Life Cycle Assessment of Asphalt Mixtures in Support of an Environmental Product Declaration

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Critical Review Statement

per ISO14071

Title of Study	Life Cycle Assessment of Asphalt Mixtures in Support of an Environmental Product Declaration
Commissioner	National Asphalt Pavement Association
Practitioner(s)	Amlan Mukherjee, Ph.D.
Version of Report	June 2016
Reviewers	Brad McAllister, WAP Sustainability Consulting
Standards and/or product Category rules evaluated	Reviewed to ISO14040/44
Stage of Performance of Review	At conclusion of project
Included or Excluded assessment of LCI model	Methodologies and boundary reviewed. Complete primary data sources and related calculations were not.
Included or Excluded an analysis of individual datasets	Excluded
Description of how comments were provided, discussed and implemented	Reviewer's comments were submitted to the LCA practitioner through a checklist that compared the LCA study to the requirements of ISO14040/44. Few modifications were required. Practitioner submitted adequate responses to the required modifications, along with an updated version of the report.
Statement of the Results	**Review to ISO14040/44** -In general the LCA study meets the requirements of the ISO14040/ 44 series of standards. The review found that there was adequate assurance that the LCA was conducted in an accurate and scientifically valid manner using LCA best practices. Data validation methodologies were implemented but calculations were not reviewed. However, descriptions of data validations procedures within the report are described and appear to be appropriate. In summary the LCA study appropriately meets the requirements of ISO14040/44.
Signed / Print Name / Date	Brad McAllister, Director, WAP Sustainability Consulting September 24 2014

Glossary of Abbreviations and Terms

ABR: Asphalt binder replacement

AI: Asphalt Institute

Btu: British thermal unit

CO_2eq: Carbon dioxide equivalents

EPD: Environmental product declaration

GTR: Ground tire rubber

GWP: Global warming potential

kWh: Kilowatt-hour

LCA: Life cycle assessment

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

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) 14025, and guided by the principles of European Committee for Standardization (CEN) EN 15804.

The study was funded by the National Asphalt Pavement Association and conducted by Dr. Amlan Mukherjee, Associate Professor in the Department of Civil & Environmental Engineering at Michigan Technological University. The study commenced in August 2015 and was completed in June 2016. The intended audience of the PCR includes the following stakeholders:

1. Asphalt mixture producers who want to quantify and declare the environmental impacts of the mixtures they produce at their plants;
2. Contractors 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 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.

It is expected that after the PCR has been externally reviewed, a software system will be deployed to automate the EPD development (the calculations in this LCA study). It is expected that this software system will allow for rapid EPD generation, allowing asphalt mixture producers to update their EPDs easily. 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 December 2016. The report was critically reviewed and *WAP Sustainability Consulting* served as the critical review party.

Declared Unit

The declared unit for this LCA is 1 U.S. short ton of asphalt mixture. All mention of "ton" in this report refers to a U.S. short ton equivalent to 2,000 pounds or 0.907 metric tonne.

System Boundaries

The system boundaries for the study are established in Figures 1, 2, and 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.

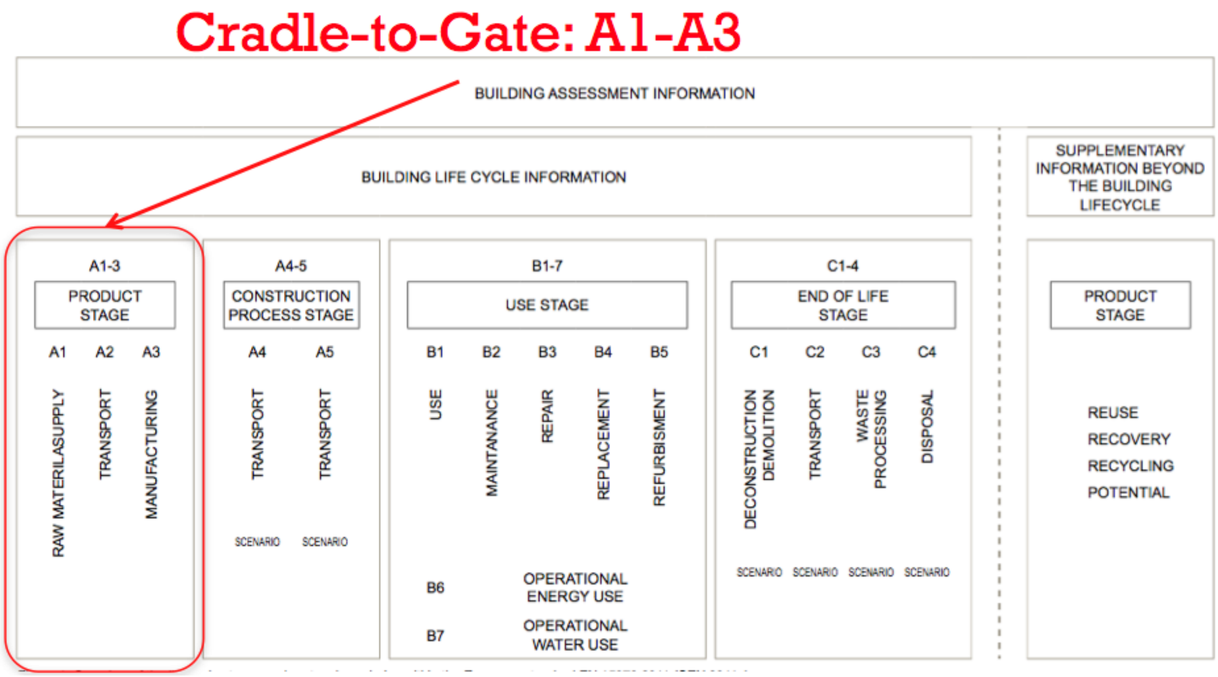

Figure 1. Diagram of Designations of Modular Information Used

Product Scope

This LCA study supports a PCR for asphalt mixtures. 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 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. However, they have not been explicitly considered in this LCA report due to unavailability of appropriate inventory data. They will be included once updated inventories 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 (in Equivalent Single Axel Loads (ESALs)) will be provided.

Purpose

The PCR is being developed to accommodate the use and implementation of environmental product declarations 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. 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 primary 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.

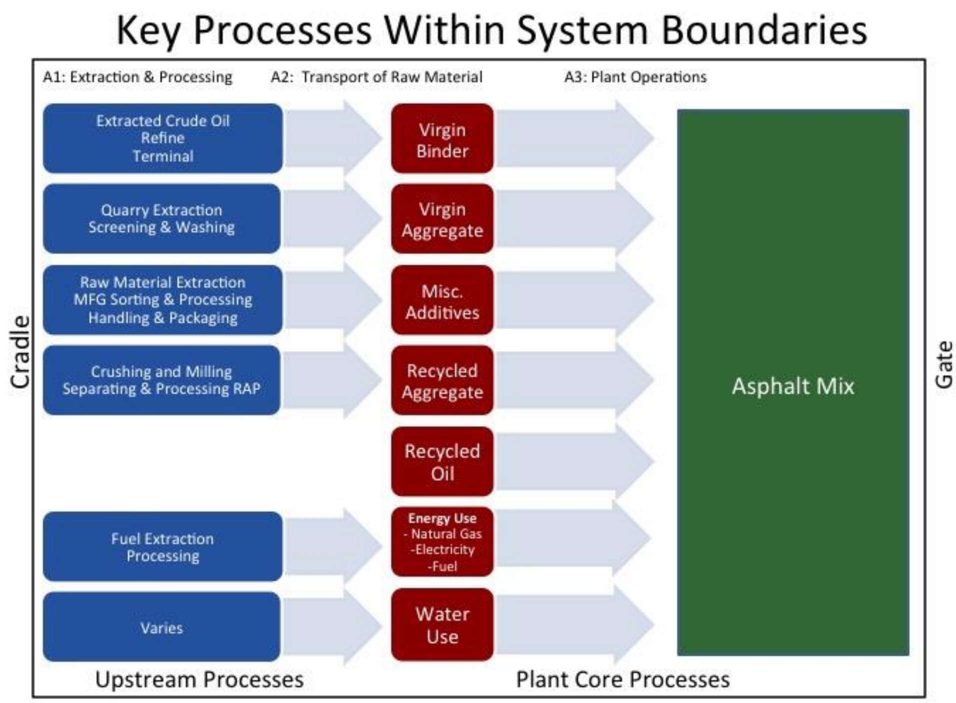

Figure 2. Diagram of the System Boundaries and Key Processes

Asphalt Production Temperature

No differentiation is 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 low temperatures can be reduced. This creates significant variability in the actual temperatures at which asphalt mixtures are produced. Therefore, it is preferable if each mixture explicitly declares the production temperature, along with a declaration of any pertinent warm-mix technology used to reduce temperatures.

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. Figure 3 summarizes the key processes and how they relate across the different life cycle phases.

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

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

1. Impacts of all co-products of crude oil refining, including extraction, refining, and storage. The co-products of interest to this PCR include gasoline, diesel, residual fuel oil, and bitumen. An economic allocation is used to allocate relative impacts of the crude oil refining process across the different co-products.
2. Impacts associated with the extraction and production of, as well as transport to the asphalt plant, of natural gas used as burner fuel.
3. Impacts associated with the mining, extraction, and production of aggregates.
4. Impacts associated with the production of electricity and its transmission to the asphalt plant.
5. Impacts associated with biofuels, if used, at the plant.
6. Impacts associated with the recycled/reclaimed materials. See section on *Allocation.*

Processes in Phase A2: Transport to Plant

Transportation distances to the plant are considered to be primary 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 secondary data.

1. 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 secondary data sources, from existing public U.S. LCI data.
2. 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 refinery, not a terminal. This assumption is being made for this study only. The PCR will eventually use an improved inventory for asphalt binder from an ongoing Asphalt Institute effort. Transportation distances for the binder from the supplier to the plant have been collected as primary data. In addition, for the sake of this LCA, it is assumed that all asphalt binder is transported by rail.
3. Transportation of virgin aggregate from source to the asphalt plant. This will be based on primary data collected for each plant.

4. Transportation of recycled materials such as recycled oil, RAP, and RAS to the asphalt plant. This will be based on primary data collected for each plant.

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 primary data.

1. 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.
2. Outputs from plant, including:
    - *a.* Total amount of asphalt mixture produced 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.

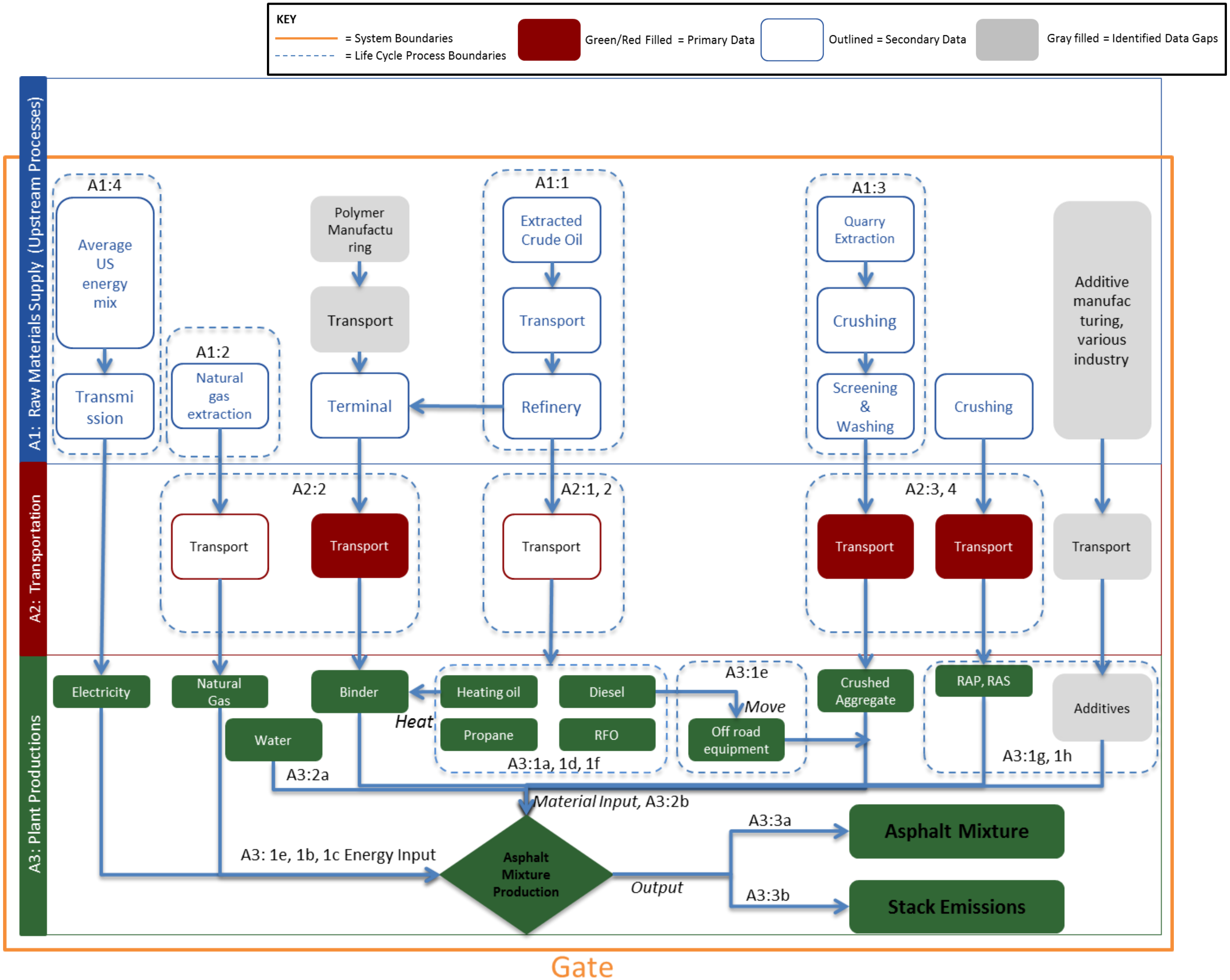

Figure 3. Description of Key Processes

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 primary 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, 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. However, significant data gaps exist in upstream life cycle inventories for these materials. Therefore, they will be included in the analysis as 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. Solar panels or any other alternative energy apparatus used to substitute traditional energy sources at the plant;
4. General management, office, and headquarter operations; and
5. 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.

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 primary and secondary data. Primary data is defined as any data item whose sources have been directly observed and collected for the purpose of this study. Secondary data is defined as data inventories from other sources and that have not been directly observed for the sake of this study. Appendix A tabulates the processes and associates them with data sources and data quality indicators.

Primary Data

The following must be considered as primary data inputs for all EPDs certifying specific asphalt mixtures. Primary data was collected over a 12-month period between August 2014 and June 2015, from 40 plants. The instrument used for the data collection process has been included as Appendix B.

1. Total asphalt produced at the plant, reported in U.S. short tons
2. Total electricity:
   a. Line power use in kWh, based on the energy production mix for the region in which the plant is located
   b. Solar power generated on site in kWh
   c. Wind power generated on site in kWh
3. Generator energy
   a. Diesel fuel in gallons
   b. Biofuels in gallons
4. Plant burner energy (primary)
   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. Plant burner energy (secondary)
   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. Recycle fuel oil in gallons or in liters

e. Biofuels in gallons or in liters

6. 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. Recycle fuel oil in gallons or in liters
   e. Biofuels in gallons or in liters

7. Mobile equipment energy
   a. Diesel fuel use in gallons or in liters
   b. Natural gas use in MCF or MMBtu

8. Aggregate used in production in U.S. short tons

9. Asphalt binder used in production in U.S. short tons

10. One-way distances travelled to plant for asphalt binder and aggregate (both virgin and recycled), expressed in U.S. short ton-miles.

11. Water used in gallons or in liters.

12. Stack emissions from plant in pounds.

Pre-determined scenarios: For the parameters that may be difficult to estimate or collect primary data for, the following has been used.

13. Default energy requirements for processing of RAP/RAS is 0.1 gal/short ton or 0.4 kWh/short ton.

14. Distance travelled by RAP/RAS to plant is 50 miles.

The primary data collection instrument has been provided as a supplement to this document (Appendix B). 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 being dealt 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, they may be sold to a downstream industry. As the cut-off method is being used for allocation, the downstream impacts of the material are not included.

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.
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 and RAS can be difficult to estimate because they often come from different construction sites. However, a 50-mile radius (or a defined distance based on typical market area) is considered a reasonable estimate for the distance travelled by the recycled materials to plant.

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.

For asphalt binder, an economic allocation at the refinery has been used pursuant to the procedure defined by Yang (2014). The allocation factors used are shown in Table 1.

Table 1: Allocation for Asphalt Binder (Yang, 2014)

Co-Products (U.S. Averages)	Allocation Factors	Mass Yield Fractions	Economic Allocation Coefficient
LPG	0.76	0.03	0.02
Finished motor gasoline	1.31	0.42	0.53
Kerosenes	1.21	0.09	0.10
Distillate fuel oil	1.2	0.21	0.25
Residual fuel oil	0.65	0.05	0.03
Special napthas	0.99	0.05	0.04
Lubricants	3.14	0.05	0.09
Petroleum coke	0.14	0.06	0.01
Asphalt and road oil	0.5	0.04	0.02

The allocation factors are defined as the ratio of the *Economic Allocation Coefficient*, that is the price-weighted average yield of each co-product, to the *Mass Yield Fraction*. Based on the mass yields of the co-products and the known allocation factors, the economic allocation coefficients were derived. The relevant numbers are illustrated in Table 1 (mass fraction and economic allocation numbers may not add up to 1 due to rounding). The economic allocation coefficients were used to develop an inventory for asphalt binder based on the *NREL U.S. LCI Crude oil, at refinery* data. An inventory for distillate fuel oil was constructed the same way.

As this LCA study was being conducted, the Asphalt Institute was in the process of conducting a detailed LCA for liquid asphalt binder. In the future, the AI LCA and the NAPA EPD program will use the LCI for asphalt binder developed through the Asphalt Institute study. Meanwhile, this life cycle inventory is a suitable and useful placeholder.

For chemical additives and polymers, when possible, a mass-based allocation is applied.

Secondary Data

The following life cycles inventories are being used:

NREL U.S. LCI: *Crude oil, at refinery.*

1. Impacts of all co-products of crude oil refining, including extraction, refining, and storage. The co-products of interest to this LCA include gasoline, diesel, recycled fuel oil, and asphalt binder. An economic allocation is used to allocate the relative impacts of the crude oil refining process across the different co-products. Refers to processes in item A1:1.
2. 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 secondary data sources, from existing public U.S. LCI data. Refers to processes in item A2:1.

The upstream datasets used for this estimation are known to be incomplete (the electricity data was updated), and this is a limitation of the study. The outcomes based on these datasets were compared with other existing LCA studies to ensure that the estimates are not entirely inaccurate. The GWP for liquid asphalt binder when calculated using this dataset was 390.19 kilograms of CO_2eq/ton. This was considered to be comparable to the other estimates discussed in Yang (2014).

NREL U.S. LCI: *Natural gas combusted in industrial boiler.*

1. Impacts associated with the extraction and production of natural gas. Refers to processes in item A1:2.

Table 2: Source: Life Cycle Inventory of Portland Cement Concrete, SN3011 (Marceau et al., 2007).

Energy Used to Produce Sand and Gravel

Fuel or Electricity	Total Energy Used		Energy/Ton Aggregate		
	Amount	**MBtu**	**Amount**	**Btu/Ton**	**kJ/Metric Tonne**
Distillate (light) grade Nos. 1, 2, 4, & light diesel fuel, gallon	58,959,600	8,177,697	0.0562	7,793	9,060
Residual (heavy) grade Nos. 5 and 6 & heavy diesel fuel, gallon	13,234,200	1,981,160	0.0126	1,888	2,200
Gas (natural, manufactured, and mixed), Mcf	1,400,000	1,437,800	0.0013	1,370	1,590
Gasoline used as a fuel, gallon	5,700,000	712,500	0.0054	679	790
Electricity purchased, 1000 kWh	2,525,053	8,615,481	0.0024	8,210	9,550
Total		**20,924,638**		**19,940**	**23,190**

Energy used to produce coarse aggregate from crushed stone

Fuel or Electricity	Total Energy Used		Energy/Ton Aggregate		
	Amount	**MBtu**	**Amount**	**Btu/Ton**	**kJ/Metric Tonne**
Coal, ton	43,000	903,516	0.0000275	577	670
Distillate (light) grade Nos. 1, 2, 4, & light diesel fuel, gallon	145,811,400	20,224,041	0.0932	12,920	15,030
Residual (heavy) grade Nos. 5 and 6 & heavy diesel fuel, gallon	22,663,200	3,392,681	0.0145	2,167	2,520
Gas (natural, manufactured, and mixed), Mcf	5,400,000	5,545,800	0.00345	3,543	4,120
Gasoline used as a fuel, gallon	14,700,000	1,837,500	0.00939	1,174	1,370
Electricity purchased, 1000 kWh	4,627,887	15,790,350	0.00296	10,088	11,730
Total		**47,693,888**		**30,469**	**35,440**

Data sources from Life Cycle Inventory of Portland Cement Concrete, SN3011 (Table 2)

1. Impacts associated with the mining, extraction, and production of aggregate. Refers to processes in item A1:3.

Electricity: Based on GREET 2013, emissions and energy use in Electricity tab, line losses assumed to be 6.5%, per GREET 2013 and average U.S. energy mix used. (See Table 3).

1. Impacts associated with the production of electricity and transmission to asphalt plant. Refers to processes in item A1:4.

Table 3: a) Power Plant Energy Use and Emissions: per MMBtu of Electricity Available at User Sites, b) U.S. Electricity Mix

Stationary Use: U.S. Mix

Energy Use: Btu	***Total (Btu/MMBtu)***
Residual oil	2.93E+04
Natural gas	5.29E+05
Coal	1.42E+06
Biomass	1.41E+04
Nuclear	2.17E+05
Other energy sources	1.04E+05
Emissions: grams	***g/MMBtu***
VOC	3.41E+00
CO	3.61E+01
NO_x	1.94E+02
PM_{10}	4.52E+01
$PM_{2.5}$	3.18E+01
SO_x	4.80E+02
CH_4	2.63E+00
N_2O	2.39E+00
CO_2	1.76E+05

Source of Electricity (U.S. average)	Btu/kWh
Residual oil (non-renewable)	1.00E+02
Natural gas (non-renewable)	1.81E+03
Coal – Bituminous (non-renewable)	4.38E+03
Coal – Lignite (non-renewable)	2.13E+02
Biomass	4.81E+01
Nuclear (non-renewable)	7.42E+02
Hydroelectric	2.39E+02
Geothermal	1.40E+01
Wind	8.70E+01
Solar PV	1.11E+00
Others (Biogenic waste, Pumped storage, etc.)	1.45E+01

NREL U.S. LCI: *Transport, train diesel powered.*

1. Transportation of asphalt binder from refinery/terminal to plant. Refers to processes in item A2:2.

NREL U.S. LCI: *Transport, combination truck diesel powered.*

1. Transportation of virgin aggregate from source to the asphalt plant. This will be based on primary data collected for each plant. Refers to processes in item A2:3.

2. Transportation of recycled materials, such as recycled fuel oil, RAP, and RAS, to the asphalt plant. This will be based on primary data collected for each plant. Refers to processes in item A2:4.

Data Quality

This section discusses the philosophical guidelines driving the primary (foreground) data collection and selection of secondary (upstream/background) data inventories. In addition, it also discusses ways in which data quality and data gaps are handled in this LCA study. Appendix A tabulates the processes and associates them with data sources and data quality indicators.

Primary Data

The following principles have supported the primary 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 primary data reporting, while also reducing the data collection burden in the long run and consequently encouraging adoption of the EPD program.
2. Data Aggregation: The total annual (12-month period) use of primary 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. Primary Data Analysis: An analysis of the primary 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: Primary 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 primary 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 insure 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. <u>Data Gaps:</u> Efforts should be made to ensure gaps in primary data collection are limited to only those items for which a predetermined scenario has been provided (Items 10 and 11 in the *Primary Data* section).

Secondary/Upstream Inventory Data

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

1. <u>Uniformity in Use of Life Cycle Inventories:</u> 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 primary 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. <u>Transparency of Life Cycle Inventories:</u> 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.

3. <u>Geography and Regionalization:</u> This report uses upstream data specific to the United States. U.S. average data is used for electricity. However, for LCA supporting EPDs, it is critical regional energy mixes from eGRID be used to reflect regional differences. Similarly, at this time, the inventory and allocation for asphalt binder is based on the U.S. average (as discussed in *Materials from Processes with Multiple Co-Products* section); however, EPDs for specific mixes should reflect regional allocation factors based on their Petroleum Administration for Defense Districts (PADD) region.

4. <u>Data Gaps:</u> 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 and polymers.

5. Dependence on LCI Data from Allied Industries: The life cycle inventory of asphalt mixtures is dependent on upstream data from various other industries, most importantly the petroleum refining industry. At this time, reasonable placeholder data is being used for the binder (as described in *Materials from Processes with Multiple Co-Products* section). NAPA is in conversation with Asphalt Institute, and as AI develops a detailed LCI for liquid asphalt binder, that LCI will be harmonized as an input to this EPD. Therefore, it is important to recognize this is currently not a data gap, but rather work in progress that will ensure harmony between asphalt mixtures and various critical upstream products.

Primary Data Analysis

This section discusses the primary data collected for this study from 50 asphalt plants from across the United States. Primary data was collected using the data collection tool that is attached to this document. These items pertain to processes described under phase A3. The primary items that were analyzed were:

1. Energy use:
   a. The energy used in a plant for primary data items 3, 4, 5 and 6 expressed in Btu (described in the *Primary Data* section)
   b. The electricity used in a plant for primary data item 1 expressed in kWh (described in the *Primary Data* section)
2. Transportation distances:
   a. The one-way distances travelled by the asphalt binder to the plant from the supplier
   b. The one-way distances travelled 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. The data collected from all 50 plants was not 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 5.

The energy use is 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** (conversion units in Appendix E).

Trends in 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 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)

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. For example, for one of the plants sampled (but not included in the above results) the distance travelled for aggregate was calculated to be 207.84 ton-miles/ton.

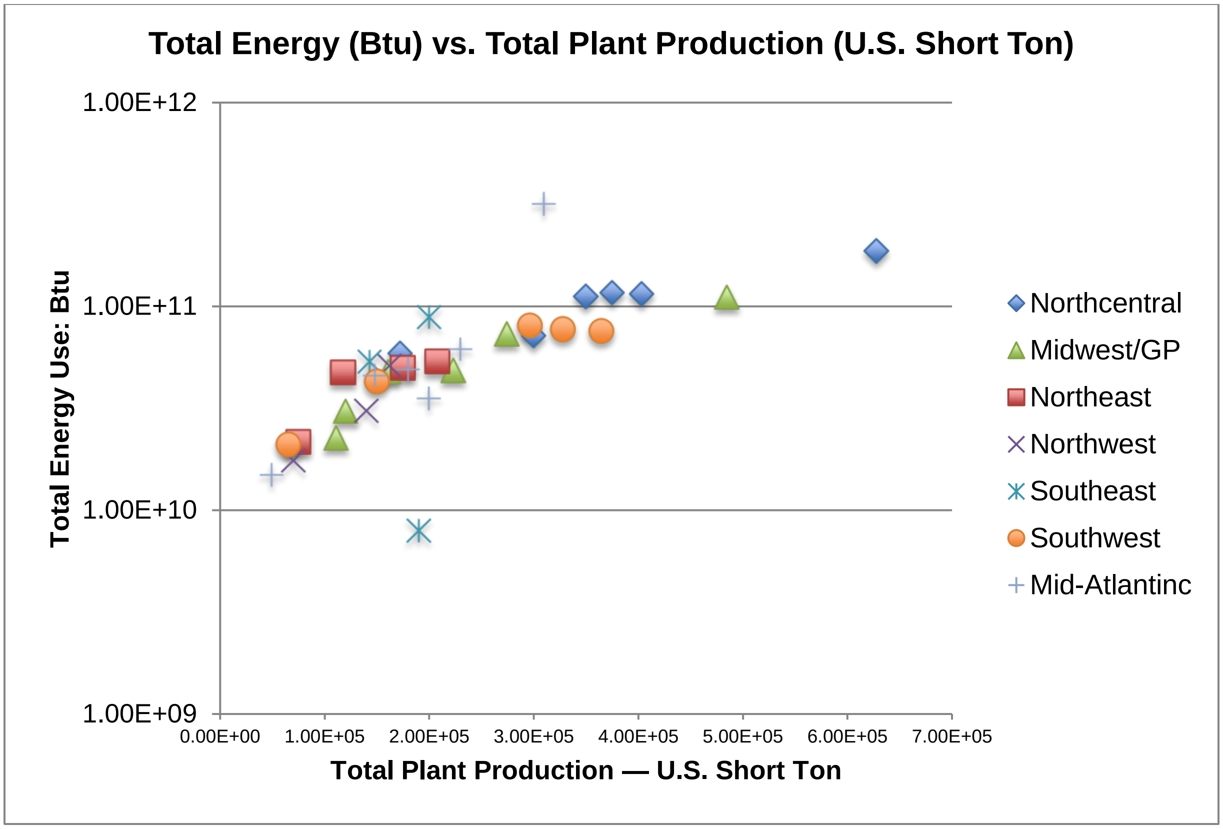

Figure 4: Plant Energy Use Trends by Production

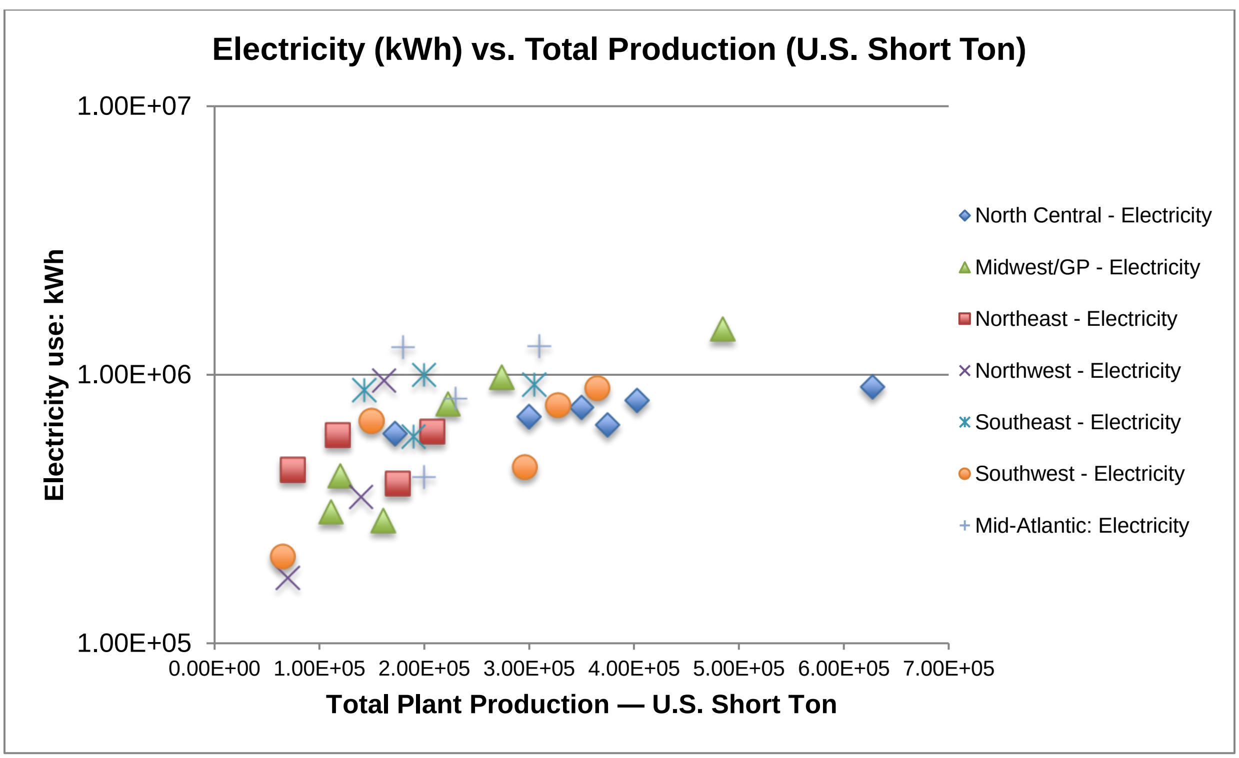

Figure 5: Plant Electricity Use Trends by Production

Life Cycle Assessment Results

Using the above data, a life cycle inventory was developed for the following types of asphalt mixes, as follows:

1. Mix 1: Plain mix, containing no RAP or RAS with 5% virgin liquid asphalt binder
2. Mix 2: 15% RAP, 3% RAS, and 4.2% virgin liquid asphalt binder
3. Mix 3: 20% RAP and 4.3% virgin liquid asphalt binder
4. Mix 4: 35% RAP and 2.8% virgin liquid asphalt binder

The primary data for the mixes are presented as annual aggregates in Appendix C. The OpenLCA platform was used to conduct the LCA. The normalization scheme used was US-CA 2008/2005, and TRACI 2.1 was used as the impact assessment method.

The choice of the impact categories was based on discussions within the PCR committee for the NAPA asphalt mixtures EPD program. The impact category descriptions as per 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: 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 primary sources of ozone precursors are motor vehicles, electric power utilities, and industrial facilities

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.

Life Cycle Input Output Inventory

The complete inventory table for the mixes including the inputs and outputs are presented in Appendix D . The main impact categories are expressed in Table 4, as follows:

Table 4: Impact Categories

Impact category	Reference unit	Mix 1	Mix 2	Mix 3	Mix 4
Acidification	kg SO_2eq	2.68E−01	2.28E−01	2.23E−01	1.74E−01
Eutrophication	kg Neq	1.24E−02	1.25E−02	1.19E−02	8.83E−03
Global Warming	kg CO_2eq	5.86E+01	3.59E+01	3.85E+01	5.13E+01
Ozone Depletion	kg CFC-11eq	5.28E−09	4.25E−09	4.41E−09	3.16E−09
Photochemical ozone formation	kg O_3eq	4.68E+00	5.23E+00	4.87E+00	3.61E+00

Energy Calculation

The energy for each asphalt mix is calculated using the following lower heating values (LHV) (Table 5):

Table 5: Lower Heating Values

LHV	**MJ/kg**
Crude oil	43.05
Gasoline	44.15
Diesel	42.91
Fuel oil	40.87
LPG	46.28
Kerosene	43.69
Hydrogen	119.95
Coal	25.75
Bitumen	40.2
Natural gas	45.86

Hence for Mixes 1 and 2 the energy calculations are as follows in Table 6, based on the input inventory in Appendix D.

The energy is reported using aggregation of the input inventory as per the following method:

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*.
- Nonrenewable energy resources as a material, in MJ: This includes the energy that is embodied in organic materials in the asphalt mixture including virgin binder, and any other organic additive. For the case of this study this is limited to the energy present in the asphalt binder. This is reported as *Non-Renewable Energy as Material*.

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.

These two categories are combined and reported as *Energy from Renewable Resources*.

Lower heating values (Table 5) shall be used to convert to physical units to MJ.

Table 6: Energy Reporting

Energy (per ton of asphalt mix)		**Mix 1**	**Mix 2**
Non-Renewable Energy From Fossil Fuels	MJ	1.90E+03	1.41E+03
Energy From Renewable Sources	MJ	4.67E+00	2.78E+00
Non-Renewable Energy as Material	MJ	1.823E+03	9.919E+02

Analysis

A comparison of Mix 1 and Mix 2 are provided based on the global warming potential indicator.

Table 7: Comparison for Mix 1 and 2

	Mix 1	Mix 2
Global Warming Potential (kg of CO_2eq/ton)	*58.6*	*35.9*
Processes		
Liquid Asphalt Binder, in refinery	33%	46%
Natural gas, combusted in industrial boiler	25%	26%
Electricity at grid, U.S., GREET 2012	24%	15%
Aggregate	7%	10%
Diesel, combusted in industrial boiler	5%	0%

Transport, combination truck, diesel powered	4%	2%
Diesel, combusted in industrial equipment	1%	1%
RAP/RAS recycling	0	1%
Transportation Distances		
Truck miles travelled (ton-mile/ton)	15.8	3.8
Train miles travelled (ton-mile/ton)	7.14	3.0
Energy (per ton)		
Total Process Energy (including the following) (MJ)	4.17E+02	2.61E+02
Process: Electricity, used in plant (kWh)	*6.14*	*2.33*
Process: Fuel, used in plant (Btu)	*3.74E+05*	*2.39E+05*
Life Cycle Energy (MJ)	1.90E+03	1.41E+03
Feedstock Energy (MJ)	1.823E+03	9.919E+02

A critical take-away from the above two results is that using decontextualized percentages for cut-off (as described in the Cutoff Criteria section) can be misleading. For instance, Mix 2 has a lower virgin binder content and consequently a lower global warming potential. However, as the transportation distance (and related impacts) for Mix 1 are higher compared to Mix 2, the relative contribution of the binder gets diluted. Hence, percentage contributions must be considered within the context of factors such as how far raw materials are travelling to the plant. Specifically, the contribution from the liquid asphalt binder can get diluted when the contribution from transportation is significantly higher. Hence, using rigid impact percentage based cut-off criteria may be misleading and of little meaningful value.

Sensitivity Analysis

Typically, a sensitivity analysis is useful for testing the impact of alternative assumptions and choices made in conducting the LCA study. In this case, a particular matter of concern is understanding the relative impact of including or excluding components of the asphalt mixture that contribute disproportionately to the impacts compared to their share as a percentage of mass (such as polymers and chemical additives). However, the primary challenge with such an analysis is that it presupposes the existence of reasonable upstream data sources that can be used to justify the inclusion or exclusion of such materials. In the absence of such data sources, it is considered acceptable to use data from comparable materials. However, given the nature of the chemicals and the complex supply chains involved in their manufacture, it is considered advisable to not include them until reliable data sources are available. Meanwhile, the need for conducting a sensitivity analysis is not important, as the results would likely be unreliable.

A second use of the sensitivity analysis is to provide decision-makers — in this case the asphalt mixture designers — with meaningful perspective on the relative contributions of different asphalt mixture contributions. The objective of such an analysis is to provide deeper insights that can, in turn, improve the overall mixture design while reducing its environmental impact. In this context, the following analysis were conducted:

1. Relative impacts of asphalt binder reduction in the mixture
2. Impact of transportation distances of raw materials to the plant

Sensitivity to Asphalt Binder Reduction

The asphalt binder content in the mixture is a combination of the virgin liquid asphalt binder content and the available binder contributed by recycled materials used such as RAP and RAS. As the RAP and RAS contents of a mixture increase, the percentage of virgin asphalt binder replaced also increases. Also, the liquid asphalt binder has the greatest relative impact of all the constituent materials in a mixture. Hence, starting with a virgin asphalt mix (with no RAP or RAS), the impacts can be reduced through a reduction in use of virgin asphalt binder and virgin aggregate. There is an added impact due to the processing and transport of the RAP and RAS from their respective sources, but over all, there is a reduction in the estimated impacts compared to the baseline impacts for a virgin mix. Of course, the baseline is specific to the primary data inputs for a particular plant, and may vary by region and plant energy use trends.

Therefore, a reasonable way to cluster asphalt mixes by environmental impacts is to rank them by reduction in virgin asphalt binder content, with respect to a baseline virgin mixture. For example, starting with a mixture that has 5% virgin liquid asphalt binder, consider a family of mixes (specific to the plant) that can be designed by introducing RAP and/or RAS till the liquid asphalt binder has been replaced by 50%, i.e., the mixture has a 2.5% virgin liquid asphalt binder. Needless to say, the individual mixtures within such a family can vary in design for different percentages of RAP and RAS. A range for the GWP for the family can be established, allowing mix designers to understand how the GWP changes as they vary their mix designs.[1] Figure 6, illustrates the sensitivity of GWP to the change in mixture through asphalt binder replacement by adding RAP and RAS, starting from two base mixes: one with 5% virgin liquid asphalt binder (referred to as 5% Initial Virgin Mix) and the other with 8% virgin liquid asphalt (referred to as 8% Initial Virgin Mix) binder for primary data specific to a plant. It is worth reiterating that the trends across a family are dependent on a baseline mix design and plant-specific energy use data.

The objective of defining mix design families is to illustrate the sensitivity of LCA indicators to marginal changes in asphalt mixture designs. It is likely to serve the following purposes:

1. As an asphalt mixture design support tool to meet LCA targets (e.g., equivalent CO_2 emissions in global warming potential), while considering alternative designs.
2. As a method to cluster mixtures that have minor variations in design and environmental impacts.

[1] This plot is plant-specific and based on working data that has not been finalized as the work is still in progress. The intention of this diagram is to highlight the trend.

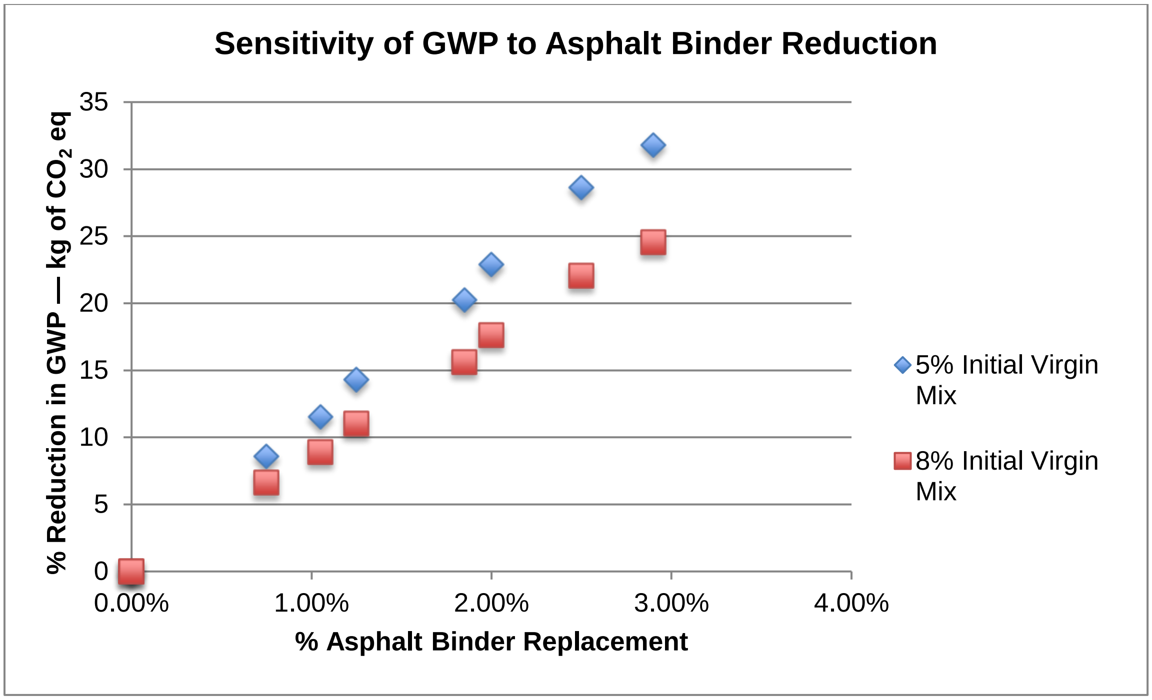

Figure 6: Percentage Change in GWP as Liquid Asphalt Binder is Reduced

Sensitivity to Distance Travelled

Generalizing the sensitivity to distance travelled, unlike asphalt binder, is not as useful as distances cannot be varied as part of a design process. However, it is useful to understand the contribution of truck miles travelled on the LCA outcomes. Figure 7, illustrates the variation in GWP calculated for each of the four mixes. Mix 1, a virgin mix has the highest impact. Mix 2, shows improvement due to the binder reduction, as well as reduced distance travelled. Comparatively, Mix 4 (35% RAP, 2.8% asphalt binder), which has a much higher binder replacement than Mix 1 (0% RAP, 5% asphalt binder) suffers in GWP performance. Hence, while the use of recycled materials is useful, when the distance travelled by the materials in the mixture is high, the benefits of the design may be reduced due to the impacts of transportation.

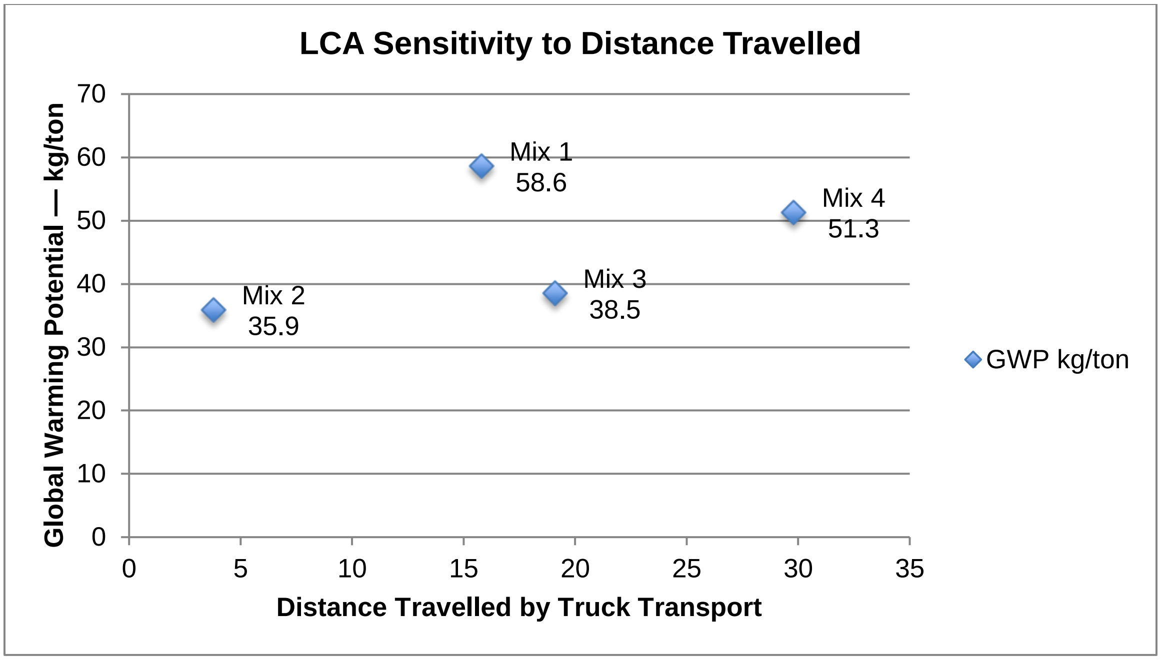

Figure 7: GWP Sensitivity to Truck Miles Travelled

Figure 8, shows the variation in GWP for Mix 1 as the ton-miles/ton of truck transportation is varied. Mix 1 was chosen for this plot as it has 0% asphalt binder reduction. The plot shows that for each truck ton-mile reduced, the GWP is reduced by 0.153 kg of CO_2eq/ton. Hence, for a 38.2 ton-mile/ton reduction in truck distance travelled, a 10% reduction in GWP can be achieved.

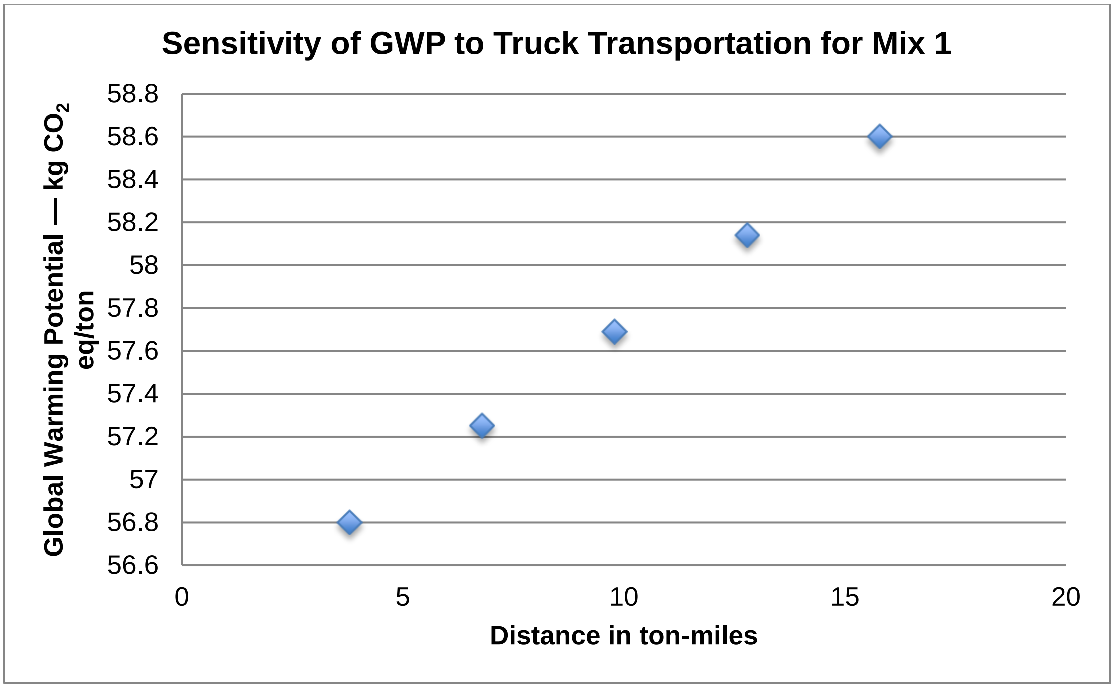

Figure 8: GWP Sensitivity to Truck Miles Travelled for Mix 1 Varying Distances

Sensitivity to Using Polymer-Modified Binder

For the sensitivity analysis, SBS was used as a polymer. The inventory used (Boustead & Cooper, 1998) does not meet the any data quality requirements, as it is more than 5 years old, and the source is not publicly available for use. However, the inventory was used to test the sensitivity of the asphalt binder impacts when modified by polymers such as styrene-butadiene-styrene (SBS) and polybutadiene. The differences in the GWP indicator for the different polymer-modified binders are illustrated in Table 8. It is expected that as the Asphalt Institute develops a detailed LCI for asphalt binder, this LCA will be modified to reflect the most recent outcomes, including the impacts of polymer modification.

Table 8: Difference in GWP for Polymer-Modified Binder and Mix (per ton)

	GWP (kg of CO_2eq)	Difference
Liquid Binder in Refinery	390.20	
Polymer-Modified: SBS	494.81	27%
Polymer-Modified: Polybutadiene	498.40	28%
Mix 1: Virgin materials, 5% Binder	58.59	
Polymer-Modified Mix 1	63.82	9%
Mix 2: 15% RAP, 3% RAS, 4.2% Binder	35.89	
Polymer-Modified Mix 2	40.29	12%

Sensitivity to Choice of Upstream Datasets (Secondary Data)

In an effort at transparency, a conscious choice was made through this study to use only life cycle inventories that are publicly available and free to use. Hence, this study used upstream life cycle inventory from the NREL U.S. LCI. Where possible, *dummy* entries (as used in NREL database) were updated using relevant data from other sources, such as U.S. GREET. Hence, while the estimates provided in this study are limited by the incompleteness of the upstream datasets, they do provide a transparent platform for decision-makers.

Table 9: Comparison for Mix 1 and 2

Asphalt Mixtures	GWP (kg of CO_2eq/ton)		% Error
	NREL US LCI	*Datasmart*	(− sign = lower)
Mix 1	58.59	63.58	−9%
Various Mixtures based on Mix 2			
0% RAP, 0% RAS, 5% Binder	39.53	50.35	−27%
15% RAP, 4.25% Binder	36.15	45.17	−25%
25% RAP, 3.75% Binder	33.88	41.70	−23%
40% RAP, 3.0% Binder	30.48	36.49	−20%
50% RAP, 2.5% Binder	28.21	33.00	−17%
15% RAP, 2% RAS, 3.95% Binder	34.97	43.37	−24%
25% RAP, 4% RAS, 3.15% Binder	31.53	38.11	−21%
40% RAP, 6% RAS, 2.1% Binder	26.96	31.09	−15%

Hence, the EarthShare LCI database representative of the North America was used to assess the level of error introduced in the LCA estimates due to the incompleteness.

The dataset provided by EarthShare/Datasmart was chosen because it is an expanded version of the NREL U.S. LCI database that has been modified using Ecoinvent v.2.2 data, along with accurate data for all 50 U.S. states' electricity mixes. This allows assessment of the sensitivity of the LCA estimates to the missing upstream data entries. Table 9 establishes the percentage differences for the GWP indicator for the 5% and 8% virgin binder variations of Mix 1 used in Figure 6. The second set of mixes is variations on Mix 2, and share the same primary data. The average error across all the Mix 2 derivatives is 22% lower, with a standard deviation of 4% and a skew of −0.22. The difference for Mix 1 is 9% lower. When Mix 1 and Mix 2 derivatives (different primary data) are compared, the average difference is 20% lower with a standard deviation of 6%, and a skew of −0.9. The negative skew indicates that the NREL U.S. LCI dataset has possibly incomplete inventories.

A comparison across all impact categories for the asphalt binder and Mix 1 is provided in Table 10. It is noted that the relative differences across all categories are within the same order of magnitude, excepting for the Ozone Depletion impact category. The difference between GWP for asphalt binder is 5% lower. This illustrates the differences between the absolute values of the indicators given the use of different upstream inventories. The next step is to investigate any differences between the relative trends in the impact categories.

Table 10: Comparison Across All Indicators for Asphalt Binder and Mix 1

Impact category	Reference unit	Binder		Mix 1	
		U.S. LCI	*Datasmart*	*U.S. LCI*	*Datasmart*
Acidification	kg SO_2eq	2.287E+00	4.592E+00	2.683E−01	2.301E−01
Eutrophication	kg Neq	1.562E−01	1.841E+00	1.239E−02	8.670E−02
Global Warming	kg CO_2eq	3.902E+02	4.087E+02	5.859E+01	6.358E+01
Ozone Depletion	kg CFC-11eq	7.837E−08	5.300E−04	5.281E−09	7.356E−07
Photochemical ozone formation	kg O_3eq	4.413E+01	3.600E+01	4.682E+00	5.259E+00

The plot in Figure 9, illustrates the sensitivity of GWP to the change in mixture through asphalt binder replacement by adding RAP and RAS, starting with the base mixes of 5% virgin liquid asphalt binder and using the NREL U.S. LCI and the Datasmart datasets. The slopes for the two cases are approximately 11.2 and 13.5, indicating a difference of approximately 17% (lower).

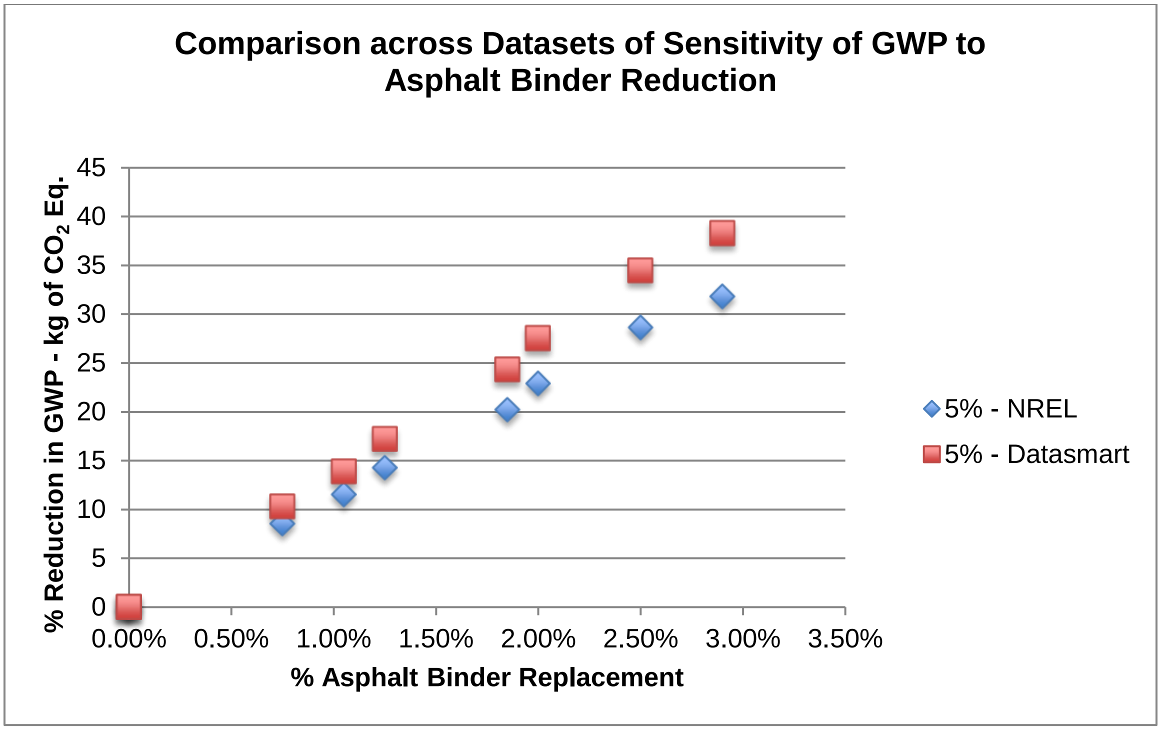

Figure 9: Percentage Change in GWP as Liquid Asphalt Binder is Reduced

An argument may be made for using the public NREL U.S. LCI so long as the primary purpose of the indicators is seen as benchmarking and decisions are made based on relative improvements between LCAs for different mixtures using the same upstream inventories.

Limitations of This LCA Study

It is important to note this LCA study applies to and justifies the PCR for asphalt mixtures. However, the mixtures used in this study and the results presented have the following limitations:

1. The LCA does not explicitly consider the impacts of various warm-mix admixtures and other additives, even though they are explicitly part of the system boundary. As reliable and publicly accessible upstream inventories for these additives become available, this study will be updated to reflect the new datasets.
2. There is some ambiguity in this study regarding the impacts of transporting the liquid asphalt binder from the refinery to the terminal. There is agreement with the Asphalt Institute that in order to maintain consistency between LCAs, the inventory being developed by AI for liquid asphalt binders will include these impacts. Meanwhile, the inventory being used for asphalt binder in this study at present only considers impacts at the refinery. Primary data was not collected for distance travelled from refinery to terminal to avoid duplication of effort with the Asphalt Institute and because it was not part of the scope of the primary data collection for this LCA. This is a temporary omission as the Asphalt Institute inventory will eventually replace the inventory used in this study.

3. As a matter of principle, as decided by the PCR committee, this EPD program is emphasizing the use of publicly available upstream data at this time. This makes the results of the study vulnerable to criticism. A comparison with the proprietary data from EarthShare/Datasmart illustrates the relative differences between indicators such as GWP to be in the 20% range. The relative differences for some other indicators tend to be higher even though the absolute differences are small and often limited to the same order of magnitude. Therefore, it is advised that EPDs from this program be used primarily for benchmarking purposes and for comparing only with products that are also certified by this program. Comparison of absolute values of indicators with EPDs from different programs or with other products using different upstream datasets is not advisable and may lead to erroneous decisions. In its current form, EPDs from this program may be best used to benchmark and improve the environmental performance of asphalt mixtures.

The above limitations are temporary and will be addressed in future updates to this program. Meanwhile, this effort will serve well in jumpstarting the adoption of EPDs by the asphalt materials industry and helping producers benchmark their environmental impacts and identify ways of improving their product and design processes to reduce said impacts.

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Appendix A: Primary and Secondary Data

Primary Data

Process	**Data Item**	**Sources**
A2:2	One-way distance travelled to plant from terminal for asphalt binder	Collected directly from surveyed plants and aggregated data reported Uncertainty: function of reporting Variability: can vary significantly from region to region Confidence interval provided for data collected in this study.
A2:3	One-way distance travelled to plant for virgin aggregate	Collected directly from surveyed plants and aggregated data reported. Uncertainty: function of reporting Variability: can vary significantly from region to region Confidence interval provided for data collected in this study.
A2:4	One-way distance travelled to plant for RAP & RAS	Collected directly from surveyed plants and aggregated data reported. Uncertainty: function of reporting Variability: can vary significantly for different plants.
A3:1a	Off road equipment energy — diesel in gallons	Collected directly from surveyed plants and aggregated data reported Uncertainty: function of reporting Variability: Confidence interval provided for data collected in this study (all energy). Variation expected due to regional climate differences.
A3:1b, 1c	Generator energy — diesel in gallons	Collected directly from surveyed plants and aggregated data reported Uncertainty: function of reporting Variability: Confidence interval provided for data collected in this study (all energy). Variation expected due to regional climate differences.

Process	Data Item	Sources
A3:1b, 1c	Plant burner energy	Collected directly from surveyed plants and aggregated data reported Uncertainty: function of reporting Variability: Confidence interval provided for data collected in this study (all energy). Variation expected due to regional climate differences.
	- Natural gas — Mcf or MMBtu	Uncertainty: function of reporting Variability: Confidence interval provided for data collected in this study (all energy). Variation expected due to regional climate differences.
	- Propane, Diesel, RFO in gallons	Uncertainty: function of reporting Variability: Confidence interval provided for data collected in this study (all energy). Variation expected due to regional climate differences.
A3:1d, 1f	Hot oil heater energy	Collected directly from surveyed plants and aggregated data reported
	- Natural gas — Mcf or MMBtu	Uncertainty: function of reporting Variability: Confidence interval provided for data collected in this study (all energy). Variation expected due to regional climate differences.
	- Propane, Diesel, RFO in gallons	Uncertainty: function of reporting Variability: Confidence interval provided for data collected in this study (all energy). Variation expected due to regional climate differences.
A3:1e	Total electricity used in kWh	Collected directly from surveyed plants and aggregated data reported Uncertainty: function of reporting Variability: Confidence interval provided for data collected in this study (electricity use). Variation expected due to regional climate differences.
A3:1g	RAP and RAS processing	Collected directly from surveyed plants and aggregated data reported Uncertainty: function of reporting

Process	Data Item	Sources
		Variability: function of demand and mixes produced.
A3:2a	Total tonnage of asphalt mixture produced at plant	Collected directly from surveyed plants and aggregated data reported Uncertainty: function of reporting Variability: function of demand and mixes produced.
	- Aggregate used in production (U.S. short ton)	
	- Asphalt binder used in production (U.S. short ton)	
	- Total RAP and RAS used in mixture (U.S. short ton)	
A3:2b	Water used in plant (dust control included) in gallons	Collected directly from surveyed plants and aggregated data reported Uncertainty: function of reporting Variability: function of locale, demand and mixes produced.
A3:2c	Stack emissions from plant in pounds	Collected directly from surveyed plants and aggregated data reported Uncertainty: function of reporting Variability: function of demand and mixes produced.

Data Quality Indicators for Primary Data

	Representativeness	The data is representative of the United States. Regional trends have been illustrated
	Age	The 5-year validity for all primary data lasts till 2020
	Time	All datasets reported from the plants was over a 12-month period in the last 3 years
	Geography	United States — with illustration of regional trends
	Technology coverage	No distinction is made for different kinds of asphalt plant technologies
		Different asphalt mixture design data was collected
		Limited success in collecting data for asphalt mixture additives
	Consistency	Cut-off allocation protocol used for recycled materials

		A combination of economic and mass based allocation used per Yang (2014)
		Best efforts were made to harmonize with other products, particularly asphalt binder
	Variability and uncertainty	Statistical confidence intervals for primary datasets have been reported: Each item has been addresses separately above, as well.

Secondary Data

Process	**Data Item**	Sources
A1:1, A2:1	NREL U.S. LCI: Crude oil, at refinery	Franklin Associates 2003 Data Details for Petroleum Refining
		U.S. EPA 2002 Inv. of U.S. GHG Emissions and Sinks: 1990–2000 CH_4 Emissions from Petroleum Systems
		Energy Information Administration 2001 Annual Energy Review 2001, Refinery Input and Output
		World Bank Group 1998 Petroleum Refining, Pollution Prevention and Abatement Handbook
		Oak Ridge National Laboratory 1996 Estimating Externalities of Oil Fuel Cycles
		Association of Oil Pipelines 2000 Association of Oil Pipelines Annual Report 2000
		1986 ASTM-IP Petroleum Measurement Tables
		U.S. EPA 1995 AP 42, Chapter 5, Petroleum Refining
A1:2	NREL U.S. LCI: Natural gas combusted in industrial boiler	Franklin Associates 2003 Data Details for Natural Gas Industrial Combustion
		Center for Transportation Research, Argo 2000 GREET Version 1.6
		EPA 1998 AP-42 Emission Factors. External Combustion Sources. Section 1.4 — NG Combustion

Process	**Data Item**	Sources
		U.S. EPA 1998 Study of Haz Air Pol Emis from Elec Utility Steam Gen Units V1 EPA-453/R-98-004a
		U.S. EPA Office of Solid Waste and Emerg 1999 Rep. to Congress on Wastes from the Combustion of Fossil Fuels EPA 530-R-99-010
		Assumption by Franklin Associates on fossil-fuel fired boiler systems
A1:3	Mining extraction and production of aggregate	Life Cycle Inventory of Portland Cement Concrete, SN3011, Portland Cement Association, 2007
A1:4	Electricity — line loss of 6.5% with U.S. average energy mix	GREET 2013
A2:2	NREL U.S. LCI: Transport, train diesel powered	Franklin Associates 2003 Data Details for Locomotive Transportation (Diesel)
		Center for Transportation Research, Argo 2001 GREET Version 1.6
		unspecified 9999 Based on assumption by Franklin Associates.
		Association of American Railroads 2002 Railroad Facts 2002.
A2:3, A2:4	NREL U.S. LCI: Transport, combination truck diesel powered	Franklin Associates 9999 Data Details for Combination Truck Transportation (Diesel)
		Center for Transportation Research, Argo 9999 GREET Version 1.6
		Assumption by Franklin Associates

Data Quality Indicators for Secondary Data
Most of the data in the US LCI database has undergone some sort of review; the database as a whole has not yet undergone a formal validation process.

	Representativeness	The data is representative of the U.S. average.
	Age	The age of the data is greater than 5 years.
	Time	It was modeled from various sources as shown above spanning 18 years.
	Geography	United States
	Technology coverage	National average data is used, not reflecting, differences in national refinery and electricity use data.
	Consistency	There may be some inconsistencies in the upstream datasets.
	Variability and uncertainty	There may be variability in datasets.

Appendix B: 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 C: Primary Data Input Tables for Mixes

Input Table — Primary Data for Mix 1

Energy		Units
Natural gas, combusted in industrial boiler (includes propane)	3.64E−01	Mcf/ton
Electricity, at grid	6.14E+00	kWh/ton
Residual fuel oil	0.00E+00	gal/ton
Diesel, combusted in industrial boiler	2.15E−01	gal/ton
Diesel, combusted in industrial equipment (Nos. 1, 2, 4, 5)	5.00E−02	gal/ton
Material		
Virgin aggregate	9.50E−01	ton/ton
Virgin binder (till delivered to gate from refinery/terminal)	5.00E−02	ton/ton
Recycled asphalt pavement (RAP) (Diesel use)	0.00E+00	ton/ton
Recycled asphalt shingles (RAS) (Diesel use)	0.00E+00	gal/ton
WMA — Additive: Water/Evotherm	—	gal/ton
Travel		
Distances travelled by truck	1.58E+01	ton-mile/ton
Distances travelled by barges	0.00E+00	ton-mile/ton
Distances travelled by rail	7.14E+00	ton-mile/ton
Water		
Volume of water used	4.80E−02	gal/ton

Input Table — Primary Data for Mix 2

Energy		Units
Natural gas, combusted in industrial boiler (includes propane)	2.33E−01	Mcf/ton
Electricity, at grid	2.33E+00	kWh/ton
Residual fuel oil	0.00E+00	gal/ton
Diesel, combusted in industrial boiler	0.00E+00	gal/ton
Diesel, combusted in industrial equipment (Nos. 1, 2, 4, 5)	3.43E−02	gal/ton
Material		
Virgin aggregate	7.50E−01	ton/ton
Virgin binder (till delivered to gate from refinery/terminal)	2.72E−02	ton/ton
Recycled asphalt pavement (RAP) (Diesel use)	2.50E−01	ton/ton
Recycled asphalt shingles (RAS) (Diesel use)	0.00E+00	gal/ton
WMA — Additive: Water/Evotherm	—	gal/ton
Travel		
Distances travelled by truck	3.00E+00	ton-mile/ton
Distances travelled by barges	0.00E+00	ton-mile/ton
Distances travelled by rail	3.88E+00	ton-mile/ton
Water		
Volume of water used	4.50E+00	gal/ton

Input Table — Primary Data for Mix 3

Energy		Units
Natural gas, combusted in industrial boiler (includes propane)	2.23E−01	Mcf/ton
Electricity, at grid	3.05E+00	kWh/ton
Residual fuel oil	0.00E+00	gal/ton
Diesel, combusted in industrial boiler	4.23E−02	gal/ton
Diesel, combusted in industrial equipment (Nos. 1, 2, 4, 5)	3.18E−02	gal/ton
Material		
Virgin aggregate	6.59E−01	ton/ton
Virgin binder (till delivered to gate from refinery/terminal)	3.44E−02	ton/ton
Recycled asphalt pavement (RAP) (Diesel use)	3.30E−01	ton/ton
Recycled asphalt shingles (RAS) (Diesel use)	0.00E+00	gal/ton
WMA — Additive: Water/Evotherm	—	gal/ton
Travel		
Distances travelled by truck	1.76E+01	ton-mile/ton
Distances travelled by barges	0.00E+00	ton-mile/ton
Distances travelled by rail	1.17E+00	ton-mile/ton
Water		
Volume of water used	8.69E−01	gal/ton

Input Table — Primary Data for Mix 4

Energy		Units
Natural gas, combusted in industrial boiler (includes propane)	1.00E+00	Mcf/ton
Electricity, at grid	4.13E+00	kWh/ton
Residual fuel oil	0.00E+00	gal/ton
Diesel, combusted in industrial boiler	1.94E−03	gal/ton
Diesel, combusted in industrial equipment (Nos. 1, 2, 4, 5)	2.96E−02	gal/ton
Material		
Virgin aggregate	7.62E−01	ton/ton
Virgin binder (till delivered to gate from refinery/terminal)	3.40E−02	ton/ton
Recycled asphalt pavement (RAP) (Diesel use)	3.04E−01	ton/ton
Recycled asphalt shingles (RAS) (Diesel use)	0.00E+00	gal/ton
WMA — Additive: Water/Evotherm	—	gal/ton
Travel		
Distances travelled by truck	4.60E+01	ton-mile/ton
Distances travelled by barges	0.00E+00	ton-mile/ton
Distances travelled by rail	1.91E+00	ton-mile/ton
Water		
Volume of water used	6.46E−02	gal/ton

Appendix D: Input/Output Inventory for Mixes

Input Inventory (for 1 U.S. short ton of asphalt mix)

Flow	Unit	Mix 1	Mix 2
Fuel grade uranium, at regional storage	sh ton	9.05E−09	5.39E−09
Lignite coal, at surface mine	sh ton	6.70E−04	3.99E−04
Natural gas, processed, at plant	m^3	1.05E+01	6.85E+00
Oil, crude, 43.7 MJ per kg, in ground	sh ton	7.40E−05	6.07E−05
Oil, crude	sh ton	3.11E−02	2.48E−02
Bituminous coal, at mine	sh ton	7.84E−03	4.69E−03
Disposal, solid waste, unspecified, to sanitary landfill	sh ton	9.82E−04	7.85E−04
Disposal, ash and flue gas desulfurization sludge, to unspecified reuse	sh ton	2.50E−04	1.49E−04
Disposal, lignite coal combustion byproducts, to unspecified reuse	sh ton	1.93E−05	1.15E−05
Disposal, solid waste, unspecified, to unspecified treatment	sh ton	9.01E−04	5.38E−04
Electricity, at wind power plant, unspecified	MJ	1.14E+00	6.80E−01
Electricity, fossil, unspecified, at power plant	MJ	1.90E−01	1.13E−01
Electricity, geothermal, unspecified	MJ	1.84E−01	1.09E−01
Electricity, hydropower, at power plant, unspecified	MJ	3.14E+00	1.87E+00
Electricity, photovoltaic, unspecified	MJ	1.46E−02	8.67E−03
Transport, pipeline, coal slurry	tonne-km	3.57E−02	2.14E−02
Transport, pipeline, unspecified	tonne-km	3.03E+01	2.24E+01
Carbon dioxide, in air	sh ton	1.63E−04	9.71E−05
Water, process	m^3	1.82E−04	1.70E−02

Input Inventory (for 1 U.S. short ton of asphalt mix)

Flow	Unit	Mix 3	Mix 4
Fuel grade uranium, at regional storage	sh ton	5.84E−09	4.70E−09
Lignite coal, at surface mine	sh ton	4.32E−04	3.48E−04
Natural gas, processed, at plant	m^3	6.29E+00	1.47E+01
Oil, crude, 43.7 MJ per kg, in ground	sh ton	6.04E−05	4.76E−05
Oil, crude	sh ton	2.62E−02	1.81E−02
Bituminous coal, at mine	sh ton	5.08E−03	4.09E−03
Disposal, solid waste, unspecified, to sanitary landfill	sh ton	8.28E−04	5.72E−04
Disposal, ash and flue gas desulfurization sludge, to unspecified reuse	sh ton	1.62E−04	1.30E−04
Disposal, lignite coal combustion byproducts, to unspecified reuse	sh ton	1.24E−05	1.00E−05
Disposal, solid waste, unspecified, to unspecified treatment	sh ton	5.83E−04	4.70E−04
Electricity, at wind power plant, unspecified	MJ	7.38E−01	5.94E−01
Electricity, fossil, unspecified, at power plant	MJ	1.23E−01	9.90E−02
Electricity, geothermal, unspecified	MJ	1.19E−01	9.55E−02
Electricity, hydropower, at power plant, unspecified	MJ	2.03E+00	1.63E+00
Electricity, photovoltaic, unspecified	MJ	9.40E−03	7.57E−03
Transport, pipeline, coal slurry	tonne-km	2.31E−02	1.86E−02

Transport, pipeline, unspecified	tonne-km	2.25E+01	2.79E+01
Carbon dioxide, in air	sh ton	1.05E−04	8.48E−05
Water, process	m^3	1.70E−02	1.59E−04

Specific outputs are as follows:

Output Emissions

Specific Emissions	Unit	Mix 1	Mix 2	Mix 3	Mix4
Carbon Dioxide (Total)	short ton	6.14E−02	3.71E−02	3.98E−02	5.46E−02
NO_x	short ton	9.02E−06	5.37E−06	5.82E−06	4.69E−06
SO_x	short ton	2.37E−04	1.70E−04	2.15E−04	1.35E−04
CH_4	short ton	1.13E−04	9.04E−05	9.54E−05	6.64E−05
CO	short ton	4.46E−04	3.52E−04	3.73E−04	2.80E−04
VOC	short ton	2.08E−05	2.62E−05	4.98E−05	7.31E−06
NMVOC	short ton	6.19E−05	4.93E−05	5.19E−05	3.59E−05

Appendix E: Conversion Factors

Conversion factors used:

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