materials (Source).

Lime

- Quicklime, at plant (Source)

Slag

- Cement slag: Data from existing EPDs. (Source)

Emulsion

- Inventory developed as a derivative of the asphalt binder inventory. Created as representative of Asphalt Emulsion used as Asphalt Rejuvenator or Tack Coat. Data retrieved from: Bitumar USA, Inc. (2015).
- Data for material amounts found on page 1, Section 3.

Portland Cement

- Portland cement, at plant (Source)

Data Gaps

The items listed in this section are part of the system boundary, however in the absence of suitable transparent upstream/background data they are considered to be data gaps. The list of additives include, but are not limited to, the following:

- Mix additives (added directly to the mix): Liquid antistrip additives**,** warm-mix additives**,** recycling agents, rejuvenators, emulsifying agents, fibers**,** and pigments
- Binder additives (blended with the binder at the terminal):Polymers, including elastomers and plastomers, pigments, binder extenders, and odor neutralizers.
- While upstream data for GTR blended at the terminal is available there is no data for GTR added at the plant.
- There is no upstream data available for aggregate slag.

Data Quality

This section discusses the philosophical guidelines driving the foreground data collection and selection of upstream/background data inventories. In addition, it also discusses ways in which data quality and data gaps are handled in this LCA study.

Foreground Data

The following principles have supported the foreground data collection design and process for this LCA study.

1. Ease of Collection: The scope of this LCA is to support a PCR for the development of an asphalt mixture EPD. Therefore, it was important to ensure the data collection process was practical and could be conducted, preferably, by plant managers who have direct access to the data and are responsible for the operations. This is likely to reduce errors in foreground data reporting, while also reducing the data collection burden in the long run and consequently encouraging adoption of the EPD program. To that extent, the

foreground data discussed in this section is based on (i) the data that was reported through the EPD program in the last five years, in addition to (ii) the plant data collected during 2014-2015.

2. Data Aggregation: The total annual (12-month period) use of foreground energy and material use data are being collected. While daily average data for consumption is collected to provide a check, the annual gross values are used as inputs. This allows assessment of differentials in impact categories due to (i) energy use (electricity, natural gas, etc.), (ii) mixture design, and (iii) distances travelled by the raw materials to the plant.
3. Foreground Data Analysis: An analysis of the foreground data is provided to examine trends in energy use and their relative sensitivity to moisture and aggregate type in different regions. The trends identified in this analysis can provide regional benchmarks individual plants can use to compare their performance with peers. The results from these analyses can help plants identify ways to improve operating efficiencies while also providing a method to identify possible errors in data reporting.
4. Data Quality Assurance: The following criteria have to be met for all data collected:
    - *a*. Time period: All data reported must be reflective of plant production over a period of 12 uninterrupted months, within the last 5 years, or the most recent data available. Data for emissions to air from the plant should be ideally based on stack test data. If stack test data from the immediate 5-year reporting period is not available, the most recent data should be reported in addition to emissions estimates as per the Environmental Protection Agency (EPA) AP-42 Compilation of Air Pollutant Emission Factors emissions estimation document.
    - *b.* Documents on file: Foreground data reported should be based on utility and energy bills, sales records, and similar documents, all of which should be kept on file and easily accessible.
    - *c.* Correctness Check: In the next section, trends in foreground data have been provided. Data reported by plants that are outliers based on these trends should be checked for reporting errors. These trends will be used to create checks and balances to ensure data quality and identify possible errors or anomalies in reporting.
    - *d.* Geography: All data reported for a plant must be specific to that plant. Company averages should not be used.
5. Data Gaps: Efforts should be made to ensure gaps in foreground data collection are limited to only those items for which a predetermined scenario has been provided (items 11 and 12 in the *Foreground Data* section and unavailable background data inventories identified in the *Data Gaps* section).

Upstream/Background Inventory Data

The following principles have supported the foreground data collection design and process for this LCA study.

1. Uniformity in Use of Life Cycle Inventories: The scope of the PCR supported by this LCA requires asphalt mixtures with EPDs from this program be comparable. Therefore, it

is critical *all* LCA supporting EPDs endorsed by this program use the same upstream inventories. Previous work has shown that even with the same foreground data a choice of different upstream inventories can create significant differences in the final LCA results (Willis, 2015). Therefore, it is of critical importance that the upstream inventories identified in this document be used in any LCA conducted to support an EPD certified by this program. If this uniformity is not maintained, EPDs provided by this program will not be comparable.

2. Transparency of Life Cycle Inventories: The NAPA EPD program intends to respect the spirit of transparency in environmental performance reporting. Therefore, it is of critical importance to this program for all upstream data sources be available *freely and publicly* to anybody who wishes to reproduce the results of the impact assessment. Excepting the proprietary mix data generated by producers, the program intends to remove barriers to providing third parties access to the processes and calculations supporting the underlying LCA. Where proprietary data is involved, system level inventories have been used as they obscure unit process information while providing detailed input-output inventories useful for LCA calculation. An example of this is the system level inventories provided by Sphera for the cradle-to-terminal impacts of asphalt binder. EPD based inventories have also been considered where available, e.g., in the case of aggregate: a comparison of the available public data is compared to the available EPDs in the market.

3. Geography and Regionalization: This report uses upstream data specific to the United States (US). US baseline inventory for electricity as published by the Department of Energy regionalized at the balancing authority level is used.

4. Data Gaps: Given the emphasis on transparency and uniform use of the same upstream inventories, a trade-off is that public datasets are not readily available for all mixture components — particularly chemical additives, GTR added at plant and aggregate slag.

5. Dependence on LCI Data from Allied Industries: The life cycle inventory of asphalt mixtures is dependent on upstream data from various other industries, including but not limited to the petroleum refining industry, aggregate industry and the materials hauling industry. This LCA reflects the best available data from each of these industries available at this time.

Data Quality Assessment Methodology

Appendix B provides a detailed data quality assessment of the background/upstream datasets used in this LCA. It is based on an extension of the US EPA's Pedigree Matrix (Edelen and Ingwersen 2016) and is aimed to standardize the practice of data quality assessment for the pavement LCA domain (Bhat 2020). This Enhanced Pedigree Matrix (EPM) is presented in a questionnaire format to ease its application and improve the specificity of the reference Pedigree Matrix. The guideline was developed to be applied across all pavement LCA projects in the future. The data quality assessment of the publicly available background datasets has been contributed to the FLCAC and was part of a research effort funded by Federal Highway Administration (Bhat et al. 2021).

This LCA and the PCR it intends to support has made a strong commitment to prescribing publicly available background data sources that provide transparency and consistency among EPDs developed through this program. Many of the inventories in the USLCI are derived from a parent dataset (Athena, Franklin &.Sylvatica 2003). Hence, as is apparent from the data quality assessment, many of the datasets do not meet the threshold established in the Enhanced Pedigree Matrix. To be sure, this data quality assessment is aspirational and the nature of how the USLCI is managed often makes it fall short. For example, the USLCI data often has limited documentation and history as they. Similarly, it is difficult to assign ownership to a dataset that has been publicly minimally managed. Having said that, it is worth noting that the use of transparent data sources ensures detection and correction of any errors. To that extent, the choice of the USLCI and the datasets in the FLCAC ensures that the inventories are subject to continuous updates and under public scrutiny. In the process of conducting this LCA, it has become apparent that errors in the USLCI have been detected and corrected in recent versions. In addition, the so-called “dummy” flows have been eliminated as well. This trend of continuous improvement will continue to bear data quality benefits for this program. In addition, in the last few years the USLCI has also become host to critically reviewed ISO 14040/44 compliant datasets (e.g., the contributed inventories for bio-fuels, steel products and asphalt binder). In that spirit the outcomes from this study are also being contributed to the USLCI.

Foreground Data Analysis

This section discusses the foreground data collected for this study from asphalt plants from across the United States. Foreground data was collected, for the items listed in processes described under phase A3, using the data collection tool in Appendix A: Data Collection Instrument. There are two sets of data used in this analysis: the original set collected in the 2014-2015 period, and then the more recent data (same items) that was reported through the NAPA EPD program. The software interface of the EPD tool directly reflects the organization of the data collection tool. The first set collected data from 50 plants, and the second set of data was recorded in the last 5-years and includes data from up to 45 plants. The analysis provides a comparison between the two datasets to establish consistency in foreground data reporting, and overall reliability of the estimates used.

The foreground items that were analyzed were:

1. Energy use:
    a. The energy used in a plant for foreground data items 3, 4, and 5 expressed in BTU/ton and MJ/ton (described in the *Foreground Data* section)
    b. The electricity used in a plant for foreground data Item 2 expressed in kWh (described in the *Foreground Data* section)
2. Transportation distances: The one-way distances travelled by the asphalt binder to the plant from the supplier and by virgin aggregate and recycled materials to the plant.

The data collected for the above items were analyzed for trends, normalized by total tonnage of asphalt mixture production at the plant. Based on the analysis a 95% confidence interval is reported for the relevant categories. Not all data collected from the 50 plants was used in this analysis. Plants that presented outliers were removed from the analysis. It was important to note that some of the outliers may be either due to erroneous reporting at the plant or due to plant-specific conditions. However, for the sake of this study, a conservative approach was taken so that meaningful trends and benchmarks for the typical plant could be developed.

Plant Energy Use Trends

The following trends are based on electricity and energy use in plants. Note the trend based on region when plotted against plant production capacity. The total energy is calculated by summing across all fuel types consumed at the plant using the lower heating values (LHV) in Table 1.

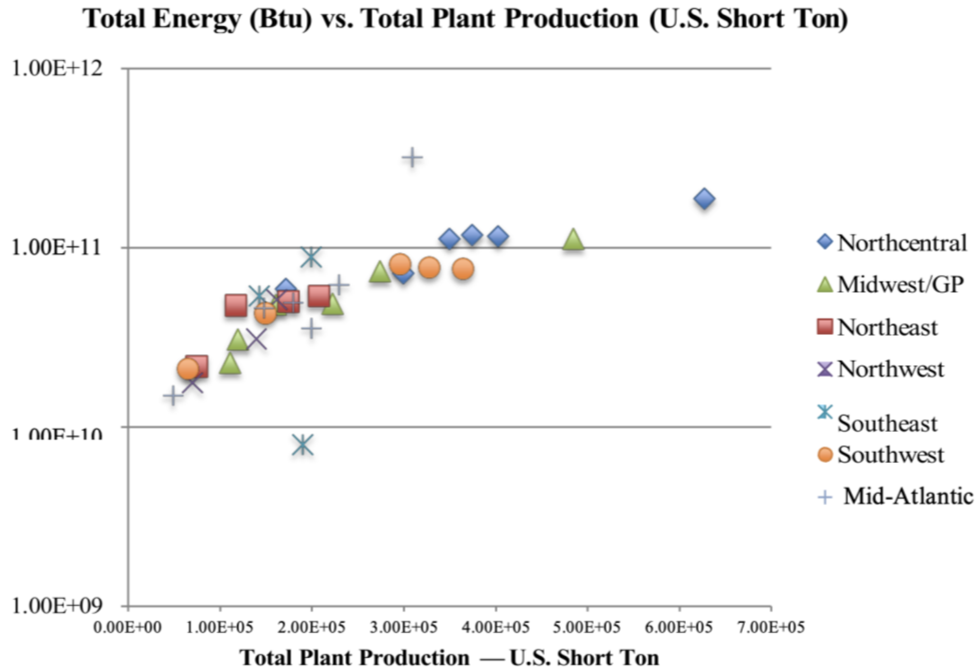


Figure 4: Plant Energy Use per Ton of Mix

The energy use as illustrated in Figure 4 and the electricity use is illustrated in Figure 5. The plots illustrate a trend in how much energy is used based on production capacity. The illustrations show differences in energy consumption per geographic region. The data plotted is based on a sample of 34 plants for energy and 32 plants for electricity. The remaining plants were considered outliers or had incomplete data reporting. The 95% confidence interval for each measure that can be used for data assurance is:

Electricity (kWh/ton): (3.32 ± 0.5) kWh/ton; and

Energy (Btu/ton): ($2.89 \times 10^5 \pm 0.52 \times 10^5$) Btu/ton.

The total process energy for the asphalt plants surveyed is a sum of the above two quantities. Hence the mean process energy is **317.096 MJ/ton or 0.349 MJ/kg** (Appendix D: Conversion Factors).

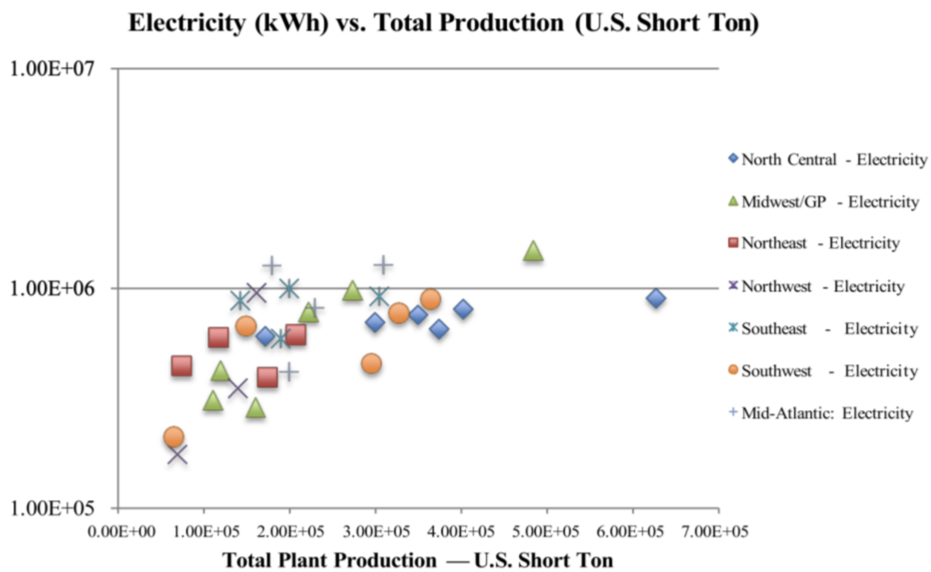


Figure 5: Plant Electricity Use per Ton of Mix

The veracity of this data, though more than five years old, is confirmed by the reporting from the data reported in the EPD program as follows:

Electricity (kWh /ton) = (3.32 ± 1.64) kWh/ton; and

Energy (BTU/ton) = $(2.90 \times 10^5 \pm 0.739 \times 10^5)$ Btu/ton.

Detailed analysis can be found in the report prepared by Trisight (Miller 2020). Figure 6, illustrates a scatter plot of the EPD data. In both the case of electricity and energy, while the means are consistent, the standard deviation of the EPD data is wider than that of the data collected in 2014.

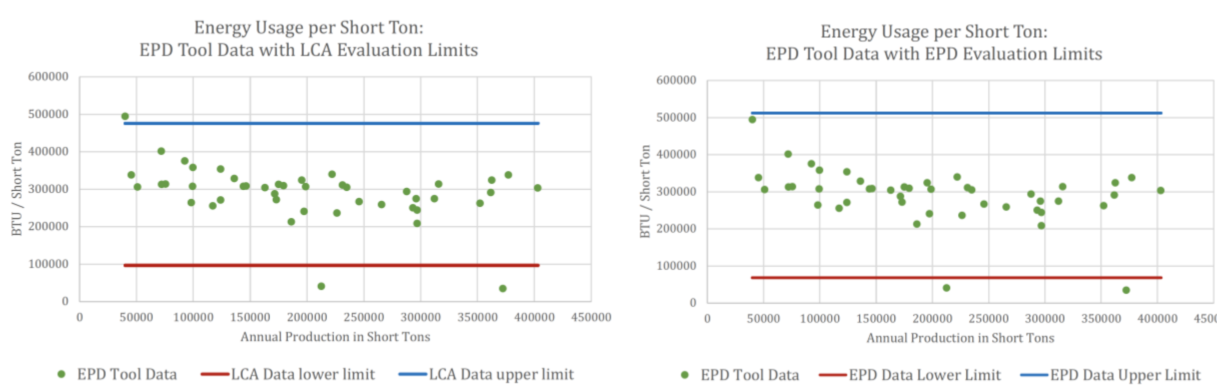


Figure 6: Energy Use from EPD Program (Reproduced with permission from Miller, 2020)

No significant trends based in regionality of the plants could be detected. While weather is a predictor of the level of moisture and therefore energy required to dry the aggregate, other confounding factors such as the ability of the aggregate to retain moisture, the geology and water table from the source of aggregate call for a more detailed study that is beyond the scope of this LCA.

The EPD program data also indicated that the primary sources of fuels used in the asphalt plants were: natural gas (23 plants), propane (11 plants) and recycled oil (13 plants). The average consumption per ton of mix produced was reported as: natural gas - 7.2459 m^3/ton, propane – 0.0109 m^3/ton and recycled oil 0.0072 m^3/ton.

Table 1: Lower Heating Values of Typical Fuels

LHV	MJ/kg
Diesel	42.91
Recycled oil	41.40
LPG - Propane	46.28
Asphalt Binder (no additive)	41.00
Asphalt Binder (8% GTR)	40.30
Asphalt Binder (0.5% PPA)	40.80
Asphalt Binder (3.5% SBS)	39.50
Bio-Diesel	38.16
Natural gas	52.35

A small number of plants have reported the use of bio-fuels (e.g. from grease trap bio-diesel). Two plants reported the consumption data over a period of 3 years for one, and 2 years for the other. The average consumption for bio-diesel was estimated to be 4.595 kg of bio-fuel per ton of mixture and 0.006 m^3 per ton of mixture. This includes a combination of bio-fuel use and diesel used to wash off residues.

The sensitivity of the GWP to the use of each of these energy sources has been provided in a later section.

Transportation Distances

Transportation distances are expressed using a product of tonnage of material transported and the distance moved in miles, and normalized by tonnage of plant production. Hence, the unit is ton-mile/ton. The average of the distances reported in the data collection for this study, with the exclusion of plants that showed very wide departures, from the average are:

- Aggregate, average: 21.5 ton-miles/ton; standard error: 7 ton-miles/ton (sample of 15 plants)
- Liquid Asphalt Binder, average: 3.9 ton-miles/ton; standard error: 1.3 ton-miles/ton (sample of 19 plants)

In addition, a recent industry survey conducted by NAPA (2021), in which 91% of respondents indicated that they were either very confident or somewhat confident in the accuracy of the data submitted, reported the following trends:

- 82% of asphalt plants received the majority of their RAP directly from the paving jobsite to the asphalt plan, with an average distance of 33 miles.
- 18% of asphalt plants received the majority of their RAP via processing or storage at an intermediate (off-site) location, with an average distance of 33 miles for the first leg and 31 miles for the second leg.

- No plants reported using rail or barge for the second leg.

These trends can be useful in informing scenario analysis using the metrics calculated in the section *Truck Travel Distances and RAP Use*.

While this measure provides a description of the most conservative trend in the subset of the primary data collected, these numbers vary quite a bit based on the where the plant is located and change over time due to shifts in markets and demand. RAP travel distances have been pegged at 50 ton-miles/ton. A detailed sensitivity analysis has been conducted to establish the impact of truck transportation miles on the impacts of the asphalt mixture.

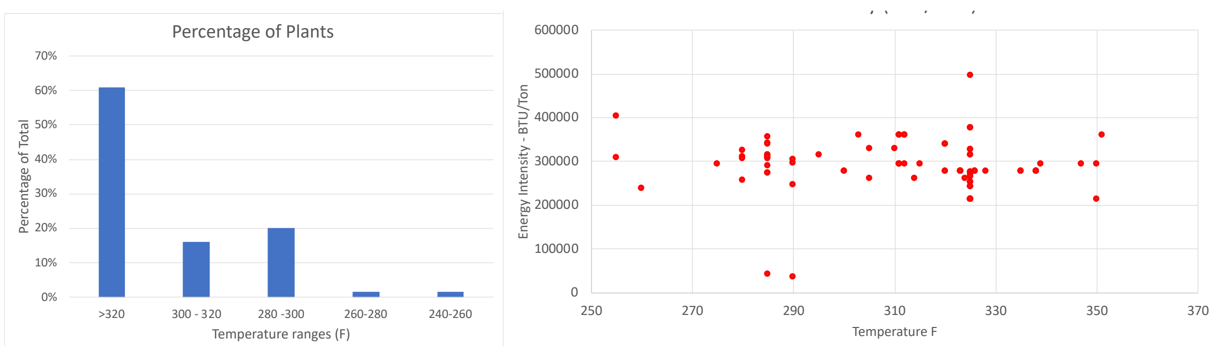


Figure 7: (a) Temperature of Mixtures in EPD Program, (b) Energy intensity v. Temperature

Asphalt Mixture Production Temperature

Data collected from 125 reporting mixtures from the 45 reporting plants indicate that a majority of the mixtures are being produced at a temperature above 320 F (Figure 7). Based on the spread of the temperatures used for the mixtures no trend could be established that directly correlates production temperature to energy intensity of the plant.

Life Cycle Assessment Results

The descriptions of the impact categories selected for reporting as per the PCR Committee, and as defined in TRACI 2.1 (Bare 2012) produced verbatim are as follows:

Acidification: Acidification is the increasing concentration of hydrogen ions (H^+) within a local environment. This can be the result of the addition of acids (e.g., nitric acid and sulfuric acid) into the environment; by the addition of other substances (e.g., ammonia) that increase the acidity of the environment due to various chemical reactions and/or biological activity; or by natural circumstances such as the change in soil concentrations because of the growth of local plant species. Acidifying substances are often air emissions, which may travel for hundreds of miles prior to wet deposition as acid rain, fog, or snow or dry deposition as dust or smoke particulate matter on the soil or water. Sulfur dioxide and nitrogen oxides from fossil fuel combustion have been the largest contributors to acid rain.

Eutrophication: Eutrophication is the enrichment of an aquatic ecosystem with nutrients (nitrates, phosphates) that accelerate biological productivity (growth of algae and weeds) and an undesirable accumulation of algal biomass. Although nitrogen and phosphorus play an important role in the fertilization of agricultural lands and other vegetation, excessive releases of either of these substances may provide undesired effects on the waterways in which they travel and their ultimate destination. While phosphorus usually has a more negative impact on freshwater lakes and streams, nitrogen is often more detrimental to coastal environments.

Global Warming Potential (GWP): Global warming is an average increase in the temperature of the atmosphere near the Earth's surface and in the troposphere, which can contribute to changes in global climate patterns. Global warming can occur from a variety of causes, both natural and human induced.

Ozone Depletion: Ozone within the stratosphere provides protection from radiation, which can lead to increased frequency of skin cancers and cataracts in the human populations. Additionally, ozone has been documented to have effects on crops, other plants, marine life, and human-built materials. Substances reported and linked to decreasing the stratospheric ozone level include chlorofluorocarbons (CFCs), which are used as refrigerants; foam blowing agents; solvents; and halons, which are used as fire-extinguishing agents.

Photochemical Ozone Formation: Ground level ozone is created by various chemical reactions that occur between nitrogen oxides (NO_x) and volatile organic compounds (VOC) in sunlight. Human health effects can result in a variety of respiratory issues including increasing symptoms of bronchitis, asthma, and emphysema. Permanent lung damage may result from prolonged exposure to ozone. Ecological impacts include damage to various ecosystems and crop damage. The main sources of ozone precursors are motor vehicles, electric power utilities, and industrial facilities.

Biogenic Carbon: There is no reporting of biogenic carbon uptake for bio-fuels or any other bio-based material due to limited guidance and inadequacy of the current estimation methods.

The life cycle environmental impact assessment results are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins, or risks. In order to reproduce the results discussed below it is important to use EPA's version of TRACI 2.1 that is compliant with the FEDEFL and can be accessed from the FLCAC website. All GWP reporting henceforth is in kg of CO_2 equivalents per ton of asphalt mixture. All reporting is expressed to three decimal places, with rounding (2 significant figures after the decimal place) plus exponent. The exception to this rule is when the number is very small but of significance, for example

The energy indicators were assessed using the cumulative energy demand (CED) LCI method that was created to support the application of the CED method to FEDEFL-adapted LCI data in the FLCAC. This CED method is based on the categorization scheme used in Frischknecht et al. (2005) found in the Ecoinvent report "Implementation of Life Cycle Impact Assessment Methods". All heating values are as per the FEDEFL method, and the list of external references is found on the EPA FEDEFL GitHub. Cumulative energy demand reporting was completed using the following indicators.

Energy pertaining to non-renewable sources:

- Nonrenewable primary energy resources for energy, in MJ: This includes energy used from uranium, coal (bituminous and lignite), natural gas, and crude oil. This is reported as *Non-Renewable Energy from Fossil Fuels and Nuclear*.
- Nonrenewable energy resources as a material, in MJ: In the context of asphalt mixtures this is primarily the feedstock energy of the binder content. Currently, there are no bio-

based materials that are included in the mixture. However, in future should bio-based binders or bio-based additives be included in the mixture, this section will also include their feedstock energy. It is also imperative to recognize that while this feedstock energy is being reported, it is ultimately never used as the asphalt pavement is not used a fuel at any point in its life cycle. Instead, between 5-6% of the asphalt binder is reclaimed when RAP is used in pavements. This is reported as *Non-Renewable Energy as Material*. Bio-based fuels such as renewable natural gas would also be reported as *Non-Renewable Secondary Fuels* – this is not reported at present as these fuels have not been considered in this LCA.

Energy from renewable sources:

- Renewable primary energy resources as a material, in MJ: This is not applicable at this point for the asphalt mixture production as no renewable materials are being used an energy source, nor are there any renewable materials present in the mixture that can be used as an energy source in future.
- Renewable primary energy resource for energy, in MJ: This includes energy sources such as wind, geothermal, and solar/photovoltaic that is used either to produce electricity supplied to the plant or generated at the plant.

Process Energy, in MJ: This is the sum of the energy used in the plant, including burner fuels, industrial equipment and electricity (kWh).

Secondary Material in Mixture, in ton: Recycled material by weight including RAP, RAS and any other material used to substitute aggregate and asphalt binder.

There is no *Land Use Change* expected as a result of asphalt mixture production. Construction of pavements – highways and parking lots – can and do indeed contribute to land use change, however, that is beyond the scope of this LCA. It is also recognized that there are upstream systems, such as mining for aggregate, that may impact land use. However, the background data for upstream processes do not report land use change at this time. As and when such data becomes available it will be included in the reporting.

The OpenLCA platform was used to conduct the LCA. The Federal Elementary Flow List compatible version of TRACI 2.1 was used as the impact assessment method. An explanation of the OpenLCA Data Model in MS Excel has been presented with this document.

Typical Mix Performance

Table 2 provides a profile of a baseline typical asphalt mixture comparable to an Oregon Department of Transportation (ODOT 2018) level 3, dense graded mix with nominal maximum aggregate size (NMAS) of one-half inch.

The foreground data in this mixture reflects data collected from an actual asphalt plant in the Mid-Atlantic area. It is representative of a typical mixture reflecting energy consumption within the ranges observed from the plant data collected. The distance for truck-based RAP and aggregate transport is set to 50 and 21.5 ton-miles respectively based on the recommendation in the current PCR.

The mixture contains 30% RAP, and an unmodified asphalt binder. The material and energy requirements per ton of the mixture, the impact indicators and energy metrics are listed. This mixture is hereto-fore referred to as the **Baseline Mix**. All mixtures discussed in subsequent sections, unless stated otherwise will use the energy profile as illustrated in Table 2.

Table 2: Profile of the Baseline Mixture (per ton)

Materials - per ton of mixture	*Units*	*Base Mix*
Asphalt binder, no additives, at terminal (3.5% virgin by wt.)	ton	3.500E-02
Aggregate (virgin) (67.5% by wt.)	ton	6.750E-01
RAP	pct	30%
* Amount of aggregate from RAP (27.5% by wt.)	ton	2.750E-01
* RAP binder content	pct	5%
***** Amount of binder from RAP (1.5% contribution)	ton	0.0015
Additive - such as Warm Mix	pct	0.00%
Energy in Plant - per ton of mixture		
Natural gas, combusted in industrial boiler - RNA	m3	7.486E+00
Diesel, combusted in industrial equipment - RNA	m3	1.600E-04
Electricity; at grid; consumption mix - US - US	kWh	2.780E+00
Transportation - per ton of mixture		
Asphalt binder: Transport, train, diesel powered – RNA	ton-mile	3.900E+00
Aggregate: Transport, combination truck, diesel powered	ton-mile	2.150E+01
RAP: Transport, combination truck, diesel powered	ton-mile	5.000E+01
Mid-Point Indicators - per ton of mixture		
Acidification	kg SO2 eq	1.576E-01
Eutrophication	kg N eq	1.125E-02
Global warming	kg CO2 eq	4.696E+01
Ozone depletion	kg CFC-11 eq	1.059E-07
Smog formation	kg O3 eq	4.364E+00
Cumulative Energy Demand - per ton of mixture		
Non-renewable Energy: Fossil Fuels and Nuclear	MJ	2.121E+03
Renewable Energy: Hydro, Wind, Solar and Thermal	MJ	6.418E+00
Other Metrics - per ton of mixture		
Process energy used at plant	MJ	2.879E+02
Secondary materials used, by weight	ton	2.900E-01
Non-renewable Energy as Material: Feedstock energy	MJ	1.302E+03
Fresh Water	m3	5.021E+00
Waste - Hazardous & Nuclear	kg	3.279E-03
Waste - Non-Hazardous	kg	6.990E+00

Figure 8 and Figure 9, illustrate a breakdown by percentage of GWP and the nonrenewable energy for one ton of the asphalt mixture. Table 3, provides a similar breakdown by life cycle phases.Figure 8: GWP Contributions for the Baseline Mix

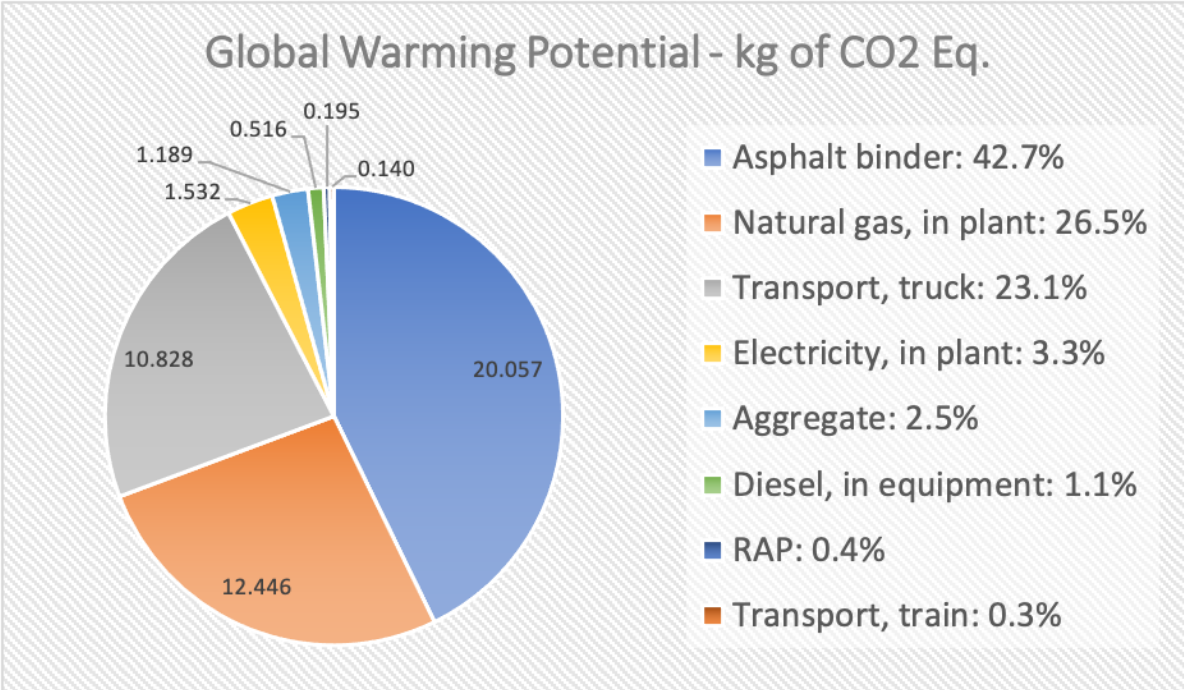


Figure 8: GWP Contributions for the Baseline Mix

Table 3: GWP and Nonrenewable Energy Breakdown by Life Cycle Phase

A1: Material Supply, Mining, and Production	kg CO2 eq	MJ
Asphalt binder	20.057	1682.768
Aggregate	1.189	16.579
RAP	0.195	2.754
A2: Transport to Plant		
Transport, truck (RAP and Aggregate)	10.828	142.529
Transport, train (asphalt binder)	0.140	1.851
A3: Plant Operations		
Natural gas, in plant	12.446	236.999
Electricity, in plan	1.532	20.389
Diesel, in equipment	0.516	7.284

The primary contributors are asphalt binder, energy used in the plant from natural gas and truck transportation. Noteworthy is the content of RAP in the mixture, as the RAP content reduces use of virgin aggregate, and also contributes to the asphalt binder reduction (ABR) in the mixture.

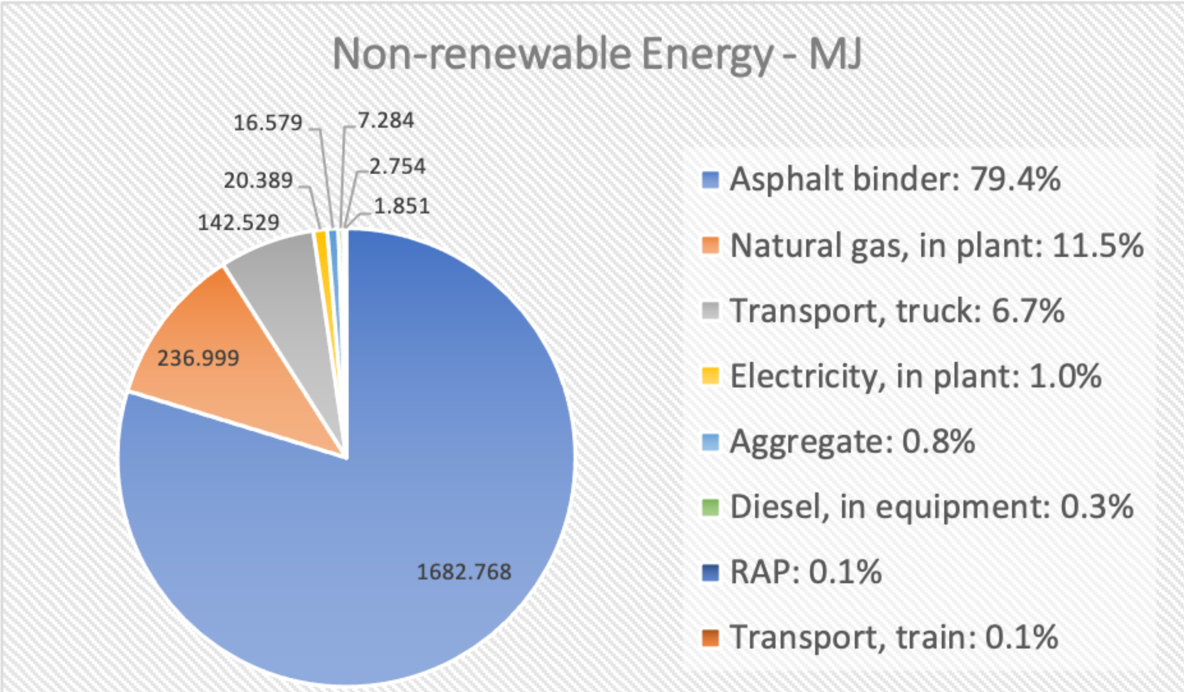


Figure 9: Non-renewable Energy Contributions for the Baseline Mix

Portable Plants

Portable plants travel from construction site to construction site and produce the mixture in-situ, in the same way as produced in a plant. The travel distances in this case signify the distance between construction sites. In addition, the load of the equipment is measures in ton-miles. The analysis in this section is based on a total of six plants from two organizations. The values estimated are:

- Average distance travelled between sites: 105 miles (low of 95 miles, high of 115 miles)
- Average production per unit: 45,250 tons (high 83,000 ton, low 24,000 ton)
- Typical profile of energy used:
    - Recycled Oil: 1.649 gal/ton
    - Diesel: 0.134 gal/ton
- Tonnage of equipment moved: 720 tons (conservative estimate, 18 trailers)

Allocation of the distance travelled between projects was derived either as:

(i) Method 1: Plant travel distances excluded

(ii) Method 2: A weighted average of the production on each site. Hence if 60 tons are produced in site A and 40 tons are produced in site B, then the total tonnage-distance moved by the plant is allocated on a 60%/40% split to each of the sites. This gives the following outcomes:

- 0.387 ton-mile/ton for an average distance of 72 miles
- Sensitivity: [0.005 ton-mile/ton] per mile

(iii) Method 3: Averaged over the total ton-miles traveled by a plant in a season (12-month period) and the total tonnage of mixture produced over the same period. This gives the following outcomes:

- 1.162 ton-mile/ton for an average of 105 miles
- Sensitivity: [0.011 ton-mile/ton] per mile

An analysis of the sensitivity of the GWP metric to the two methods for estimating distance travelled by the portable plant is discussed in a later section. The OpenLCA Data model includes an inventory for portable plants. Reporting for portable plants is no different than for regular stationary plants and the relevant indicators have been included in Table 4.

Table 4: LCA Indicators for Baseline Mix with 0% RAP for a Portable Plant

Indicator	Unit	Method 1	Method 2	Method 3
Acidification	kg SO2 eq	6.528E-01	6.531E-01	6.537E-01
Eutrophication	kg N eq	3.716E-02	3.718E-02	3.721E-02
Global warming	kg CO2 eq	6.315E+01	6.321E+01	6.333E+01
Ozone depletion	kg CFC-11 eq	9.304E-08	9.339E-08	9.410E-08
Smog formation	kg O3 eq	1.820E+01	1.821E+01	1.823E+01
Non-renewable: Fossil Fuel and Nuclear	MJ	3.085E+03	3.086E+03	3.088E+03
Renewable: Hydro, Wind, Solar & Thermal	MJ	1.010E+01	1.010E+01	1.010E+01
Fresh Water	m3	6.82E+00	6.82E+00	6.82E+00
Waste - Hazardous & Nuclear	kg	5.16E-03	5.16E-03	5.16E-03
Waste - Non-Hazardous	kg	1.10E+01	1.10E+01	1.10E+01

Baghouse Fines

Baghouse fines are produced in the asphalt production process. The vast majority of this material is introduced back into the production process as a fine through a closed loop recycling process. A small fraction of it is directed to beneficial re-use in scenarios that are outside the system boundary. A smaller fraction is landfilled and this impact is considered to be within the system boundary. The distribution of how baghouse fines are used was not available from the industry – with a vast majority of the responses being that it is completely recycled in a closed loop fashion within the plant. However, it is prudent to include a delta impact that should be added to the mid-point indicators for an asphalt mixture when a plant landfills its baghouse fines.

The landfilling process includes the use of diesel used in the landfilling process and the distance travelled in moving the baghouse fines from the plant to the landfilling site. Data is used from EPA’s Waste Reduction Model life cycle inventory for "MSW, landfilling of asphalt concrete" or "MSW, landfilling of fly ash" from US EPA's Waste Reduction Model (WARM), Version 15. The FEDEFL compliant version of this inventory has been added in the data repository. The WARM inventory uses a default travel distance of 20 ton-miles. As this distance may vary from plant to plant, this has been parameterized in the inventory. For a ton of landfilling baghouse fines, the impacts for 20 ton-miles of distance travelled to the landfilling site is listed in Table 5.

Table 5: Additional impact per ton of baghouse fines per 20 ton-mile of travel

Name	Impact result	Unit
Acidification	0.275	kg SO2 eq
Ozone depletion	0.000	kg CFC-11 eq
Eutrophication	0.017	kg N eq
Smog formation	9.365	kg O3 eq
Global warming	23.544	kg CO2 eq
Non-renewable energy: Fossil and Nuclear	332.217	MJ

The way to use the numbers in Table 5, is to allocate to each ton of mixture sold, the impact from the total mass of baghouse fines landfilled. Hence, if 1000 tons of baghouse fines are landfilled from a plant and the landfilling site is 20 ton-miles away, the addition GWP is 23,544 kg of CO_2 eq., to be allocated on a per-ton basis to the total mass of asphalt mixture sold. Hence, if the plant sold 50,000 tons of mixture, then the additional impact per ton of mixture is (23,544/50,000 =) 0.471 kg of CO_2 eq. This same calculation will apply to all the other mid-point indicators. The parameterized inventory will allow for easy calculation of impacts for different travel distances.

Sensitivity Analysis

The primary focus of this section is to explore the impact of specific variables on the GWP and the Nonrenewable Energy impacts of an asphalt mixture. The choice of these two indicators over all other indicators, is justified as they are of specific interest in current LCA informed decision-making. It is expected that the insights from this section will support the design of asphalt mixtures that are optimized to meet GWP and energy targets. In addition, the analysis also sheds light on the choice of energy and material flows and their relative impacts on the asphalt mixture.

Besides, the Baseline Mix discussed in the last section the two other mixes used in this section are:

The 5% Virgin Mix: A virgin mixture (no RAP) with 5% unmodified asphalt binder is used. The energy use is the same as the baseline mixture discussed in the previous section and illustrated in Table 2. Aggregate truck travel distance is pegged at 5.81 ton-miles and the truck travel distance for RAP is varied starting with 10 ton-miles.

The Null Mix: A mixture that has a basic 5% asphalt virgin mix with 0 truck ton-miles and 0 train ton-miles, and a fixed energy profile, the same as described for the baseline mix in Table 2. The GWP for the Null Mix is 45.858 kg of CO_2 Eq./ton.

Truck Travel Distances and RAP Use

This section considers the relative impact of truck travel distances on the GWP impact indicator for an asphalt mixture. For the sake of this sensitivity analysis we use the 5% virgin mix and use it in our sensitivity analysis. Figure 10 illustrates the rate of change of GWP (G) with respect to changes in truck ton-miles.

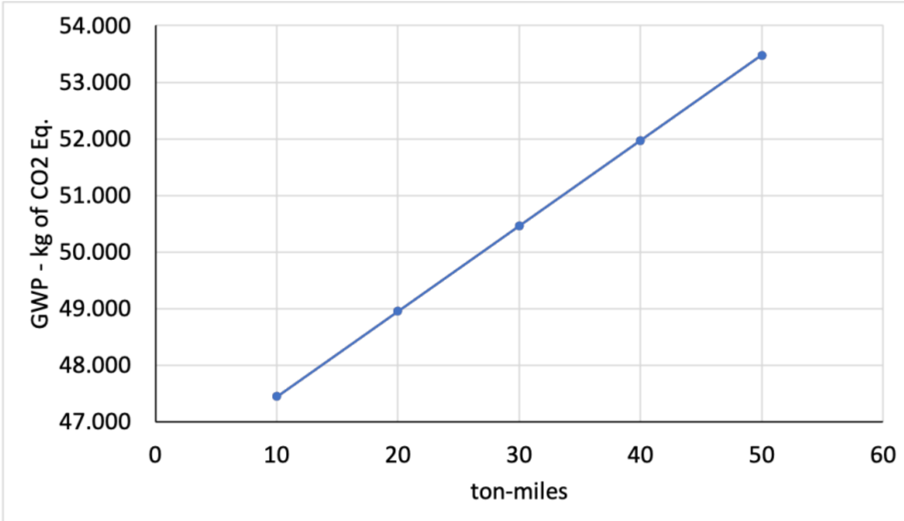


Figure 10: GWP v. Truck Transportation (ton-mile/ton)

The slope of the line in Figure 10 is t = 0.1506 kg of CO_2 Eq. per ton-mile of truck travel is arrived at empirically by running the LCA for multiple 5% virgin asphalt mixes while varying the truck travel distance in ton-miles from 10 to 50. This can be reconciled with the GWP associated with the truck travel inventory of 0.1514 kg of CO_2 Eq. per ton-mile. When rounded to the third decimal place these are comparable.

A similar analysis is conducted with starting the same 5% virgin asphalt binder mix with a constant RAP transportation distance of 10 ton-miles, aggregate transportation of 5.81 ton-miles and the same energy profile as in the baseline mix in Table 2. This time, the RAP content is varied starting with 0% up to 35%. Assuming a 5% contribution of asphalt binder to the 5% mix, that is a variation in ABR from 0% to 1.75%, reflecting a corresponding reduction in virgin asphalt binder use.

The slope of the line in Figure 11 is r = – 5.9232 kg of CO_2 Eq. per % ABR, the negative sign indicating a reduction in GWP with an increase in ABR. This can be reconciled with the GWP associated with one ton of asphalt binder of 573.06 kg of CO_2 Eq. and compares with 1% of ABR, which is approximately 0.01 ton of the mix per ton, with an error accounting for miscellaneous added effects of the include RAP.

The correspondence of the slopes of the plots closely with the unit impacts of the underlying inventories, while not surprising, raises the question can the GWP of a mix be derived from the so-called Null Mix that does not account for any travel distances.

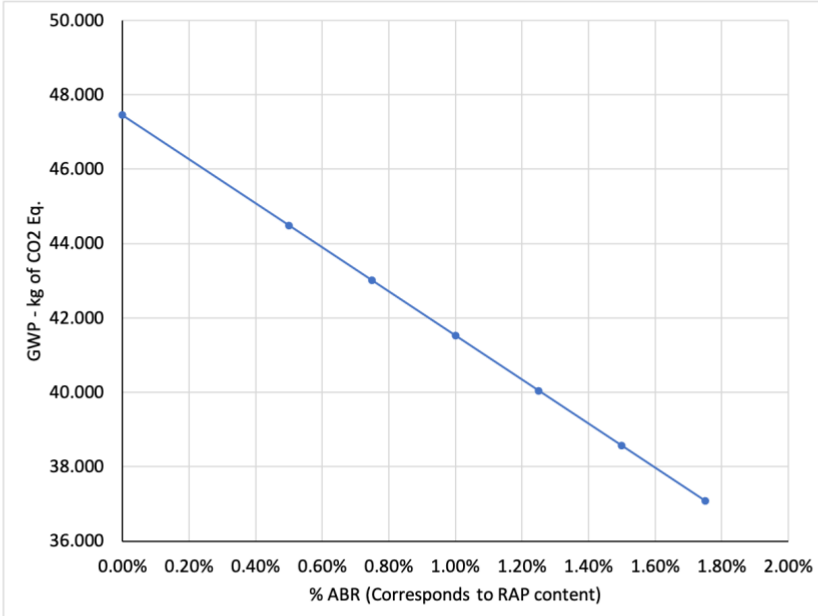


Figure 11: GWP v. Asphalt Binder Reduction (%)

Using the delta differentials as shown in Table 6, the GWP for the baseline mix can be derived from the Null Mix by:

- Addition of impacts due to truck and train ton-miles - 50 ton-miles for RAP, 21.5 ton-miles for aggregate (71.5 ton-miles), and 3.9 train ton-miles.
- Subtraction of impacts due to ABR of 1.5% for the 30% RAP, and addition of the impacts for processing RAP content.
- Subtraction of the impacts due to the reduction of the use of virgin aggregate.

The sum of the differences when added to the GWP for the Null Mix of 45.858 kg of CO_2 Eq./ton gives us an estimate for the GWP for the baseline mix of 46. 941 kg of CO_2 Eq./ton, compared to the OpenLCA calculation for the same to be: 46.962 kg of CO_2 Eq./ton – implying that the delta impacts in the table can be used to make reasonable thumb rule estimates of GWP with varying ABR and transportation distances.

Table 6: GWP Estimation Emission Factors

Items	GWP Differentials (kg of CO2 Eq./ton)	Delta	Net difference
Trucking (ton-miles) (+)	1.514E-01	71.5	1.083E+01
ABR (per %) (-)	-5.731E+02	1.50%	-8.596E+00
Train (ton-miles) (+)	3.597E-02	3.9	1.403E-01
Aggregate reduction (ton) (-)	-1.761E+00	0.27503	-4.844E-01
RAP content (+) (ton)	7.097E-01	0.27502	1.952E-01

It is worth pointing out that, while, from an LCA point-of-view all truck ton-miles – aggregate and RAP – are equivalent, in reality the amount of each material transported varies depending on the density of each material. The density of aggregate can vary from 2400 – 2900 kg/m^3 (149 – 182 lb/ft^3), while the density of RAP can vary from 1600 – 2000 kg/m^3 (100 – 125 lb/ft^3). A typical truck with a volume of 16 cubic yards (cyd) with a weight restriction of 30,000 lb can transport approximately 7 cyd of aggregate compared to 11 cyds of RAP.

Construction of Pareto Frontier

This leads to the next question: can Pareto frontiers be constructed to establish equivalent mixture classes that have the same GWP with trade-offs between ABR and travel distances. We start with a 5% virgin mix that has a GWP of 47.450 kg of CO_2 Eq./ton – let us refer to this quantity as *B*. Next, we recognize that as the ABR increases the GWP of a mixture decreases, while as the number to truck ton-miles increase the GWP goes up. As per the calculation presented in the last section, we can derive the GWP, of a mixture *X* as a function of the delta change in truck miles and ABR. Hence, if the delta change in truck miles is denoted by ΔT, and the change in ABR is ΔR, the rate of change of GWP for a unit change in ton-miles of truck distance is *t*, and the rate of change of GWP for a unit change in %ABR is -*r*, where the negative sign indicates a reduction in GWP, then we can assert that:

$$X = B + \Delta T * t + \Delta R * (-r) \qquad \textit{Eq. 1}$$

If *X* = *B*, i.e., we get the condition in which the net change in GWP is zero (*X* – *B* = 0), as the increase in GWP due to increased truck ton-miles is balanced by the decrease due to increased ABR. Therefore:

$$\Delta T * t = \Delta R * r \qquad \textit{Eq. 2}$$

Hence, as long as the ratio of ΔT to ΔR is equal to $\frac{r}{t}$ the net change in GWP is null. As expressed in the last section, *r* = 5.9232 kg of CO_2 Eq. per % ABR and *t* = 0.1506 kg of CO_2 Eq. per ton-mile. Therefore, $\frac{r}{t} = 39.33$ ton-mile per %ABR, for *B* = 47.450 kg of CO_2 Eq./ton. Of course, it is evident that the condition in Eq. 2 holds true for different values of *B* and for any mix design for any given energy profile. This slope is referred to as *equivalence slope*.

It can be generally stated that for a given mix design, an increase in truck miles ΔT, can be compensated by an increase in ABR of ΔR, as long as the ratio $\frac{\Delta T}{\Delta R}$ is approximately 40, and the set of mixes that qualify present a Pareto frontier – i.e., a family of mixes with equivalent GWP based on a trade-off between increasing truck ton-miles and % ABR.

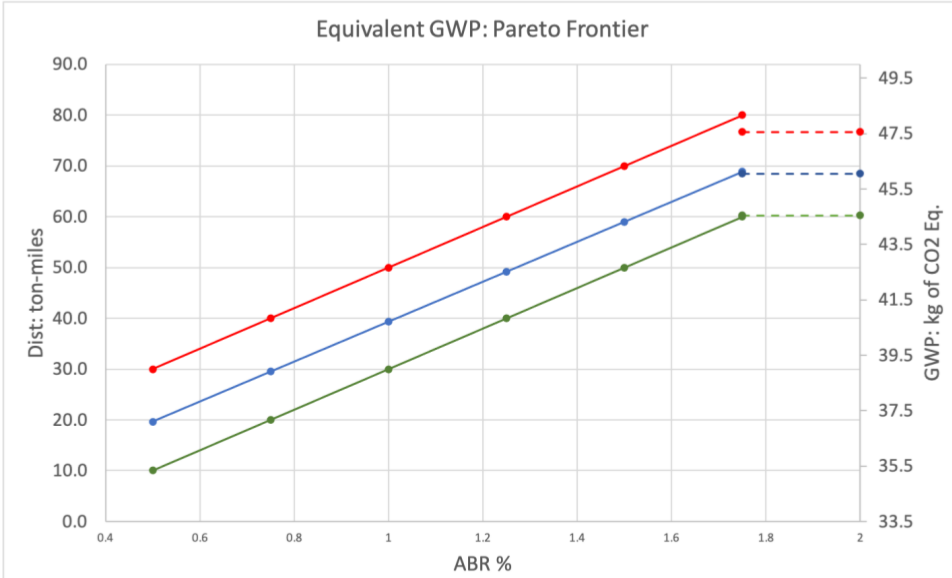


Figure 12: Pareto Frontiers for Truck (ton-miles) v. ABR (%)

Figure 12 illustrates three different pareto frontiers. The three lines all have the same slope of ~40, and feature the trade-off between truck ton-miles and % ABR. Asphalt mixtures on each of the lines have the same GWP (X) (± 1.38 kg of CO_2 Eq./ton), and each of the lines correspond to the GWPs (B) on the secondary axis. As the Pareto frontier shifts up, the GWP also goes up. The higher values of GWP could be because of underlying changes in energy profile or mix design, the slope defining the Pareto frontier remains invariant.

Figure 13 illustrates the outcomes when the $\frac{\Delta T}{\Delta R}$ ratio is greater than or less than the equivalence slope (~ 40). The solid lines plot mixtures with different combinations of truck ton-miles and % ABR derived from a 5% virgin mix, while the dashed line plots the corresponding GWP on the secondary axis for each of the mixtures. The plot can be and can be explained as:

- The reference line with slope 40 is in the middle, and its corresponding values of constant GWP is the dashed line in the center.
- The green arrow illustrates the case where the slope $\frac{\Delta T}{\Delta R}$ > 40, i.e., the central line is rotated up, signifying that the ton-miles are contributing to the GWP faster than the rate at which the % ABR is reducing the GWP, with a net increase in the GWP. Hence, the corresponding dashed GWP line has an increasing slope and is rotated by a corresponding angle with respect to the reference constant GWP line.
- The red arrow illustrates the case where the slope $\frac{\Delta T}{\Delta R}$ < 40, i.e., the central line is rotated down, signifying that the ton-miles are contributing to the GWP slower than the rate at which the % ABR is reducing the GWP, with a net decrease in the GWP. Hence, the corresponding dashed GWP line has an decreasing slope and is rotated by a corresponding angle with respect to the reference constant GWP line.

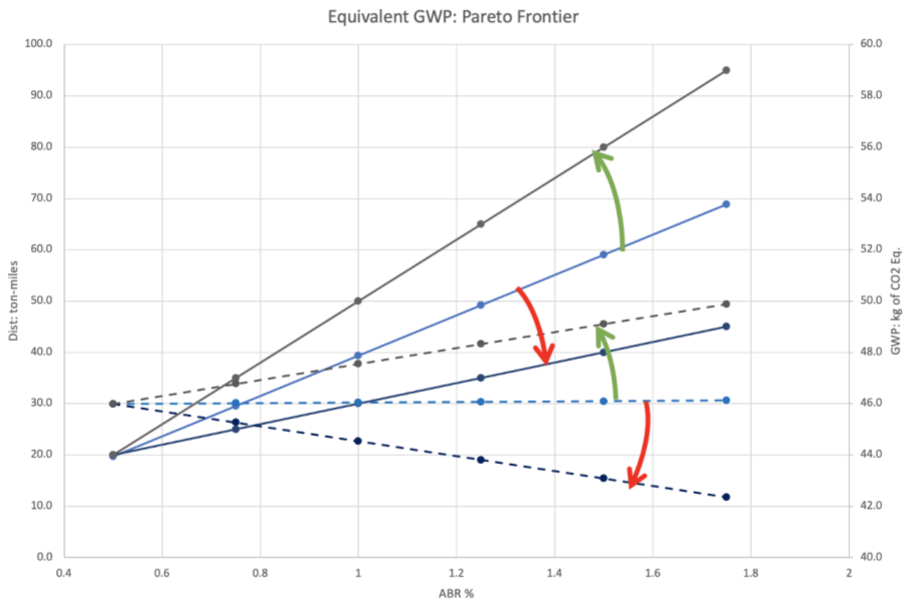


Figure 13: Variations from the Equivalence Slope

In summary, the primary takeaways from the trade-off analysis in this section are:

- The rate of increase of GWP (G) when truck travel distances in ton-miles increases as % ABR remains constant is, $\frac{\Delta G}{\Delta T} = t =$ 0.1506 kg of CO_2 Eq. per ton-mile
- The rate of decrease of GWP when truck travel distances in ton-miles remains constant but as % ABR increases is, $\frac{\Delta G}{\Delta R} = r = -$ 5.9232 kg of CO_2 Eq. per % ABR
- For a given mixture design and a given energy profile, the GWP can be maintained constant if the rate of change $\frac{\Delta T}{\Delta R} \sim$ 40 ton-mile per %ABR.

The usefulness of these results are in their potential use in developing mixture designs that optimize the net GWP per ton of mix. The analysis is critical to the adoption of life-cycle thinking and can be extended to consider pavement performance as well, as discussed in Bhat & Mukherjee (2020).

Different Energy Sources

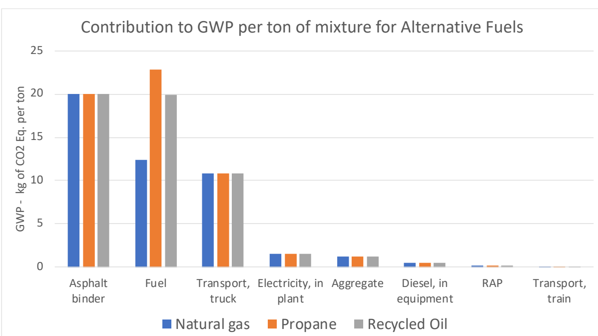
Asphalt plants in the EPD program use primarily one of three sources of fuel in the burner: natural gas, propane and recycled oil (Item 4 in *Foreground Data*). Three scenarios are compared, each using natural gas, propane and recycled oil respectively, as the burner fuel source. Using the average usage per ton of mix as reported from the EPD program, the contributions to GWP and non-renewable energy per ton of mixture for each of the three fuels was analyzed.

This analysis uses the Baseline Mix using the energy consumption (volume use per ton of mixture) as observed from the EPD plant data. Table 7 illustrates the three cases along with the GWP and non-renewable energy for each case. As is expected, all else remaining the same, the main differences are in the fuel use category. For, GWP, propane has a 22.1% higher impact and recycled oil is 15.8% higher impact.

Table 7: Energy Types - Consumption and Impacts

	Consumption (m^3/ton)	GWP (kg of CO_2 Eq./ton)	Nonrenewable Energy (NRE) (MJ/ton)	Fuel - % of GWP	Fuel - % of NRE	Binder - % of GWP	Binder - % of NRE
Natural gas (Baseline)	7.2459	46.962	2111.1545	26.50	11.23	42.71	79.71
Propane	0.0109	57.329	2186.6478	**39.79**	14.29	34.99	76.96
Recycled oil	0.0072	54.397	2139.8320	36.55	12.42	36.87	78.64

For nonrenewable energy, propane has a 3.6% higher impact and recycled oil is 1.4% higher impact. Figure 14 below illustrate the relative contributions. Notably, in the case of use of propane the contribution to GWP is higher than the contribution from asphalt binder, and in the case of reused oil, the contributions to GWP are comparable.



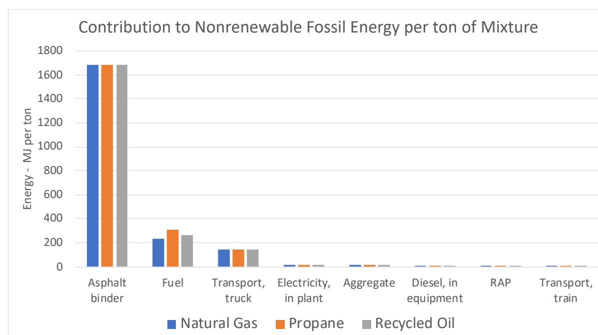


Figure 14: GWP and Energy Contributions for Different Fuel Types

This analysis points to the recommended use of natural gas as a primary fuel in the asphalt plant and arguably a preferred source of energy compared to both propane and reused oil.

Use of Bio-Fuels

On rare occasion asphalt plants tend to use grease trap oil as a burner fuel, in addition to other fuels such as bio-diesel. This LCA is prescribing use of the third-party reviewed *Soy biodiesel, production, at plant* inventory that is available in the USLCI. Hums et al., (2016) make the case that for grease trap waste biodiesel *at lipid concentrations greater than 10%, most of the environmental metrics studied are lower than those of low Sulphur diesel and comparable to soybean biodiesel*. Hence, the identified inventory is considered suitable for grease trap oil. However, this inventory does not include any combustion data as it is limited to the production stage. Bio-diesel combustion data for emissions in *firetube boiler designed for use in institutional, commercial, and light industrial applications* Miller (2008) [Source: Table 6, 7], is used to compliment the *production, at plant* inventory. In addition, plant data for consumption of biofuels – provided by industry partners is used as foreground data. This includes a combination of bio-fuel use (4.595 kg of bio-fuel per ton of mixture) and diesel (0.006 m^3 per ton of mixture) used to wash off residues. Two following options are compared:

Option 1: Use of *Soy biodiesel, production, at plant* with standard combustion emissions data already reported from asphalt plants.

Option 2: Use of *Soy biodiesel, production, at plant* with combustion emissions data reported from Miller (2008).

The reason for this comparison is that most of the combustion data for bio-diesels (e.g., Hums et al., and GREET) are in the context of auto combustion engine use, the asphalt plant emissions stack data is based off of asphalt plant smoke stack emissions from natural gas combustion, while the Miller (2008) data is primarily experimental.

Table 8: Difference between alternative combustion data for Bio-Fuels

Indicator	Unit	Option1	Option2
Global warming	kg CO2 eq	6.659E+01	6.665E+01
Non-renewable: Fossil Fuel and Nuclear	MJ	2.294E+03	2.294E+03
Renewable: Hydro, Wind, Solar & Thermal	MJ	6.475E+00	6.475E+00

As is evident from Table 8, the net difference in GWP and energy is extremely low ~ 0.089%.with Option 2, being more conservative. Hence, Option 2 is recommended and has been included as an inventory in the OpenLCA inventory. However, this presents an example of using a proxy data source in combination with a second unrelated data source. Option 1, is also considered to be an acceptable fall back, as the underlying USLCI inventory is of very high quality and because it uses asphalt plant specific emissions.

Finally, biogenic carbon uptake is not reported for bio-fuels, and neither is combustion of biogenic carbon reported separately. The USLCI inventory reports a 2.823 kg of CO_2 Eq. of biogenic carbon sequestration per kg of soy-biodiesel used. This would translate to a biogenic carbon sequestration of 12.968 kg of CO_2 Eq. (based on 4.595 kg of bio-fuel per ton of mixture), and reduce the GWP from 66.59 to 53.62 kg of CO_2 Eq. (~ 14% higher than the Baseline Mix). However, this number has not been included in the reporting as it does not account for other greenhouse gas emissions, such as nitrous oxide, released during the soybean cultivation process. Appropriate accounting for it could reduce the impact of using bio-based fuels as compared to the use of natural gas.

Polymer Modification of Asphalt Binders

Asphalt binder can be modified using polymers such as Styrene Butadiene Styrene (SBS), Solution Styrene Butadiene Rubber (SSBR), Poly-phosphoric Acid (PPA), and Ground Tire Rubber (GTR). Polymer modification of the asphalt binder provides significant performance benefits during the use phase of the pavement. In addition, polymer modification can be used for developing different asphalt binder grades. The trade-off is a relatively higher environmental impact associated with the polymer modifiers.

Table 9: GWP and Nonrenewable Energy for Polymer Modified Binders

	GWP (kg of CO_2 Eq. per ton)		Nonrenewable Energy (MJ/ton)	
	Mixture	Binder portion	Mixture	Binder portion
Unmodified	46.962	42.71%	2111.155	79.71%
3.5% SBS	51.002	47.25%	2118.956	79.78%
0.5% PPA	47.520	43.38%	2118.956	79.78%
8% GTR	46.469	42.10%	1994.675	78.52%

The inventories used in this study as provided by Sphera are for 3.5% SBS, 8% GTR and 0.5% PPA. The inventories do include transportation impacts up to the terminal gate. However, the inventory for SBS uses SSBR as a proxy. In addition, the data is limited to addition of polymer at the terminal – processes used to add the polymer at the plant are not accounted for and is considered to be a data gap at this time.

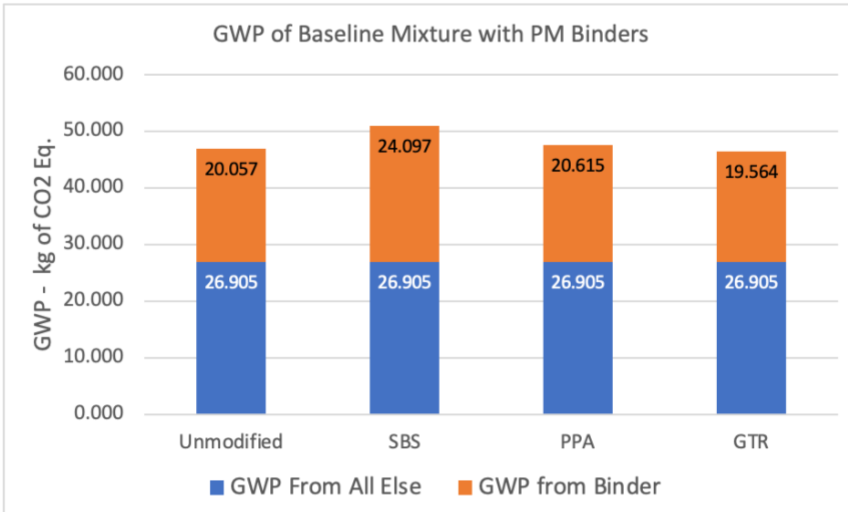


Figure 15: Contribution from Different Binders to GWP

As illustrated in Table 9, binder modified with 3.5% SBS increases the GWP of the mixture by 8.6% (difference between 46.962 and 51.002 kg of CO_2 eq.); and the binder modified with 0.5% PPA increases the GWP of the mixture by 1.2% (difference between 46.962 and 47.520 kg of CO_2 eq.. Addition of SBS increases the asphalt binder contribution to the asphalt mixture GWP by ~ 4.5%. This is also illustrated in Figure 15, which presents the additional contribution to GWP from the unmodified and modified asphalt binders in addition to the 26.905 kg of CO_2 Eq. per ton from the rest of the mixture material and energy flows. In the case of GTR, the net impact of adding 8% of GTR to the binder reduces the GWP by ~ 1%. GTR is considered to be a secondary material being used in the asphalt binder.

Typically, the percentage of polymer that is added to the asphalt binder as a percentage by weight is: SBS/SSBR between 1.5% – 7.5%, with typical range of 3% to 4.5%, GTR up to 20%, and PPA up to 1%. Information provided by Sphera (as shown in Table 10) indicates the relative increases in impact of the asphalt binder.

Table 10: Change in Midpoint Indicators for % Addition of Polymer to Asphalt Binder (Sphera)

	SBS			PPA			GTR		
Indicator	0%	3.50%	10%	0%	0.50%	2%	0%	8.00%	15%
GWP100	0	20%	58%	0	2.70%	10.80%	0	2.50%	4.90%
PED, non-renew	0	4.10%	10.90%	0	0.90%	2.40%	0	7.00%	14.50%
Water	0	42.70%	121.90%	0	5.00%	20.00%	0	9.70%	19.90%

This study does not have access to complete inventories for all levels of polymer addition. However, based on the slopes provided by Sphera, an interpolation has been made for the asphalt mixture impacts for varying percentages of polymer addition. This is not an accurate estimation, as interpolating on mid-point indicators that have been arrived at through impact assessment methodologies can lead to significant errors especially when the impact factors are non-unitary. However, given the very significant contribution of asphalt binder to the GWP of the asphalt mixture (between 42-47%), and that over 90% of said impact is based on CO_2 with an impact factor of 1 (the rest is methane), a reasonable conservative estimate can be made for the GWP indicator.

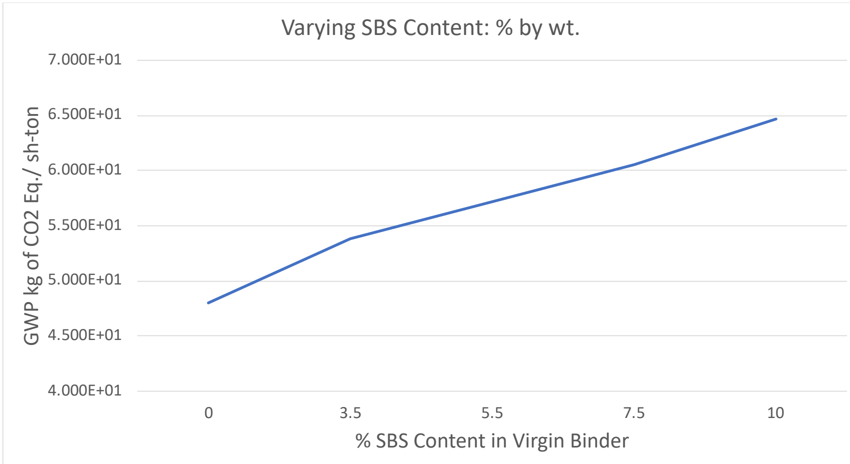


Figure 16: Change in GWP of Asphalt Mixture per % of SBS

In the case of SBS/SSBR, the rate of change of GWP for a ton of asphalt mixture was estimated for a % change in added polymer. Figure 16 illustrates the trend in GWP per ton of asphalt mixtures. The slope is approximated to an increase of approximately 1.675 kg of CO_2 Eq. per % SBS. Approximated inventories for SBS and GTR have been developed for use only for the GWP indicator.

Mix additives with no available upstream (background) data or proxy data that comprise more than 0.01% of the mixture by mass shall be declared on the EPD as a data gap. For the baseline mix, the non-renewable energy (fossil + nuclear) benchmark is 2121 MJ/ton. At the 1% cutoff mark, the contribution to this energy is ~21.21 MJ/ton. At 0.01% by mass, the energy intensity of the material would be of the order of 212,100 MJ/ton – an extremely conservative margin (asphalt binder is < 1000 MJ/ton). The 0.01% mass fraction for the additive translates to 0.2% by mass of the additive for an 5% asphalt binder mix. Hence, when a mix additive with no available upstream (background) data or proxy data is more than 0.2% of the asphalt binder by mass, a data gap will be declared for the EPD.

Portable Plant Sensitivity to Distance

The GWP of the portable plant per ton of mix produced is 63.151 kg of CO_2 Eq per ton. This is 16% higher than a comparable stationary plant mixture produced using recycled oil (54.397 kg of CO_2 Eq per ton) and 10% higher when the mixture produced using propane (57.329 kg of CO_2 Eq per ton).

The difference in GWP for the two methods for allocating ton-miles/ton of mixture produced due to the portability of the plant, for a Portable Mix is less 0.3%. Indeed, the sensitivity of the GWP and energy metrics to estimated average distance travelled by the plant is < 1% placing the distance travelled by the plant well within the limits of exclusion. However, as the distances may vary from case to case, and the current data is limited to two portable plant histories, a threshold of 260 ton-miles/ton (the 1% mark) is established as the threshold beyond which distance reporting is necessary.

Use of EPD for Aggregate

The inventory for aggregate that is currently being used is based on the inventory that was developed for the current EPD program using the dataset in Marceau et al., (2007), Life Cycle Inventory of Portland Cement Concrete, SN3011 (*Table 2)*. However, in the last five years, the aggregate industry has developed their own EPD program and there are publicly available EPDs. Therefore, the inventory associated with this LCA also provides a set of available EPDs that can be used as an alternative. The current aggregate inventory underestimates the impact indicators (GWP = 1.78 kg of CO_2 Eq. per ton, compared to 4.0 ± kg of CO_2 Eq. per ton). For the baseline mix, all else, remaining equal, this translates to a difference of 4% per kg of CO_2 Eq. per ton of asphalt mixture. The inventory has various EPDs available for consideration.

Asphalt Mixture Use Cases

A life cycle inventory was developed for the following types of asphalt mixes, as follows:

1. Mix 1: 30% RAP, 4.87% asphalt binder, 5% contribution to asphalt from RAP
2. Mix 2: 30% RAP, 5.7% asphalt binder, 5.3% contribution to asphalt from RAP
3. Mix 3: 30% RAP, 5.5% asphalt binder, 6.5% contribution to asphalt from RAP, 0.5% Evotherm
4. Mix 4: 20% RAP, 5.5% asphalt binder, 5% contribution to asphalt from RAP, 0.5% Evotherm (Polymer modified)
5. Mix 5: 30% RAP, 5.7% asphalt binder, 5% contribution to asphalt from RAP
6. Mix 6: 20% RAP, 5.6% asphalt binder, 5% contribution to asphalt from RAP (Polymer modified)
7. Mix 7: 30% RAP, 4.9% asphalt binder, 5% contribution to asphalt from RAP
8. Mix 8: 35% RAP, 3.25% asphalt inder, 5% contribution to asphalt from RAP
9. Mix 9: 15% RAP, 3% RAS, and 5% asphalt binder, 5% contribution to asphalt from RAP and 15% contribution to asphalt from RAS

The detailed results are expressed in Appendix C: LCIA Results. These mixes were obtained from the Oregon Department of Transportation (ODOT) and where possible the use cases are established as in Table 11. The mixture application cases to either Wearing, Base or Levelling courses for the pavement have been identified along with the typical expected traffic loading. The binder grades (PG) have been identified including in the cases of mixtures 4 and 6 where they are polymer modified (assumed to be SBS). Typical use case specifications per ODOT specifications are:

- *High Traffic:* 100 gyration dense-graded mix with one-half inch NMAS, for highway wearing, leveling and base courses.

- *Moderate traffic:* 80 gyration dense-graded mix with one-half inch NMAS, for highway wearing and base courses.
- *Low Traffic:* 65 gyration dense-graded mix with one-half inch NMAS for highway wearing courses.

None of the mixtures had any declared warm mix additive, excepting for mixture 3 that has 0.5% Evotherm.

Table 11: Mixture Use Cases

Mix #	Wearing	Base	Leveling	Traffic	PG
Mix 1	X	-	-	Moderate	64-22
Mix 2	X	X	-	Moderate	64-22
Mix 3	-	X	X	High	70-22ER
Mix 4	-	X	-	High	PM 70-22
Mix 5	-	X	-	Moderate	64-22
Mix 6	X	-	-	High	PM 70-22
Mix 7	X	-	-	Low	64-22
Mix 8	X	-	-	Moderate	64-22
Mix 9	X	-	-	Low	64-22

The distance for truck-based RAP and aggregate transport is set to 10 ton-miles per ton and 5.81 ton-miles per ton respectively, with train distance at 5.89 ton-miles per ton.

Figure 17 illustrates a spread of the GWP estimated using this LCA for each of the use case mixtures. The percentages in bracket in the label is the amount of virgin binder in the mix. Hence, Mixture 8 has an ABR of 1.75% while it has a virgin binder content of 1.5%, which is in line with the total binder content of 3.25%.

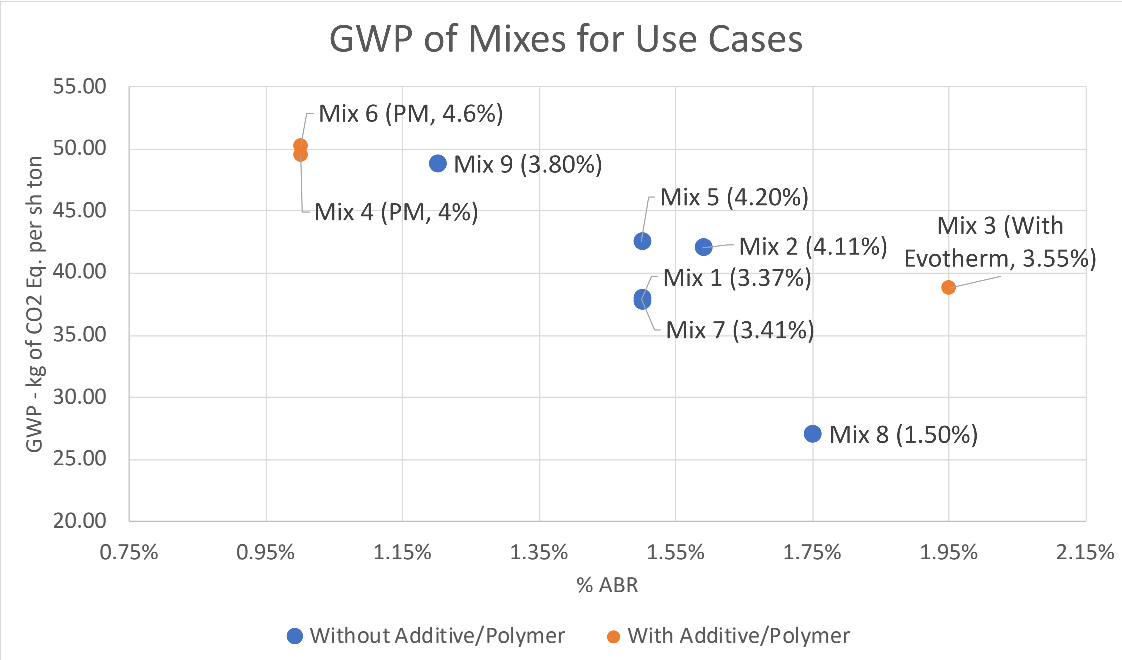


Figure 17: Use Case Mixtures - GWP v. ABR

The following additional observations can be made:

- While PG binder grades have been identified, at this time, the asphalt binder inventory does not distinguish between them and they are all treated effectively as the same. Hence, this information is primarily for understanding use cases.
- Mixture 3, has the warm mix additive Evotherm (0.5%). At this time due to a data gap, no impact is accounted for Evotherm. Hence, while the high ABR of the mix is lowering the GWP, with the inclusion of the impacts of Evotherm, it is likely to be higher than illustrated.
- Mixtures 4 and 6 both are polymer modified and therefore expectedly have a higher impact.
- The plot exhibits the expected trend of a reduction in GWP for mixtures with respect to the ABR. Typically, in cases where a mixture with a higher ABR has a higher GWP, it is because the net virgin asphalt binder in the mix is comparatively higher. For instance, consider Mixtures 2 and 1: while Mixture 2 has a higher ABR, it has a higher GWP compared to Mixture 1 due to the net differences in virgin asphalt binder. Mixture 2 has higher virgin binder (4.11%) compared to Mixture 1 (3.37%).

The outcomes further confirm the notion that the primary factors driving the GWP of an asphalt mixture are the ABR, the net virgin binder content and the use of environmentally significant polymers and additives.

Discussion and Limitations

The primary limitations of this LCA study, and associated recommendations are:

- The scope of this study is limited to cradle-to-gate (A1-A3). As our knowledge of pavement LCA and pavement-vehicle interaction models become more advanced, a comprehensive LCA of pavement will include the use and end-of-life stages. This LCA can serve as a building block for LCAs of pavement systems, and construction and maintenance operations that use asphalt mixtures.
- There continue to be data gaps with respect to additives, rejuvenators, emulsifiers, and polymers that are used in the mixture. While these components are a very small fraction of the asphalt mixture, they have a significant environmental impact. There is a need to continue to work with industry partners to create high quality datasets that can be used for the purpose of this LCA. The approach followed by the Asphalt Institute in publishing a system level inventory is exemplary and more industries are encouraged to do the same.
- As discussed in the section on *Data Quality Assessment Methodology*, the data quality of the public datasets prescribed in this LCA are considered the best choice for ensuring transparency and consistency. However, background datasets are constantly being reviewed and updated, and therefore, the PCR outlines a hierarchy of data sources that can be used as and when improvements are made. For example, slag aggregate has been identified as a significant data gap: if the slag aggregate industry were to conduct an ISO reviewed LCA, or provide a reliably developed inventory, it would be considered for use. It is the goal of this program to encourage data providers for materials that share a supply chain to use the common background inventories for fossil fuels, electricity and transportation available through the FLCAC to ensure consistency.
- The inventories associated with polymer modified binders do help in recognizing the difference in GWP of a polymer modified mixture at construction and hence can be used to identify trade-offs in long-term performance. However, the LCA does not distinguish between asphalt binder grades – this limits the ability to associate GWP and other associated impacts with pavement performance and use case scenarios.
- The LCA does not have enough empirical data to establish conclusive differences between warm mix asphalt and hot mix asphalt mixtures. An empirical study is called for in future to identify conditions under which a mixture is classified as hot or warm, and establish LCIA differences, if any, between the two classes of mixtures.
- Travel distances for RAP and aggregate continue to be difficult to estimate reliably, even though truck travel distances have a not insignificant impact on the LCA outcomes.
- The emphasis of analysis of this LCA is limited to the midpoint indicators of GWP and use of non-renewable energy. This is considered appropriate, given the current trends in how LCA information is being used in the construction industry, however in future there may be benefits to a more comprehensive assessment of other midpoint impact indicators.
- The LCA does not report on human health related impact indicators. The primary reason for this is the uncertainties associated with the underlying models, and the toxicity pathways, in estimating impacts. In addition, at this time there is no accounting for the level of human exposure and the associated risk to human health due to the life cycle of an asphalt mixture. However, this concern is assuaged by the environmental health and safety work for asphalt materials and production in plants that is already in practice. It is also worth noting that ISO 21930 does not require inclusion of human health indicators.

Despite the above continuing limitations, this LCA has made significant improvements compared to the LCA conducted in 2016 as follows:

- The quality of the background data is significantly improved with greater transparency, regionalization and verifiability of public and free to use LCIs. Transparency is crucial as it helps identify and remove errors thus significantly improving the reliability of the LCA.
- Foreground data trends observed in the 2016 study have been largely validated by the data that has been available through the EPD program in the last five years, while helping identify new directions that need further investigation (such as the difference between warm mix asphalt and hot mix asphalt mixtures).
- The sensitivity analysis in this study provides guidelines for optimizing the GWP and energy requirements for mixture design and for developing sustainability strategies associated with sourcing materials (travel distances) and choice of plant energy sources and management.
- The LCA is written keeping in mind the evolving needs in the construction materials industry to comply with regulations such as the Buy Clean Act (2017) in California.

As the world moves towards a carbon neutral future this LCA provides the foundations for exploring ways in which renewable fuels (e.g., renewable natural gas), and other innovative bio-based materials can be integrated into asphalt mixtures. As the science behind accurate accounting for carbon sequestration and biogenic carbon capture evolves, this LCA would provide a starting point for identifying strategies to make asphalt mixtures become carbon neutral.

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Appendix A: Data Collection Instrument

Data Collection Instrument: Asphalt Plant

Plant Address:

Completed by: Name
Phone:

A. Plant Details

Plant characteristics:
Please state technical specifications of the plant type model and year:
Please state technical specifications of the burner type model and year:
Please state number of mix silos and their capacity:

Has the plant been through any recent upgrades or maintenance? *Yes* *No*
If ***Yes*** please state type of most recent maintenance and date:
Type of maintenance:
Date of maintencance:

Binder storage tanks:
Please state number of binder storage tanks and their technical specification :

Please complete the following table explaining how binder is stored in your plant (include details on warm-mix and mixes with RAP/RAS):

Binder grade	*Storage temp(F)*	*Duration (days)*	*Mix type*	*Storage temp(F)*	*Duration (days)*

Plant operation by season:

Average Operation	*Jan-Mar*	*Apr-Jun*	*Jul-Sep*	*Oct-Dec*
Number of hours/day:				
Number of days/week:				
Number of weeks/year:				

List all construction equipment on site used to move aggregate:

Equipment Type	Year/Model	HP	Type of Fuel	Fuel use/year	% Time used in asphalt plant (if applicable)

Plant efficiency reporting: Please report the efficiency of the following processes.
Aggregate Dryer:
Heat transfer oil for asphalt mix and binder storage:
Variable frequency drives:

Dust control:
Estimate the total amount of dust collected in the plant:
--- % of the dust that is recycled back into the plant:
--- What is being done to the recycled dust? (e.g., is it being sold?)

B. Energy Inputs

		Unit:		
Natural gas usage/year:		*MCF*	~ Purpose	
Natural gas usage/day:		*MCF/day*		
Electricity usage/year:		*BTU*	~ Purpose	
Electricity usage/day:		*BTU/day*		

What is the split and/or source of your electricity? (e.g., x% Hydro + y% Coal powered + z% Nuclear):
~ Are any non-traditional energy sources being used? (e.g., solar) What percentage?

Does the plant have an onsite generator? (Check one) *Yes* *No*
If Yes, please answer the following:
~ What kind of fuel does the generator use? Total number of hours the generator was used? *hrs*
~ Total volume of fuel used:

Volume of oil used to heat binder bins:

Other fuel types used in the plant: (Consider the use, if any, of gasoline, diesel, fuel oil, waste oil and other heavy distillates such as residual oil)
~ What kind of fuel used? Total number of hoursof use? *hrs*
~ Purpose used for: ~ Total volume of fuel used annualy: *gal*
~ Source location:

~ What kind of fuel used? Total number of hoursof use? *hrs*
~ Purpose used for: ~ Total volume of fuel used anually: *gal*
~ Source location:

For each of the above categories, please indicate sulfur content, for diesel and fuel oils (No. 2 fuels).

C. Material Inputs

Unit:

Total Asphalt produced/year:		*Ton*
Average plant production rate:		*Ton/hr*

Asphalt Mixes: **Please list all mixes at your plant. An EPD will be provided only for the mixes listed.**

Mix 1 (Name)	*% Production*		*Production rate (Tons/hr):*		*MSDS Sheet incl.?*	*Yes No*	
Aggregate Type	*% Aggregate*	*Source / Location*	*Additive*	*Volume, Source / location*	Mixing Temp		*F*
New			Anti Strip		Binder Type	PG xx-xx	*F*
RAP (Fractionated)			WMA - Chemical		Mix Type	SMA	
Ash			Fiber		*% AC (new)*	4.00%	*%*
RAS (Tear Off)			WMA - Zeolite		*% Total AC (Pb)*	5.20%	*%*
New			WMA - Organic		*Water*		*Gal*
			Binder Type	*Unmodified*			

Mix 2 (Name)	*% Production*		*Production rate (Tons/hr):*		*MSDS Sheet incl.?*	*Yes No*	
Aggregate Type	*% Aggregate*	*Source / Location*	*Additive*	*Volume, Source / location*	Mixing Temp		*F*
					Binder Type	PG xx-xx	*F*
					Mix Type	Dense	
					% AC (new)	4.00%	*%*
					% Total AC (Pb)	5.20%	*%*
					Water		*Gal*
			Binder Type	*Polymer Modified*			

Mix 3 (Name)	*% Production*		*Production rate (Tons/hr):*		*MSDS Sheet incl.?*	*Yes No*	*F*
Aggregate Type	*% Aggregate*	*Source / Location*	*Additive*	*Volume, Source / location*	Mixing Temp		*F*
					Binder Type	PG xx-xx	
					Mix Type	OGFC	*%*
					% AC (new)	4.00%	*%*
					% Total AC (Pb)	5.20%	*Gal*
					Water		
			Binder Type	*Polymer Modified + GTR*			

Mix 4 (Name)	*% Production*		*Production rate (Tons/hr):*		*MSDS Sheet incl.?*	*Yes No*	*F*
Aggregate Type	*% Aggregate*	*Source / Location*	*Additive*	*Volume, Source / location*	Mixing Temp		*F*
					Binder Type	PG xx-xx	
					Mix Type	SMA	*%*
					% AC (new)	4.00%	*%*
					% Total AC (Pb)	5.20%	*Gal*
					Water		
			Binder Type	*Ground Tire Rubber (GTR)*			

Information about binder: Total binder tonnage: 0 *Ton*

Location/Source 1

Check the kind of source: *Terminal* *Refinery* Address:

Type	*Polymer Modified*	
Total annual tonnage from this source:		*Ton*
Tons/day used from this source:		*Ton/day*

Location/Source 2

Check the kind of source:	*Terminal* *Refinery*		Address:	
Type	*Polymer Modified + GTR*			
Total annual tonnage from this source:		*Ton*		
Tons/day used from this source:		*Ton/day*		

Location/Source 3

Check the kind of source:	*Terminal* *Refinery*		Address:	
Type	*Ground Tire Rubber (GTR)*			
Total annual tonnage from this source:		*Ton*		
Tons/day used from this source:		*Ton/day*		

Information about aggregate: Total tonnage: 0 *Ton*

Location/Source 1

Address:				
Is this from a recycled source?	*Yes* *No*		Type:	RAP (Fractionated)
Total annual tonnage from this source:		*Ton*		
Tons/day used from this source:		*Ton/day*		

Location/Source 2

Address:				
Is this from a recycled source?	*Yes* *No*		Type:	RAS (Tear Off)
Total annual tonnage from this source:		*Ton*		
Tons/day used from this source:		*Ton/day*		

Location/Source 3

Address:				
Is this from a recycled source?	*Yes* *No*		Type:	RAS (Manufactured)
Total annual tonnage from this source:		*Ton*		
Tons/day used from this source:		*Ton/day*		

Location/Source 4

Address:				
Is this from a recycled source?	*Yes* *No*		Type:	Slag
Total annual tonnage from this source:		*Ton*		
Tons/day used from this source:		*Ton/day*		

Location/Source 5

Address:	

Is this from a recycled source?	*Yes No*	Type:	Ash
Total annual tonnage from this source:		*Ton*	
Tons/day used from this source:		*Ton/day*	

Information about water use: Total volume: 0 *Gal*

Volume used in plant:		*Gal*
Volume used for dust control:		*Gal*
Is the water being reycled?	*Yes No*	
What pecentage of the total is recycled?		%

D. Outputs

Greenhouse Gas		*Unit*
Nitrogen Oxides (NOx)		*Ton*
Sulphur Oxides (SOx)		*Ton*
Carbon Oxides (CO)		*Ton*
Volatile Organic Comps		*Ton*
Particulate Matter		*Ton*
Total Greenhouse Gases		*Ton*

Appendix B: Data Quality Assessment

This section outlines the recommended data quality assessment methodology using the Enhanced Pedigree Matrix (Bhat 2020). A pragmatic desired data quality is defined (indicated in blue) for each category and limitations to reach this desired data quality are assessed for different background data categories. This methodology and assessment was completed for the background data recommended for the FHWA Pavement Framework and used in the *LCA Pave* tool, and therefore ensures consistency of this LCA with the Framework.

Flow Level

Flow level assessment enables evaluation of metadata associated with both product flows and elementary flows such as name, unit, CAS number and molecular formula.

Reliability of the data

Reliability is assessed at the flow level and indicates the methods used to generate the data and verification/validation of these methods. In order to point at the specifics of the data collection methods and their validation, the pavement-specific pedigree matrix details four questions within the reliability criterion and the data quality assessment needs to be carried as follows:

a) Is the inventory data checked for mass/ energy balance, recalculation etc.?
   - i) Verified data based on measurements – give a score of 1
   - ii) Verified data based on a calculation or non-verified data based on measurements – give a score of 2
   - iii) Non-verified data based on a calculation – give a score of 3
   - iv) Documented estimate – give a score of 4
   - v) Undocumented estimate – give a score of 5

b) What is the status quo for the ownership and continuous support of data?
   - i) Hosts and Owns – give a score of 1
   - ii) Owns but does not host – give a score of 2
   - iii) Hosts but does not owns – give a score of 3
   - iv) Hosts and owns partially – give a score of 4
   - v) Does not host or own – give a score of 5

c) Is the data regularly updated?
   - i) Regular updates – give a score of 1
   - ii) Less frequent updates – give a score of 2
   - iii) No updates – give a score of 3

d) Is the data of deterministic nature or are there statistically established confidence intervals stated for the data?
   - i) Confidence Intervals developed considering parameter, scenario and model uncertainty based on directly measured or calculated data – give a score of 1
   - ii) Confidence Intervals developed considering either of parameter, scenario and model uncertainty based on assumed probability distribution – give a score of 2

iii) Deterministic value provided – give a score of 3

Data Collection Methods

Data collection methods are assessed at the flow level and they reflect the robustness of the sampling methods used (i.e. sample size) and the data collection period. In order to point at the specifics of the data collection methods, the pavement-specific pedigree matrix lists two questions within the data collection methods criterion and the data quality assessment needs to be carried as follows:

a) How representative is the data of the market?
   i) Representative data from >80% of the relevant market, over an adequate period – give a score of 1
   ii) Representative data from 60-79% of the relevant market, over an adequate period OR representative data from >80% of the relevant market, over a shorter period – give a score of 2
   iii) Representative data from 40-59% of the relevant market, over an adequate period OR representative data from 60-79% of the relevant market, over a shorter period – give a score of 3
   iv) Representative data from <40% of the relevant market, over an adequate period OR representative data from 40-59% of the relevant market, over a shorter period – give a score of 4
   v) Unknown OR data from a small number of sites and from shorter periods – give a score of 5

b) How compatible is the life-cycle inventory data with TRACI 2.1 impact assessment method from LCA Commons?
   i) Life-cycle inventory data is enough to calculate all the 9 mid-point indicators as per TRACI 2.1 impact assessment method – give a score of 1
   ii) Life-cycle inventory data is enough to calculate only 6 out of 9 mid-point indicators as per TRACI 2.1 impact assessment method – give a score of 2
   iii) Life-cycle inventory data is enough to calculate only 3 out of 9 mid-point indicators as per TRACI 2.1 impact assessment method – give a score of 3
   iv) Life-cycle inventory data is not compatible with TRACI 2.1 impact assessment method from LCA Commons – give a score of 4

Time Period of Data

Time period is assessed at the flow level and is used for either assessing the age difference between the temporal data quality guidance, and the age of the data; or just the actual age of the data. In order to point at the specifics of time period, the pavement-specific pedigree matrix lists three questions within the time period criterion and the data quality assessment needs to be carried as follows:

a) Does the data capture seasonal variations?
   i. All three (fall, spring and summer) seasons are covered – give a score of 1
   ii. Only two out of three seasons are covered – give a score of 2
   iii. Only one season is covered – give a score of 3

    iv. Not Specified – give a score of 4

b) How well is the time period the data correlated with the data quality objective?
    i. Less than 3 years of difference – give a score of 1
    ii. Less than 6 years of difference – give a score of 2
    iii. Less than 10 years of difference – give a score of 3
    iv. Less than 15 years of difference – give a score of 4
    v. Age of data unknown or more than 15 years – give a score of 5

c) How old is the data at the time of data quality assessment?
    i. Less than 3 years old – give a score of 1
    ii. Less than 6 years old – give a score of 2
    iii. Less than 10 years old – give a score of 3
    iv. Less than 12 years old – give a score of 4
    v. Age of data unknown or more than 15 years – give a score of 5

Now, the question "b" is relevant in the case of individual LCA studies with specific data quality objectives whereas "c" is relevant for assessing the data quality of background data without specific data quality objective. As the scope of this roadmap is relevant to background data only, questions "a" and "c" are used to assess the data quality.

Geography of Data

Geography is assessed at the flow level and is designed to capture differences in data quality related to differences in area of study and resolution between the geography DQGs and the data used for modeling. In order to point at the specifics of time period, the pavement-specific pedigree matrix lists two questions within the geography criterion and the data quality assessment needs to be carried as follows:

a) How well is the geography of the data correlated with the data quality objective?
    i. Data from same resolution AND same area of study – give a score of 1
    ii. Within one level of resolution AND a related area of study – give a score of 2
    iii. Within two levels of resolution AND a related area of study – give a score of 3
    iv. Outside of two levels of resolution BUT a related area of study – give a score of 4
    v. From a different or unknown area of study – give a score of 5

b) What is the regional granularity associated with the data?
    i. State level – give a score of 1
    ii. Country level – give a score of 2
    iii. Continental level – give a score of 3
    iv. Global level – give a score of 4
    v. Data granularity unknown – give a score of 5

Now, the question "a" is relevant in the case of individual LCA studies with specific data quality objectives whereas "b" is relevant for assessing the data quality of background data without specific data quality objective. As the scope of this roadmap is relevant to background data only, question "b" is used to assess the data quality.

Technology of Data

Technology is assessed at the flow level and is designed to capture process design, operating conditions, material quality, and process scale. In order to point at the specifics of technology, the pavement-specific pedigree matrix lists two questions within the technology criterion and the data quality assessment needs to be carried as follows:

a) How well is the technology of the data correlated with the data quality objective?
   i. All technology categories are equivalent – give a score of 1
   ii. Three of the technology categories are equivalent – give a score of 2
   iii. Two of the technology categories are equivalent – give a score of 3
   iv. One of the technology categories are equivalent – give a score of 4
   v. None of the technology categories are equivalent – give a score of 5

b) How well is the technology of the data described?
   i. Specified – give a score of 1
   ii. Not Specified – give a score of 2

Now, the question "a" is relevant in the case of individual LCA studies with specific data quality objectives whereas "b" is relevant for assessing the data quality of background data without specific data quality objective. As the scope of this roadmap is relevant to background data only, question "b" is used to assess the data quality.

Process-Level

Process level review enables the assessment of level of detail pertaining to a unit process i.e. whether it is possible to obtain specific unit process information or only aggregated process (combined processes to maintain confidentiality) information is available.

Process Review

Process review is assessed at the process level and is designed to evaluate the level of review a dataset has undergone at the unit process level. In order to point at the specifics of process review, the pavement-specific pedigree matrix lists one question within the process review criterion and the data quality assessment needs to be carried as follows:

a) How well is the process reviewed?
   i. The process has documented reviews by a minimum of two types of third-party reviewers – give a score of 1
   ii. The process has documented reviews by a minimum of two types of reviewers, with one being a third party – give a score of 2
   iii. The process has documented review by a third-party reviewer – give a score of 3
   iv. The process has documented review by an internal reviewer – give a score of 4
   v. The process has no documented review – give a score of 5

Process Completeness

Process review is assessed at the process level and is designed to evaluate the level of review a dataset has undergone at the unit process level. In order to point at the specifics of process review, the pavement-specific pedigree matrix lists one question within the process review criterion and the data quality assessment needs to be carried as follows:

b) How complete is the process?
    i. >80% of determined flows within the process have been evaluated and given a value – give a score of 1
    ii. 60-79% of determined flows within the process have been evaluated and given a value – give a score of 2
    iii. 40-59% of determined flows within the process have been evaluated and given a value – give a score of 3
    iv. <40% of determined flows within the process have been evaluated and given a value – give a score of 4
    v. Process completeness not scored – give a score of 5

The data quality assessments for the background and foreground data is included in a separate file.

Appendix C: LCIA Results

Materials - per ton of mixture	*Units*	*Base Mix*	*Mix 1*	*Mix 2*	*Mix 3*
Asphalt binder (virgin) - unmodified, except Mixes 4 and 6	ton	3.500E-02	3.370E-02	4.110E-02	3.550E-02
Aggregate (virgin)	ton	6.750E-01	6.759E-01	6.706E-01	6.709E-01
RAP	pct	30%	30%	30%	30%
*** Amount of aggregate from RAP**	ton	2.750E-01	2.754E-01	2.724E-01	2.691E-01
*** RAP binder content**	pct	5.0%	5.0%	5.3%	6.5%
RAS	ton	-	-	-	-
*** Amount of aggregate from RAS**	ton	-	-	-	-
***RAS binder content**	pct	-	-	-	-
Amount of Binder from RAP & RAS	pct	1.5%	1.5%	1.59%	1.95%
Additive - such as Warm Mix	pct	0.00%	0.00%	0.00%	0.50%
Energy in Plant - per ton of mixture					
Natural gas, combusted in industrial boiler	m3	7.486E+00	7.486E+00	7.486E+00	7.486E+00
Diesel, combusted in industrial equipment	m3	1.600E-04	1.600E-04	1.600E-04	1.600E-04
Electricity; at grid; consumption mix - US - US	kWh	2.780E+00	2.780E+00	2.780E+00	2.780E+00
Transportation - per ton of mixture					
Asphalt binder: Transport, train, diesel powered – RNA	ton-mile	3.900E+00	5.890E+00	5.890E+00	5.890E+00
Aggregate: Transport, combination truck, diesel powered	ton-mile	2.150E+01	5.810E+00	5.810E+00	5.810E+00
RAP: Transport, combination truck, diesel powered	ton-mile	5.000E+01	1.000E+01	1.000E+01	1.000E+01
Midpoint Indicators - per ton of mixture					
Acidification	kg SO2 eq	1.576E-01	1.127E-01	1.245E-01	1.155E-01
Eutrophication	kg N eq	1.125E-02	8.606E-03	9.753E-03	8.881E-03
Global warming	kg CO2 eq	4.696E+01	3.782E+01	4.205E+01	3.884E+01
Ozone depletion	kg CFC-11 eq	1.059E-07	5.798E-08	5.807E-08	5.792E-08
Smog formation	kg O3 eq	4.364E+00	2.975E+00	3.217E+00	3.032E+00

Cumulative Energy Demand - per ton of mixture					
Non-renewable Energy: Fossil Fuels and Nuclear	MJ	2.121E+03	2.055E+03	2.412E+03	2.142E+03
Renewable Energy: Hydro, Wind, Solar and Thermal	MJ	6.418E+00	6.181E+00	7.536E+00	6.511E+00
Other Metrics - per ton of mixture					
Process energy	MJ	2.879E+02	2.879E+02	2.879E+02	2.879E+02
Secondary materials used, by wt.	ton	2.900E-01	2.904E-01	2.883E-01	2.886E-01
Non-renewable Energy as Material: Feedstock energy	MJ	1.302E+03	1.253E+03	1.529E+03	1.320E+03
Fresh Water	m3	5.021E+00	4.946E+00	5.814E+00	5.156E+00
Waste - Hazardous & Nuclear	kg	3.279E-03	3.157E-03	3.851E-03	3.326E-03
Waste - Non-Hazardous	kg	6.990E+00	6.731E+00	8.209E+00	7.090E+00

Materials - per ton of mixture	*Units*	*Mix 4 (PM)*	*Mix 5*	*Mix 6 (PM)*
Asphalt binder (virgin) - unmodified, except Mixes 4 and 6	ton	4.000E-02	4.200E-02	4.600E-02
Aggregate (virgin)	ton	7.595E-01	6.700E-01	7.627E-01
RAP	pct	20%	30%	20%
*** Amount of aggregate from RAP**	ton	1.805E-01	2.730E-01	1.813E-01
*** RAP binder content**	pct	5.0%	5.0%	5.0%
RAS	ton	-	-	-
*** Amount of aggregate from RAS**	ton	-	-	-
***RAS binder content**	pct	-	-	-
Amount of Binder from RAP & RAS	pct	1.00%	1.5%	1.00%
Additive - such as Warm Mix	pct	0.50%	0.00%	0.00%
Energy in Plant - per ton of mixture				
Natural gas, combusted in industrial boiler	m3	7.486E+00	7.486E+00	7.486E+00
Diesel, combusted in industrial equipment	m3	1.600E-04	1.600E-04	1.600E-04
Electricity; at grid; consumption mix - US - US	kWh	2.780E+00	2.780E+00	2.780E+00
Transportation - per ton of mixture				

Transport, train, diesel powered - RNA	ton-mile	5.890E+00	5.890E+00	5.890E+00
Aggregate: Transport, combination truck, diesel powered	ton-mile	5.810E+00	5.810E+00	5.810E+00
RAP: Transport, combination truck, diesel powered	ton-mile	1.000E+01	1.000E+01	1.000E+01
Midpoint Indicators - per ton of mixture				
Acidification	kg SO2 eq	1.442E-01	1.260E-01	1.461E-01
Eutrophication	kg N eq	1.374E-02	9.893E-03	1.397E-02
Global warming	kg CO2 eq	4.957E+01	4.257E+01	5.027E+01
Ozone depletion	kg CFC-11 eq	5.933E-08	5.808E-08	5.941E-08
Smog formation	kg O3 eq	3.604E+00	3.247E+00	3.644E+00
Cumulative Energy Demand - per ton of mixture				
Non-renewable Energy: Fossil Fuels and Nuclear	MJ	2.680E+03	2.456E+03	2.730E+03
Renewable Energy: Hydro, Wind, Solar and Thermal	MJ	9.813E+00	7.701E+00	1.003E+01
Other Metrics - per ton of mixture				
Process energy	MJ	2.879E+02	2.879E+02	2.879E+02
Secondary materials used, by wt.	ton	1.905E-01	2.880E-01	1.913E-01
Non-renewable Energy as Material: Feedstock energy	MJ	1.433E+03	1.562E+03	1.648E+03
Fresh Water	m3	6.790E+00	5.919E+00	6.920E+00
Waste - Hazardous & Nuclear	kg	4.943E-03	3.935E-03	5.053E-03
Waste - Non-Hazardous	kg	1.080E+01	8.388E+00	1.104E+01

Materials - per ton of mixture	*Units*	*Mix 7*	*Mix 8*	*Mix 9*
Asphalt binder (virgin) - unmodified, except Mixes 4 and 6	ton	3.400E-02	1.500E-02	3.800E-02
Aggregate (virgin)	ton	6.757E-01	6.400E-01	7.884E-01
RAP	pct	30%	35%	15%
*** Amount of aggregate from RAP**	ton	2.753E-01	3.275E-01	1.371E-01
*** RAP binder content**	pct	5.0%	5.0%	5.0%
RAS	ton	-	-	3%
*** Amount of aggregate from RAS**	ton	-	-	2.453E-02

***RAS binder content**	pct	-	-	15%
Amount of Binder from RAP & RAS	pct	1.5%	1.75%	1.2%
Additive - such as Warm Mix	pct	0.00%	0.00%	0.00%
Energy in Plant - per ton of mixture				
Natural gas, combusted in industrial boiler	m3	7.486E+00	7.486E+00	7.486E+00
Diesel, combusted in industrial equipment	m3	1.600E-04	1.600E-04	1.600E-04
Electricity; at grid; consumption mix - US - US	kWh	2.780E+00	2.780E+00	2.780E+00
Transportation - per ton of mixture				
Transport, train, diesel powered - RNA	ton-mile	5.890E+00	5.890E+00	3.900E+00
Aggregate: Transport, combination truck, diesel powered	ton-mile	5.810E+00	5.810E+00	2.150E+01
RAP: Transport, combination truck, diesel powered	ton-mile	1.000E+01	1.000E+01	5.000E+01
Midpoint Indicators - per ton of mixture				
Acidification	kg SO2 eq	1.132E-01	8.294E-02	1.629E-01
Eutrophication	kg N eq	8.652E-03	5.716E-03	1.173E-02
Global warming	kg CO2 eq	3.799E+01	2.708E+01	4.886E+01
Ozone depletion	kg CFC-11 eq	5.799E-08	5.721E-08	1.076E-07
Smog formation	kg O3 eq	2.985E+00	2.371E+00	4.470E+00
Cumulative Energy Demand - per ton of mixture				
Non-renewable Energy: Fossil Fuels and Nuclear	MJ	2.069E+03	1.151E+03	2.268E+03
Renewable Energy: Hydro, Wind, Solar and Thermal	MJ	6.236E+00	2.755E+00	6.968E+00
Other Metrics - per ton of mixture				
Process energy	MJ	2.879E+02	2.879E+02	2.879E+02
Secondary materials used, by wt.	ton	2.903E-01	3.450E-01	1.491E-01
Non-renewable Energy as Material: Feedstock energy	MJ	1.265E+03	5.579E+02	1.413E+03
Fresh Water	m3	4.981E+00	2.736E+00	5.595E+00
Waste - Hazardous & Nuclear	kg	3.185E-03	1.405E-03	3.560E-03
Waste - Non-Hazardous	kg	6.791E+00	2.996E+00	7.589E+00

Appendix D: Conversion Factors

1 short ton =	907.185	kg
1 tonne =	1000	kg
1 tonne =	1.102310995	short ton
1 gallon =	0.00378541	m^3
1 m^3 =	35.3147	cf
1 km =	0.621371	miles
1 tonne-km =	0.684944085	ton-miles
1 ton-mile =	1.459973188	tonne-km
1 Mcf =	28.31681991	m^3
1 Btu =	0.00105587	MJ
1 kWh =	3.6	MJ
1 m^3 =	0.0353147	Mcf